Tekes projekti SuperMachines loppuraportti

Mika Salmi, Jouni Partanen, Jukka Tuomi, Sergei Chekurov, Iñigo Flores, Roy Björkstrand, Pekka Lehtinen

Aalto-yliopisto, Koneenrakennustekniikan laitos

Yhteystiedot:

Mika Salmi
Aalto-yliopisto
Koneenrakennustekniikan laitos
P.O.Box 14300, FI-00076 Aalto
Puumiehenkuja 5, Espoo
+358 50 512 2746
mika.salmi@aalto.fi

ISBN 978-952-60-3709-7 (pdf)
http://urn.fi/URN:ISBN:978-952-60-3709-7

Esipuhe

Tämä on loppuraportti Aalto-yliopiston Tekes rahoitteisesta elinkeinoelämän kanssa verkottuneesta tutkimusprojektista SuperMachines, jossa tutkittiin ja kehitettiin uudenlaisia materiaalia lisäävän valmistuksen mahdollistamia tuote- ja valmistuskonsepteja. Hanke toteutettiin aika välillä 1.1.2013 – 28.2.2015.

Aalto-yliopiston Insinööritieteiden korkeakoulun Koneenrakennustekniikan laitoksen Tulevaisuuden tuotantomenetelmien tutkimusryhmä haluaa kiittää Innovaatiorahoituskeskus Tekesiä, Genimate Oy:tä, DeskArtes Oy:tä, TP-Tools Oy:tä, Relicomp Oy:tä, Nokian Renkaat Oyj:tä, Multiprint Oy:tä, Wärtsilä Finland Oy:tä, sekä Nokia Oyj:n entistä matkapuhelinyksikköä nykyistä Microsoft Mobile Oy:tä projekti yhteistyöstä ja rahoituksesta.

Sisältö

1. Tausta

Tuotesuunnittelua rajoittavat käytettävissä olevat valmistusteknologiat ja niiden kustannukset. Tuotteiden valmistamiseksi perinteisin menetelmin täytyy investoida työvälineisiin ja apulaitteisiin, mistä johtuu, että tuotemuutokset johtavat lisäinvestointeihin. Pienten sarjojen ja asiakaskohtaisten tuotteiden toteuttaminen on hidasta ja kallista. Perinteisten suunnittelusääntöjen mukaan valmistettavan tuotteen geometria on kompromissi valmistuksen ja käyttötarkoituksen suhteen.

Materiaalia lisäävä valmistus (3D tulostus, pikvalmistus, Additive Manufacturing, AM, Rapid Prototyping and Manufacturing, RP & RM) tarjoaa joukon valmistusmenetelmiä, joilla voidaan toteuttaa joustavasti geometrioita, joita ei perinteisillä valmistusmenetelmillä pystytä valmistamaan. Nämä menetelmät eivät yleensä edellytä erityisiä työvälineinvestointeja ja niiden kustannukset täysin automatisoituina laitteina ovat melko riippumattomia paikallisesta palkkatasosta. Ainetta lisäävä valmistus on erittäin lupaava tuotantoteknologia Suomen kaltaisille maille, joissa tuotetaan korkean teknologian ja jalostusasteen tuotteita.

> *Pikavalmistuksella tarkoitetaan fyysisen kappaleen valmistusta materiaalia lisäävällä menetelmällä suoraan numeerisen määrittelyn (3D-CAD) pohjalta kerros kerrokselta nopeasti, täysin automaattisesti, geometrisilta rajoituksiltaan vapaassa prosessissa.*

Materiaalia lisäävä valmistus mahdollistaa toimivien mekanismien valmistamisen ilman erillistä kokoonpanotyötä. Tätä ei toistaiseksi ole juuri hyödynnetty kuin messu- ja näytekappaleiden valmistuksessa. Suunnittelu- ja mitoitusohjeilla pystytään edesauttamaan vaativien kappaleiden suunnittelua ja nopeuttamaan käyttöönottoa. Teollisuudessa mekanismeilla ilman kokoonpanotyötä voidaan saavuttaa kustannusetua tai se mahdollistaa sellaisten mekanismien valmistamisen, joita ei ole aikaisemmin voitu perinteisin menetelmin valmistaa. Useampien materiaalien samanaikaisen valmistuksen tultua mahdolliseksi voidaan valmistaa toimivia kokoonpanoja, joissa eri osissa on erilaiset materiaaliominaisuudet. Selvästikin tällainen mekaniikka on omiaan erikoiskohteissa ja pienen mittakaavan monimutkaisissa laitteissa. Taloudellinen kannattavuus saavutetaan todennäköisemmin laitteilla, joilla päästään hyödyntämään välillisiä hyötyjä – esimerkiksi korvaamalla laajahko monesta komponentista koostuva mekaniikka huomattavasti aiempaa monimutkaisemmalla mutta kompaktimmalla ratkaisulla.

Materiaalia lisäävää valmistusta on käytetty muun muussa polttoainesuuttimissa ja lentokoneen suihkumoottorin kuorien kiinnityssaranoissa (Kuva 1). Molemmissa on erityisen tärkeää geometrian optimointi. Polttoainesuuttimessa voidaan optimaalisemmalla geometrialla parantaa polttoaineen virtausta. Myös luotettavuus lisääntyy, koska kokoonpantavia osia ja näin ollen juotossaumoja on vähemmän. Parempi luotettavuus pienentää huolto- ja varaosakustannuksia. Samalla myös asiakkaalle tuolee mahdollisuus nostaa käyttöastetta. Materiaalia lisäävällä kiinnityssaranalla saavutetaan samat lujuusominaisuudet, kuin perinteisesti valmistetulla, mutta se on 50% kevyempi. Noin yhden kilon painonsäästö säästää lentokoneen elinaikana noin 3 tonnia polttoainetta [17].

Kuva 1. Uuuden sukopolven polttoainesuutin Morris Technologies, Inc

Sarana suihkumoottorin kuorille perinteinen (yllä), uusi malli (alla) EADS

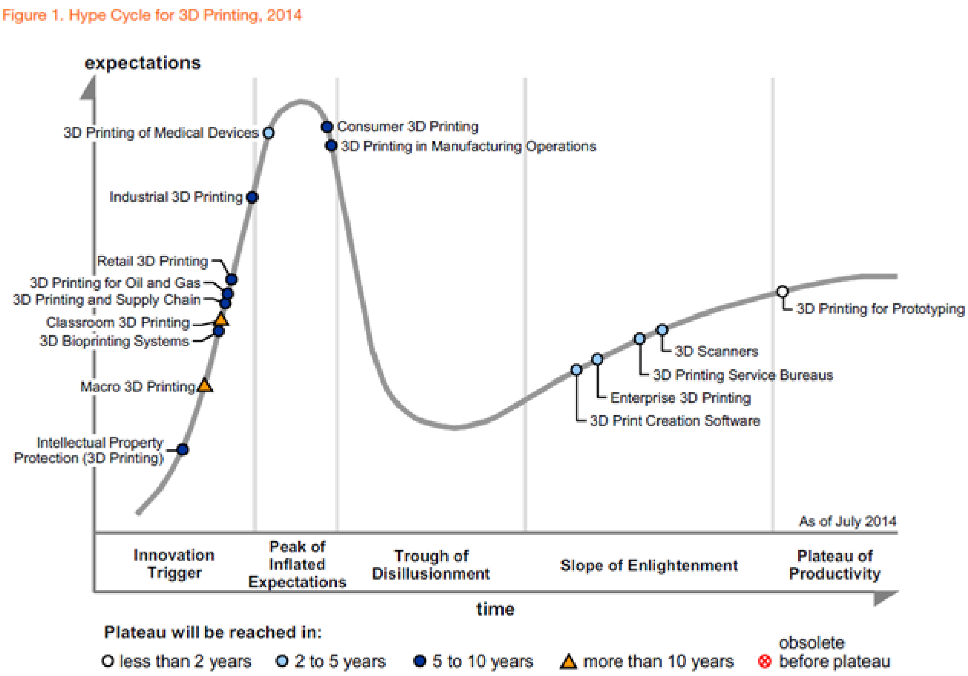
Materiaalia lisäävän valmistusmenetelmien ja materiaalien osalta kehitys on ollut viime vuosina erittäin nopeaa (myytyjen laitteiden määrä on kasvanut keskimäärin 30 % vuodessa). Markkinoille on tullut useita materiaaleja yhdistäviä laitteita, erittäin läpinäkyviä materiaaleja, bioyhteensopivia polymeerejä, joustavia materiaaleja, sekä high-end muoveja kuten PEEK ja ULTEM. Myös metallisten kappaleiden valmistusteknologioiden saralla on tapahtunut nopeaa kehitystä tarkkuuden ja laadun osalta. Viime vuosina on myös esitelty täysin uusia potentiaalisia pikavalmistusteknologioita, kuten esim. selective heat sintering (SHS).

Laskentaa ja simulointia käytetään nykyisin paljon erilaisten geometrioiden lujuusominaisuuksien mallinnuksessa. Jos halutut lujuusominaisuudet ovat tiedossa, on mahdollista optimoida kappaleen geometria tätä lopputulosta silmällä pitäen unohtaen perinteisten valmistusmenetelmien rajoitukset. Näin optimoidut geometriat olisivat mahdollista valmistaa ja saavuttaa tuotteisiin lisäarvoa tai aivan uusia ominaisuuksia. Sovelluksia optimoidulle geometrialle olisi esim. akustiikassa, virtausteknisissä laitteissa ja kevytrakenteissa.

Suomalaiset ja kansainväliset lehdet ovat huomanneet pikavalmistuksen potentiaalin. The Economistissa on esiintynyt kaksikin artikkelia. Toisessa esiteltiin lasersintraus teknologialla valmistettu viulu ja toisessa pohdittiin millainen on tulevaisuuden maailma, jossa suurin osa valmistuksesta suoritetaan pikavalmistamalla[10, 11]. The Guardian pohti, voiko pikavalmistus lopettaa nykyisen kertakäyttökulttuurin [12]. Newscientist kirjoitti jutun, jossa esiteltiin ensimmäistä kokonaan pikavalmistettua pienen radio-ohjattavan lentokoneen runkoa [13]. Myös Aamulehdessä ja Talouselämässä on kirjoitettu pikavalmistuksesta [8,9]. Yhdysvaltoihin ollaan perustettu National Additive Manufacturing Innovation Institute (NAMII), jonka tarkoituksena on viedä pikavalmistusta ja sen sovelluksia eteenpäin Yhdysvalloissa. Insituutti on saanut 30 M$ rahoitusta valtiolta ja 40 M$ rahoitusta yrityksiltä, yliopistoilta ja muilta tahoilta [14]. Iso-Britannissa hallitus on päättänyt investoida 7 M£ pikavalmistuksen kehittämiseen [15]. Kiina on suunnitellut investoivansa 80 M$ 3D-tulostus innovaatiokeskuksen perustamiseen [18]. Myös Singapore on vahvasti investoimassa tulevaisuuden valmistusteknologioihin 500M$ panostuksella seuraavan viiden vuoden aikana [19].

Tietoisuus materiaalia lisäävän valmistuksen periaatteista on lisääntynyt merkittävästi, mutta sen hyödyntäminen ei ole helppoa. Valitsemalla väärä menetelmä, sovellukseen tulos on huono ja tämä hidastaa aiheetta sen yleistymistä. Saadun julkisuuden ja alalla tapahtuvan nopean kehityksen perusteella voidaan todeta, että pikavalmistus tulee lisääntymään tulevaisuudessa radikaalisti. Myöhästyminen tämän teknologian hyödyntämisessä voi tarkoittaa pahimmillaan kilpailukyvyn ratkaisevaa heikkenemistä. Materiaalia lisäävän valmistuksen teolliset sovellukset luokitellaan tyypillisesti prototyyppien, työvälineiden ja komponenttien valmistukseksi (kuva 2) [1,2,3,4]. Gartnerin 3D tulostuksen hypekäyrässä (Kuva 3) prototyyppejä ja työkaluja voidaan muutaman vuoden päästä pitää arkipäivänä, mutta komponenttien valmistuksen arkipäiväistyminen vienee vielä 5-10 vuotta [20]. Tosin yksittäisissä komponentti sovellutuksissa materiaalia lisäävä valmistus voi olla arkipäivää jo aikaisemmin, eikä sitä juurikaan missään mainosteta tai kerrota. Esim. kuulolaitteiden kuoret tehdään pääasiassa 3D tulostamalla ja näin ovat suurimmat valmistajat tehneet jo kymmenen vuoden ajan [21].

Kuva 2. Materiaalia lisäävän valmistuksen teolliset sovellukset – uutuutena komponenttien tuotantosovellukset.

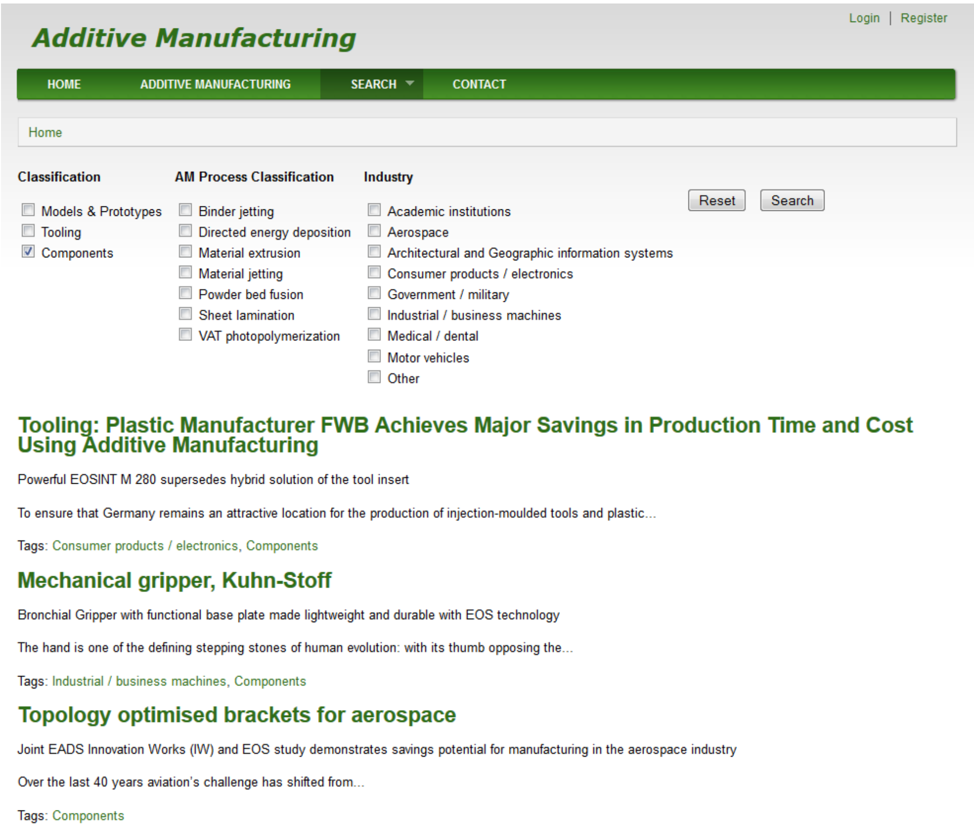


Kuva 3. 3D tulostuksen Hype käyrä. Gartner heinäkuu 2014 [20].

2. Best Practice - aineisto

Best Practice aineistoa kerättiin kansainvälisen kirjallisuustutkimuksen ja tutkijoiden henkilökohtaisia verkostoja apuna käyttäen. Aineistoon etsittiin erilaisia esimerkkejä materiaalia lisäävän valmistuksen teollisista sovelluksista, suunnitteluparametreista, sekä lopputuotteiden tai asiakkaalle toimitettavan tuotteen tai palvelun tuottamisesta. Aineistosta tuotettiin internetpohjainen datapankki, joka on avoimesti saatavilla osoitteessa: http://www.amcase.info/. Aineistoa pystyy hakemaan sen mukaan onko kyseessä malli, prototyyppi, työkalua vai komponentti. Haussa on mahdollista valita tietty ASTM standardin [16] mukainen prosessi luokitus, sekä mille teollisuuden alalle case sijoittuu (Kuva 4). Vaikuttavuuden ja ihmisten tavoittamisen lisäämiseksi Suomen Pikavalmistusyhdistys FIRPA ry on lisännyt internet sivuilleen http://www.firpa.fi/ linkin kyseiseen am-case pankkiin. Linkki löytyy kohdasta: AM-tietoa –> AM-casepankki. (http://www.firpa.fi/html/am-tietoa.html).

Case pankkiin pystyy rekisteröitymään kuka vaan. Rekisteröityminen mahdollistaa casejen syöttämisen. Katseluun ei vaadita rekisteröintiä. Tavoite on kerätä case pankkiin lisää tietoa ja pyrkiä siihen että kriittinen massa saavutettaisiin, jolloin ihmiset alkaisivat syöttää itse pankkiin tietoa, eikä tietoa kasaantuisi vain muutaman tutkijan voimin. Case pankkia käytettiin myös opetuksen apuna Aalto Yliopiston kurssilla Kon-15.4126 Production Technology, special topics (3 op). Kevään 2014 kurssin oksiskelijoita pyydeltiin lisäämään case pankkiin heidän mielestään mielenkiintoisia caseja. Aivan suurta suosioita tämä ei saavuttanut, mutta tätä on tarkoitus yrittää uudelleen keväällä 2015.



Kuva 4. Esimerkki haku AM-case pankista.

AM-case pankista löytyy tällä hetkellä noin 30 eri prosessilla ja eri teollisuuden alalla tehtyä merkittävää ja innovatiivista sovellusta. Caset on pyritty kuvaamaan tehokkaasti antamalla ensin hieman taustaa, sitten kuvauksen ongelmasta / tavoitteista ja ratkaisuehdotuksen (Kuva 5). Lisäksi kaikkiin caseihin on pyritty poimimaan hyviä kuvia tehdyistä kappaleista. Kuvauksen lopusta löytyvät myös tekniset tiedot käytetystä prosessista ja prosessiluokasta, sekä teollisuuden alasta.

Mechanical gripper, Kuhn-Stoff

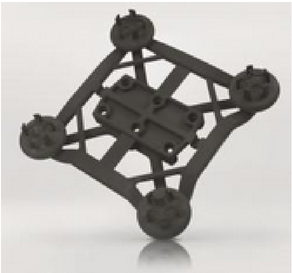
Submitted by ldmuser on Tue, 2013-10-22 10:00

Bronchial Gripper with functional base plate made lightweight and durable with EOS technology

The hand is one of the defining stepping stones of human evolution: with its thumb opposing the other fingers, the human hand is an ideal tool for gripping, exploring, and working. As such, it is the key to cultural activity and technical progress. Industry often exploits this ingenious principle: one of the processes for which machines are used is the automated gripping of almost any desired part for transporting to the next operational step.

Such gripping machines are masterpieces of engineering. Kuhn-Stoff GmbH & Co KG has dedicated itself to specialized engineering through the application of EOS Additive Manufacturing technology. The process entails the formation of machine parts, layer by layer, from plastic powder that is melted with a laser beam. In this way, Kuhn-Stoff has developed and produced an extremely lightweight, strong, and durable bronchial gripper for Wittmann Robot Systeme GmbH, in Nuremberg, Germany. Four of these grippers sit on a support frame with integrated pneumatic ducts.

Challenge:
The customer is a manufacturer of robots and automation systems. Kuhn-Stoff was asked to re-design a mechanical gripper that raises, transports, and then sets down machine parts from a production machine via a pneumatic mechanism. The following requirements were established: the gripper should be lighter than its predecessor, while still being capable of moving the required loads. The complexity of the design should be simplified and the part must be able to satisfy efficiency criteria. The significance of the weight comes down to physics: grip systems such as this must work quickly in order to move as many machine parts as possible within a given unit of time. The fact that mass is inert means that force must be applied to set it in motion – the heavier a load is, and the faster it moves, the greater the forces necessary for both acceleration and deceleration. Quite apart from the viewpoint of energy efficiency, this fact also has particularly negative consequences on the durability of the system: the greater the forces in play, the higher the wear on the machine. The previous version of the gripper was made from aluminum, rubber tubes, and multiple connecting elements, and was expensive to produce. The layer manufacturing experts from Kuhn-Stoff set themselves the goal of significantly simplifying the design. The new structure of the machine part should contribute to a portion of the weight reduction. Another portion should be arrived at through structural optimization of the remaining parts – one of the central advantages of Additive Manufacturing. As work began it soon became clear that the new gripper could be produced as a single piece, without the need for post-production finishing or further assembly.
Solution:
The team from Kuhn-Stoff began by examining the functionality and working requirements of the gripper: when compressed air flows into a flexible membrane, the claws of the gripper will open; likewise the system closes when the compressed air is turned off. In addition to the plastic's flexibility, the part should be able to swivel through 90° to carry out the necessary motion sequence. Taking these requirements into consideration, it was possible to reduce the necessary number of parts to just two components. With the completion of the design process, Kuhn-Stoff began work on the production of the new grip system using a FORMIGA P 100. In just a few hours the two components of the grip system were produced from polyamide. Thanks to EOS technology the pneumatic ducts and connectors were fully integrated in the base plate. "As usual, production using the EOS system was smooth and problem-free. The end result, once again, impressed all those involved. In a single process step we were able to create a functionally integrated part that exceeded all of the requirements of the client. In short: Additive Manufacturing is now an every-day reality, but the results are still extraordinary," says Hannes Kuhn, CEO at Kuhn-Stoff GmbH.
Case Images:

Technical Information

Classification: Components
AM process Classification:
Powder bed fusion
Additive Manufacturing Technology: Selective Laser Sintering (SLS)
Industry: Industrial / business machines

Kuva 5. Esimerkki sivuilta löytyvästä case kuvauksesta.

3. Pikavalmistettavan kappaleen suunnitteluohjeet

Materiaali lisäävästi valmistettaville kappaleille ei ole suunnitteluohjeita saatavilla lähinnä kuin palveluntarjoajien toimesta. Näissä ohjeissa ei ole kuin ohjeita niille prosesseille ja materiaaleille mitä palveluntarjoajalla on tarjolla. Materiaalia lisäävä valmistus mahdollistaa perinteisten valmistusmenetelmien tuomien rajoitusten kiertämisen, mutta tuo mukanaan menetelmä- ja materiaalikohtaisia yksityiskohtia, jotka täytyy ottaa huomioon suunniteltaessa kappaleita sillä valmistettavaksi.

3.1Suunnitteluohjeet prosessin mukaan

Projektin puitteissa kerättiin tutkimusryhmän kokemuksen perusteella suunnitteluarvoja yleisemmille käytössä oleville prosesseille. Näitä arvoja sitten verrattiin eri palveluntarjoajilta saataviin tietoihin ja niistä koostettiin kuvan 6 mukainen ohjeistus. Kansallisen tietoisuuden lisäämiseksi suunnitteluohje julkaistiin Suomen pikavalmistusyhdistys Firpan internet-sivuilla: http://firpa.fi/html/am-tietoa.html, kohdassa Suunnitteluohje. Suunnitteluohjeessa prosessien kauppanimet on luokiteltu ASTM standardin mukaisen luokittelun alle. Ohjeesta löytyy suositeltu minimi seinämänvahvuus, suositellun pienimmän yksityiskohdan koko, tyypillinen markkinoilta löytyvä rakennuskammin koko, tyypilliset materiaalit ja käyttötarkoitus, sekä kommentti kenttään kerätty prosessin erityispiirteitä.

AM Standarized process category	Commertial definition	Recomended Min. Wall Thickness	Recomended Min. Details	Typical Max. Build volume	Typical Material capabilities	Typical Use	Comments
Binder Jetting	Three Dimensional Printing (3DP)	1.5 to 2 mm	0.8 mm	340 x 240 x 200 mm	C (19)	RP	Excellent for demonstration models with color printing.
	Voxeljet (Sand Casting)	1 mm	0.8 to 1 mm	4000 x 2000 x 1000 mm	S (20)	RT	Typical use for manufacturing of castings molds
	Binding and sintering porcesses	1 mm	0.8 to 1 mm	762 x 393 x 393 mm	M (13,14, 15, 16, 17, 18)	RM	A porcess in which a powder bed is binded layer by layer and then sintered in a oven for end use aplications
Direct Energy Deposition	Laser-Engineered Net Shaping (LENS)	1 mm	0.5 mm	900 x 1500 x 900mm	M (13,14, 15, 16, 17, 18)	RT, RM	Production of tooling, hybrid manufacturing, reverse engineering and repair medical and aeronautic aplications
Material Extrusion	Fused Deposition Modeling (FDM)	1 mm	0.3 mm	400 x 355 x 400 mm	P (1, 2, 3, 4, 5, 6)	RP, RM	Ideal for Conceptual models, Engineering models, and Functional testing prototypes
Material Jetting	Polyjet	1 mm	0.2 to 0.3 mm	500 x 400 x 200mm	P (7, 8, 9, 10, 11, 12)	RP	Multimaterial printing possibilities (Connex series machines)
	Multijet Modeling (MJM)	0.7 mm	0.2 mm	150 × 150 × 150 mm	P (7, 8, 9, 10, 11, 12)	RP	Models with color printing, hard plastic or cast-friendly wax parts. Applications ranging from concept models to RM
Powder Bed Fusion	Selective Laser Sintering (SLS)	0.7 to 1 mm	0.5 mm	650 x 330 x 560 mm	P (2)	RP, RM	Ideal for durable, functional parts, capable of producing snap fits and living hinges
	Direct Metal Laser Sintering (DMLS)	0.3 mm	0.127 mm	400 x 400 x 400 mm	M (13,14, 15, 16, 17, 18)		Industrial demanding applications, for automotive, aeronautics, engineering, medical and dental engineering
	Selective Laser Melting (SLM)	0.3 mm	0.180 mm	500 x 280 x 325 mm	M (13,14, 15, 16, 17, 18)	RM	Industrial demanding applications, for automotive, aeronautics, engineering, medical and dental engineering
	Electron Beam Melting (EBM)	1 mm	0.3 mm	Ø350 x 380 mm	M (16,17,18)	RM	Industrial demanding application, for orthopedic implants and aerospace applications
	Selective Heat Sintering (SHS)	1 mm	N/A	200 x 157 x 140 mm	P (2)	RP	Functional samples of prototypes for tests and use in practice, before putting the final product into production.
Sheet Lamination	Laminated Object Manuafcturing (LOM)	1 mm	0.205 mm	812 x 559 x 508 mm	SM (21)	RP, RT	Form/fit testing, Less detailed parts an dtoling patterns
Vat Photopolymerization	Stereolithography (SLA)	1 mm	0.3 mm	2100 x 700 x 800 mm	P (7, 8, 9, 10, 11, 12)	RP, RT, RM	Demo models, accurate models and models with limited functionality.
	Digital Light Processing (DLP)	1 mm	0.5 mm	192 x 120 x 230 mm	P (7, 8, 9, 10, 11, 12)	RP, RT	prototyping and investment casting or lost wax casting aplication

P - Plastics	Thermoplastic materials	ABS	1
		Polyamide	2
		PLA	3
		PC	4
		Ultem	5
		Thermoplastic blends (PC-ABS, Bio PLA, etc...)	6
	Thermoset photopolymers	High detail resin	7
		Transparent resin	8
		Coloured plastics	9
		Rubber-like	10
		ABS-like	11
		PP-like	12
M - Metals	Ferrous materials	Stainless steel	13
		Maraging Steel (tool steels)	14
	Non-Ferrous materials	Aluminum Alloy	15
		Titanium Alloys	16
		CoCr Alloys	17
		Nickel Alloys (Inconel)	18
C - Ceramics		aluminun oxides	19
S - Sand casting		SiO2	20
SM - Sheet Materials			21

Rapid Prototyping (RP):
AM of a design, often iterative, for form, fit, or functional testing, or combination thereof.

Rapid Tooling (RT):
The use of AM to make tools, either directly, by making parts that serve as the actual tools or tooling components, such as mold inserts. Or indirectly, by producing patterns that are used in a secondary process to produce the actual tools.

Rapid Manuafcturing (RM):
The use of AM for direct part production to be used in end applications.

Kuva 6. Suunnitteluohjeet

3.2 Suunnitteluohjeet liikkuville non-assembly kappaleille

Materiaalia lisäävillä menetelmillä voi rakentaa kappaleita, jotka ovat valmistuessaan kokoonpanoja. Tämä tarkoittaa sitä, että kokoonpantavuus ei ole ongelma, ja että voidaan valmistaa kappaleita, joita ei käsin voisi kokoonpanna. Kokoonpantujen kappaleiden rakentamisen rajoitukset ovat hyvin läheisesti tekemisissä porrasvaikutuksen, rakennusorientaation ja tukirakenteiden kanssa.

Akseleiden ja pallonivelten ollessa pyöreitä porrasvaikutus on hyvin tärkeä tekijä. Mitä pahempi porrasefekti on, sitä jäykemmin akseli pyörii ja pallonivel kääntyy. Akseleiden kohdalla rakennusorientaatio ratkaisee porrasvaikutuksen määrän. Porrasefekti on suurimmillaan kun akseli valmistetaan vaakasuunnassa ja pienimmillään kun se valmistetaan pystysuunnassa.

Tukirakenteiden poistaminen on suurin yksittäinen tekijä kokoonpantujen kappaleiden valmistuksessa. Parhaiten soveltuvissa valmistusmenetelmissä jauhemaiset tukirakenteet voi puhaltaa ulos. Painevedellä poistettavat tukirakenteet ovat myös hyviä, mutta ne tarvitsevat isompia poistumiskanavia ja niiden poistumiskyky rajoittuu paineveden tavoittamalle alueelle. Samasta materiaalista tehdyt tukirakenteet ovat haastavia ja joissain tapauksissa lähes mahdottomia poistaa.

Teknologioiden soveltuvuus kokoonpantujen kappaleiden valmistukseen perustuu laajalti siihen kuinka helppo tukirakenteita on poistaa. Taulukossa 1 on lueteltu materiaalia lisäävän valmistuksen seitsemän teknologiaryhmää ja niiden tukirakenteiden poistamiseen yleisimmin käytetyt toimenpiteet.

Taulukko 1. Teknologioiden tukirakenteiden poistamismenetelmät

Teknologiaryhmä	**Yleisin tukirakenteiden poistamismenetelmä**
Binder Jetting	Paineilma
Directed Energy Deposition	Mekaaninen
Material Extrusion	Liuottaminen
Material Jetting	Painevesi
Powder Bed Fusion	Paineilma
Sheet Lamination	Mekaaninen
Vat Photopolymerization	Mekaaninen

Parhaiten teknologioista kokoonpantujen kappaleiden valmistamiseen taulukon perusteella soveltuvat binder jetting ja powder bed fusion. Binder jettingissä käytetään kuitenkin tällä hetkellä hyvin haurasta materiaalia, joten liikkuvien kappaleiden valmistaminen tällä teknologialla ei ole toteuttamiskelpoista. On huomionarvoista, että koska powder bed fusion-prosessissa käytetään lämpöä, rajoittaa se pienten välysten valmistusta suuresti. Material jettingin tukirakenteet voi poistaa painevedellä, joten se on varteenotettava ehdokas tukirakenteiden poistamiseen. Material extrusionin liuottamismenetelmällä poistettavat tukirakenteet tekevät siitä myös hyvän teknologian tähän tarkoitukseen. Directed energy deposition, sheet lamination ja vat photopolymerization vaativat tukirakenteiden mekaanista poistoa, minkä takia niiden käyttäminen kokoonpantujen kappaleiden valmistamiseen ei ole käyttökelpoista. Sheet laminationista on lisäksi tällä hetkellä kaupallisesti tarjolla vain paperia tai metallikalvoa materiaalina käytettäviä laitteita.

Jotta tietyn laitteen kyvykkyys kokoonpantujen kappaleiden valmistuksessa saadaan selville, pitää valita oikeat ominaisuudet testattavaksi. Näitä ovat aksiaalinen minimivälys, radiaalinen minimivälys ja pienin rako.

(a) (b) (c)

Kuva 7. (a) Aksiaalisen minimivälyksen testausgeometria. (b) Radiaalisen minimivälyksen testausgeometria. (c) Pienimmän raon testausgeometria

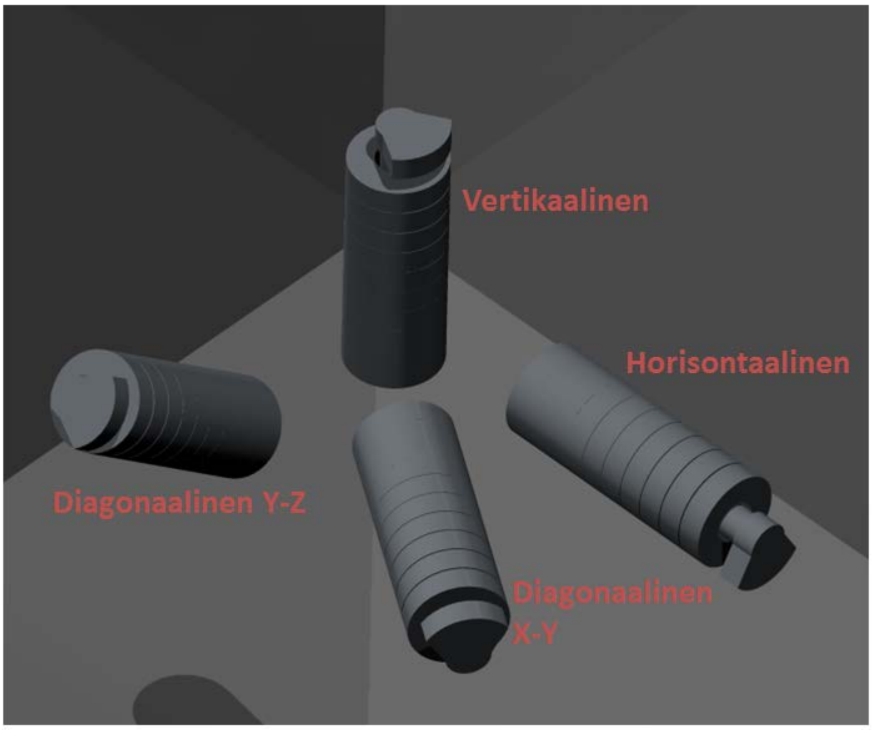
Geometrioiden välykset pienimmästä suurimpaan ovat:

0,01 mm	0,02 mm	0,05 mm
0,09 mm	0,1 mm	0,15 mm
0,2 mm	0,2 mm	0,3 mm

Jokainen geometria asetetaan valmistettavaksi neljässä eri orientaatiossa: x-akselille, z-akselille, 45 asteen kulmassa x- ja z-akseleiden välille, sekä 45 asteen kulmassa x- ja y-akseleiden välille. 3D-mallien pohjassa on lukuja, jotka kertovat mihin asentoon kappale tulee. Tämä auttaa muistamaan, mikä kappale oli missäkin asennossa tukimateriaalin poistamisen jälkeen. Taulukossa 2 ja kuvassa 8 näytetään miten kappaleet tulee asetella.

Taulukko 2. Rakennussuuntien selitys

Numero	Akseli
Horisontaalinen	X
Diagonaalinen Y-Z	45 asteen kulmassa Y:n ja Z:n muodostamassa tasossa
Diagonaalinen X-Y	45 asteen kulmassa X:n ja Y:n muodostamassa tasossa
Vertikaalinen	Z



Kuva 8. Testikappaleiden asettelu

Tulosten analysoimiseen käytetään binäärijärjestelmää eli rengas joko pyörii tapin ympärillä tai ei, sekä rako on selkeä tai ei. Tässä projektissa suoritettiin testit Objet 30- ja uPrint SE+-laitteille. Testien tulokset löytyvät taulukoista 3-4.

Taulukko 3. Objet 30:n kokoonpantujen kappaleiden suunnitteluohjeet

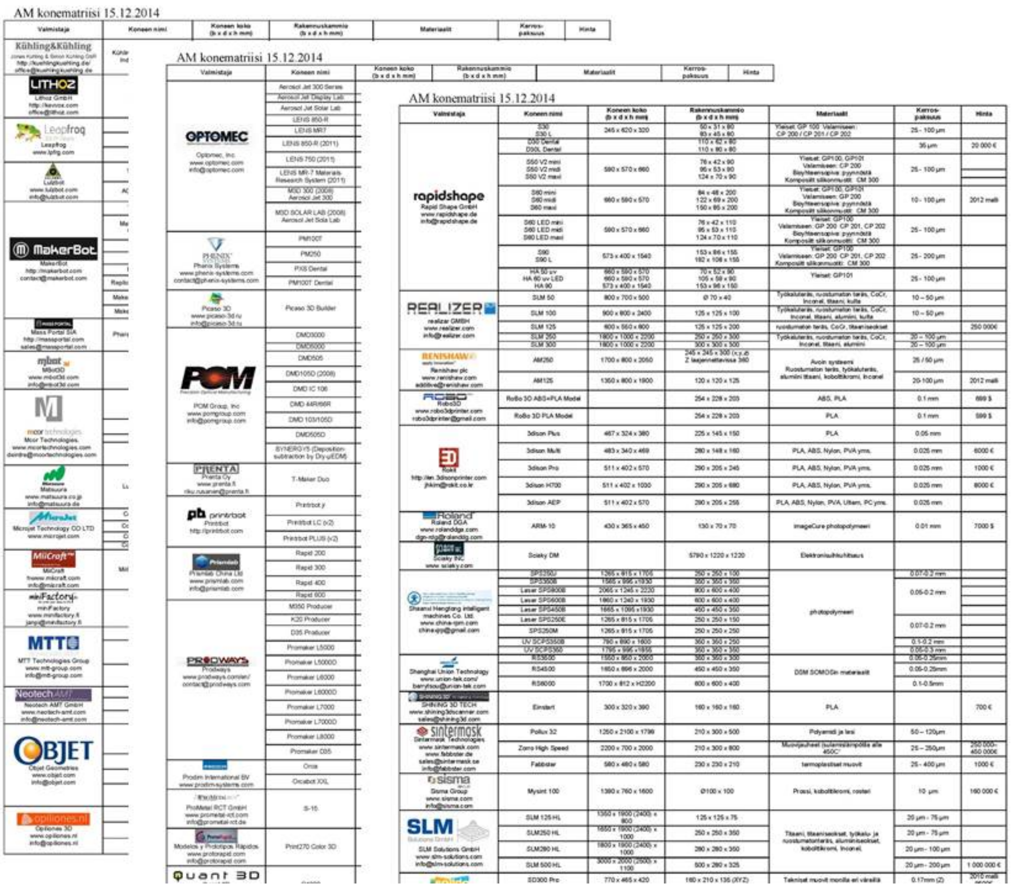
	Piirre		
Rakennussuunta	**Radiaalinen välys (mm)**	**Aksiaalinen välys (mm)**	**Pienin rako (mm)**
Horisontaalinen	0,15	0,05	0,15
Vertikaalinen	0,15	0,15	0,15
Diagonaali Y-Z	0,2	0,15	-
Diagonaali X-Y	0,2	0,2	0,2

Taulukko 4. uPrint SE+:n kokoonpantujen kappaleiden suunnitteluohjeet

	Piirre		
Rakennussuunta	**Radiaalinen välys (mm)**	**Aksiaalinen välys (mm)**	**Pienin rako (mm)**
Horisontaalinen	0,25	0,25	0,15
Vertikaalinen	0,3	0,05	-
Diagonaali Y-Z	0,25	0,25	-
Diagonaali X-Y	0,25	0,3	0,15

4. Teknologiakehitys

Viime vuosina on materiaalia lisäävissä teknologioissa havaittu nopeaa kehitystä prosessien ja materiaalien osalta. Kehitys on vain nopeutunut aikaisempiin vuosiin verrattuna ja onkin havaittavissa, että materiaalia lisäävät teknologiat ovat kilpailukykyisiä yksittäiskappaleissa sekä pienissä sarjoissa verrattuna perinteisiin valmistusteknologioihin. Hankkeen aikana on ylläpidetty tietoa markkinoilla olevista laite ja materiaalitoimittajista, sekä saatavilla olevista laitteista ja materiaaleista. Ajantasainen listaus laitteista ja materiaaleista löytyy Suomen pikavalmistus yhdistyksen sivuilta: http://firpa.fi/html/am-tietoa.html kohdasta AM-matriisi. Kuvassa 9 on esimerkki muutamasta sivusta listalta. Projektin alkaessa vuonna 2013 listalla oli noin 50 eri laite valmistajaa ja noin 200 erilaista laitetta. Vuoden 2014 loppuun mennessä listalla oli noin eri 100 laitevalmistajaa ja melkein 500 erilaista laitetta. Lista on teollisten laitteiden osalta yksi maailman kattavimmista vapaasti saatavilla olevista listauksista. Listalle ei ole edes pyritty keräämään kaikkia mahdollisia kotitulostin valmistajia, sillä lista on tarkoitettu teollisuuden käytettäväksi. Kahdessa vuodessa on nähty huima valmistajien ja laitemäärän lisääntyminen. Taulukkoon 5. on kerätty merkittävimpiä laitejulkistuksia vuosilta 2013 – 2014.



Kuva 9. Esimerkki AM-matriisista – materiaalia lisäävän valmistuksen valmistaja- ja laitelistaus.

4.1 Merkittävimmät uudet julkistukset 2013-2014

Taulukko 5. Merkittävimmät laitejulkistukset 2013 - 2014

Yritys	Laite		Hintaluokka	ASTM luokka
3D Factories	MAXI3DPRINTER	1000 x 1000 x 1000 -laajennettavissa 6000?, lämmitetty kammio	78 k€	Material Extrusion
3D Systems	Prox 500	381 x 330 x 457, SLS muovi	450 k€	Powderbed fusion
	Prox 300	250 x 250 x 300, DMP metalli	550 k€	Powderbed fusion
	Prox 950	1500 x 750 x 550, stereolitografia, 2 laseria	1 M€	Vat photopolymerization
	Projet 4500	203 x 254 x 203, CJP, värilliset kappaleet, ei jälkikäsittelyitä	53 k€	Binder jetting
	Prox 400	500 x 500 x 500 metalli, 2 x 500W laseria,vaihdettava rakennuskammio	1 M€	Powderbed fusion
Arburg	Freeformer	3 tai 5 akselinen, materiaalien yhdistämien mahdollista, materiaali pelletteinä	120 k€	Material Extrusion
Arcam	Q10& Q20	ortopediset implantit sarjatuotanto, kamerapohjainen laadunvalvonta		Powderbed fusion
Bigrep	BigRepOne	1060 x 1070 x 1105	36 k€	Material Extrusion
Blueprinter	BluePrinter SHS	Uusi selective heat sintering teknologia	19 k€	Powderbed fusion
Concept Laser	M2 Cusing multilaser	2 laseria, 250 x 250 x 280	600 k$	Powderbed fusion
DMG Mori	Lasertec 65	Hybridi, materiaalin lisäys ja koneistus	1 M€	Direct energy deposition
DWS System	Xfab	SLA	5 000 €	Vat photopolymerization
EOS	M400	400 x 400 x 400, mahdollisuus 4 laseria x 400W	1.25 M€	Powderbed fusion
	P396	340 x 340 x 600, 15% tuottavampi kuin aikaisempi sukupolvi		Powderbed fusion
Envisiontec	Xtreme 3SP	254 x 381 x 330 liikuteltava laserlähde ja optiikka	100 k€	Vat photopolymerization
		457 x 457 x 457 liikuteltava laserlähde ja optiikka	240 k€	Vat photopolymerization
Fabrisonic	SonicLayer tuoteperhe	Metallikalvojen ultraäänihitsaus, usemman materiaalin yhditäminen		Sheet lamination
Formalabs	Form 1	Stereolitografia, 125 x 125 x 165	3300 $	Vat photopolymerization
Keyence	Agilista 3100W	297 x 210 x 200	50 k€	Material Jetting
Makerbot	Replicator Z18	305 x 305 x 457, lämmitetty kammio	7 000 €	Material Extrusion
Prodways	K20 Producer	myös pastamaiset materiaalit (keraamit, metallit) 150 x 500 x 150	350 k€	Vat photopolymerization
	D35 Producer	DLP pohjaiset, projektorin liikutus, 720 x 230 x 100	250 k€	Vat photopolymerization
	M360 Producer	DLP pohjaiset, projektorin liikutus, 840 x 660 x 550	350 k€	Vat photopolymerization
	Promaker series	DLP pohjaiset, projektorin liikutus		Vat photopolymerization
Quant 3D	Q1000	350 x 350 x 350, lämmitetty kammio	20k€	Material Extrusion
Realizer	SLM 125	125 x 125 x 200, 200-400 W	250 k€	Powderbed fusion
Sisma laser	Mysint 100	Ø100 x 100	160 k€	Powderbed fusion
SLM Solutions	SLM 500HL	4 laseria	1 M€	Powderbed fusion
Stratasys	Fortus 450 & 380 mC	406 x 355 x 406 & 355 x 305 x 305		Material Extrusion
	Objet Eden 260VS	liukenevat supportit		Material Jetting
	Objet Connex3	82 eri väriä samassa material jetting osassa		Material Jetting
Xery	Victory SLS	350 x 350 x 650 SLS	200k$	Powderbed fusion
Voxel8	Voxel8	3D tulostettu elektroniikka, PLA materiaalin pursotus ja hopeapasta	9000 $	Material Extrusion
Voxeljet	VX2000	2000 x 1000 x 1000	1 M€	Binder jetting
WAY2Production	Solflex 350 26k€	60 x 120 x 110 Liikkuva DLP, Pikseli 50 mikrometriä	26 k€	Vat photopolymerization
	Solflex 650 35k€	128 x 120 x 110	35k€	Vat photopolymerization
XYZ Printing	DA Vinci 1.0 A	ABS / PLA	600 €	Material Extrusion

4.2Kehityssuunta

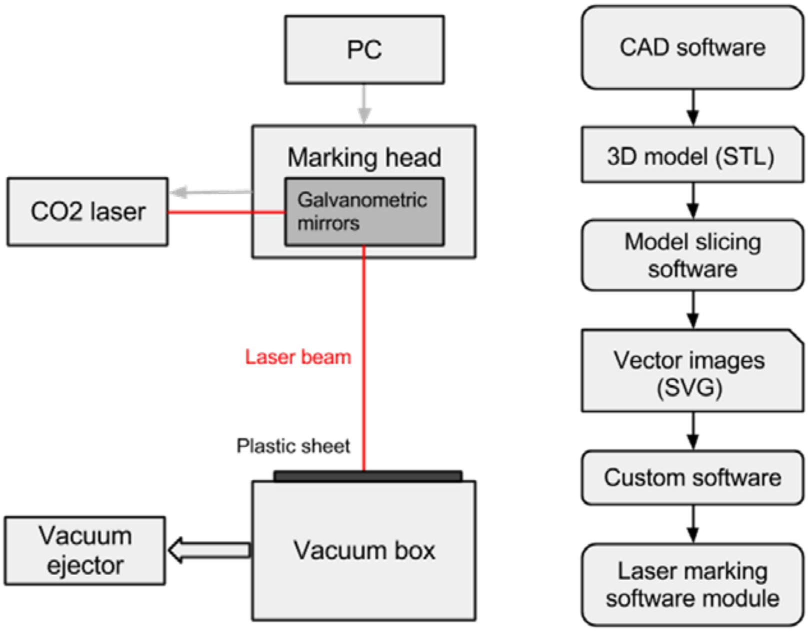
Vuosien 2013-2014 aikana materiaalia lisäävän valmistuksen laitteita valmistajien yritysten määrä on lisääntynyt todella merkittävästi. Suuri osa uusista yrityksistä on keskittynyt kotitulostimiin, mutta myös teolliselle puolelle on uusia tulijoita. Myös muiden alojen markkinoille vakiintuneet yritykset ovat yrittäneet laajentua materiaalia lisäävän valmistuksen markkinoille, kuten esimerkiksi työstökonevalmistaja Mori Seiki ja ruiskupuristuskonevalmistaja Arburg. Mori Seikin laite sekä koneistaa, että lisää materiaalia. HP on ilmoitti tulevansa markkinoille Multijet Fusion teknologialla kesällä 2014, mutta sittemmin tämä siirtyi vuodelle 2016. Multijet Fusion teknologia on yhdistelmä Powderbed fusionia ja Binder Jettingiä ja HP lupailee sen olevan kymmenkertaa nopeampi kuin mikään teknologia markkinoilla. Laitteessa pitäisi olla myös erinomainen tarkkuus, materiaaliominaisuudet ja värit. Tämä on aika paljon luvatta yritykseltä ja jos se tulee onnistumaan muuttaa se markkinoita merkittävästi. Blueprinter tuli myös markkinoille uudella teknologialla 2011 ja aloitti toimitukset 2014.

Kotitulostimien puolella suosituin teknologia on pursotukseen perustuvat teknologiat, mutta myös valokovettavia laitteita on tullut markkinoille. Pursotukseen perustuvissa kotilaitteissa on selvästi kova hintapaine alaspäin. Formlabs toi myös ensimmäisenä laseriin perustuvat valokovettavan laitteen kuluttajien ulottuville. Tätä seurasi vastaavanlaisen laitteen julkistaminen DWS Systemssin toimesta. Suoranaisesti ei kotiin, mutta esim. mallistudiolle tai vastaaville suunnattuja pursotuslaitteita isolla rakennuskammiolla on tullut myös useita markkinoille. Edullisimpien kotitulostimien hinnat ovat jo painuneet alle 500 euron.

Metallien lasersulatuksen puolella suunta on selvästi tuotantokäyttöön. Laitteita pyritään samaan nopeammaksi esim. lisäämällä lasereiden määrää ja tehoa. Samoin myös pyritään, että pystyttäisiin rakentamaan isompia kappaleita. Teollisissa laitteissa hinnat eivät ole merkittävästi laskeneet, mutta laitteet ovat parantuneet. ASTM luokittelun mukaisista prosesseista material extrusion, powderbed fusion ja vat photopolymerization ovat suosituimpia laitevalmistajien keskuudessa. Vat photopolymerization laitteissa on alettu liikuttamaan valonlähdettä ja optiikkaa ja näin ollen voidaan tehdä isompia kappaleita samalla tarkkuudella kuin aikaisemmin. Material jetting teknologian suurimpia uudistuksia ovat olleet veteen liukeneva tukimateriaali ja moniväristen kappaleiden valmistamismahdollisuus. Voxel8 on tuomassa markkinoille laitteen jossa pursotetaan sekä PLA muovia ja hopeapastaa. Näin voidaan samassa ajossa tuottaa kappaleeseen johdotukset ja prosessin aikana voidaan lisätä käsin elektroniikan komponentteja kappaleeseen. Tulevaisuuden kehityssuuntina voidaan nähdä nopeammat ja isommat laitteet, post prosessoinnin automatisointi, hybridi valmistuslaitteet, alle 100 euron kotitulostimet, laajemmat materiaalivalikoimat ja paremmat materiaaliominaisuudet, pienten osien valmistus, uudet teknologiset innovaatiot, sekä teollisten laitteiden ja materiaalien hintojen maltillinen lasku. Lopputuotteiden ja komponenttien valmistus antaa materiaalia lisäävälle valmistukselle erittäin suuren kaupallisen potentiaalin, sekä laitevalmistajan, että sitä hyödyntävän yrityksen osalle.

5. DDShape

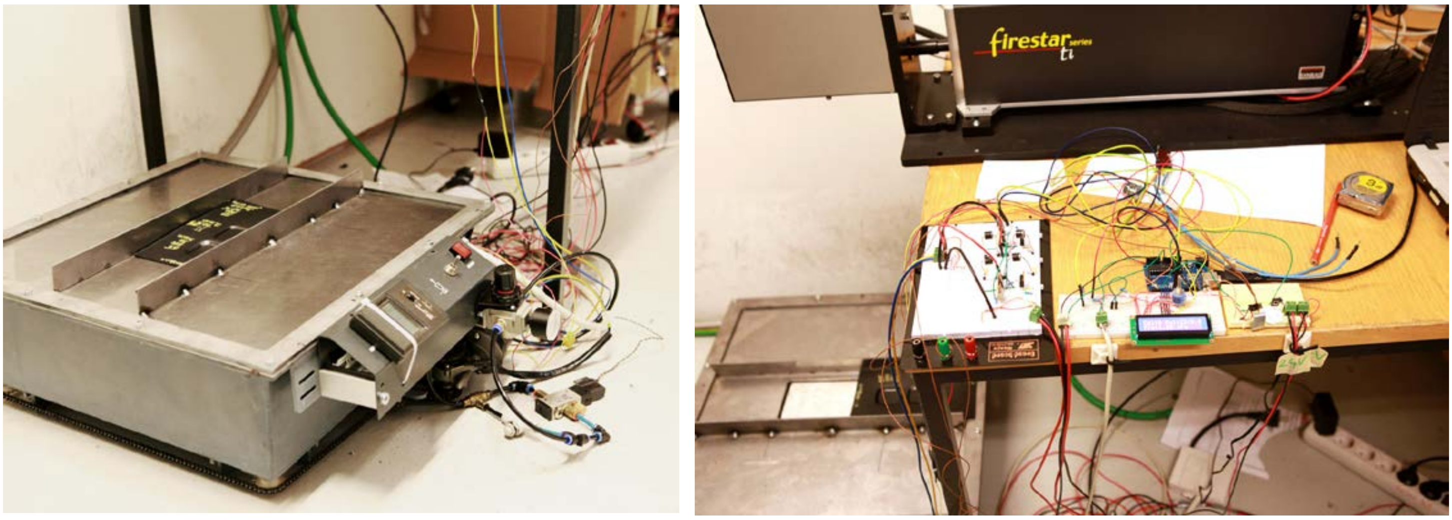
Aalto Yliopistossa on tehnyt tutkimusta muovilevykomponenttien muovaamiseen laserilla ja alipaineella (Direct Digital Shape, DDShape). Laite perustuu muovilevyn paikalliseen lämmittämiseen niin, että muovilevyn välillä on paine-ero. Pehmetessään muovilevyn paikallinen pehmennyt kohta siirtyy kohti alempaa painetta. Laitteisto sisältää CO2 laserin, optiikan, tyhjiölaatikon ja tyhjiö ejektorin. Ohjaus tapahtuu tietokoneen avulla. Periaatekuva laitteisto ja 3D mallin siirrosta laitteelle on esitetty kuvassa 10.



Kuva 10. DDShape laitteiston periaatekuva ja 3D mallin siirto fyysiseksi muodoksi

Laitteiston etuna verrattuna alipainemuovaukseen voidaan pitää, sitä että tässä paikallisesti muovaavassa laitteistossa ei ole tarvetta muotille. Yhden kappaleen tekeminen on myös suhteellisen nopeaa, suurimmillaan minuutteja. Geometrian tuottokyky laitteella on kuitenkin vielä rajoittuneempaa kuin alipainemuovauksessa. Menetelmällä on paikkansa yksittäiskappaleiden tuotannossa ja pienissä sarjoissa, sekä varsinaisten imumuovattavien kappaleiden prototyyppien teossa ennen muotin valmistamista. 1. Sukupolven testilaitteisto on esitetty kuvassa 11. Laitteella on valmistettu erilaisia testikappaleita ja näitä on näkyvillä kuvissa 12 ja 13. Laitteistossa on vielä paljon kehitettävää, mutta perusperiaatteelta konsepti on osoitettu toimivaksi.

Laitteiston kehittämiseksi ja kaupallistamisen tueksi Tekes on myöntänyt "Tutkimusideoista uutta tietoa ja liiketoimintaa" (TUTLI) rahoituksen. Hankkeessa on tarkoitus tehdä lisää kaupallistamisselvitystä, sekä kehittää seuraavan sukupolven tutkimuslaitteistoa.



Kuva 11. DDShape laitteisto. Vasemmalla tyhjiölaatikko ja sen päällä muovattava levy. Oikealla laser ja laitteen ohjaus elektroniikkaa.

Kuva 12. DDShape laitteistolla valmistettu testikappale.

Kuva 13. DDShape laitteistolla valmistettuja testikappaleita.

6. ISF mini

ISF mini osaprojektin tavoitteena oli kehittää pienien ohutlevykomponenttien painomuovaamiseen soveltuva tutkimuslaitteisto ja kerätään sen avulla tietotaitoa pienten kappaleiden muovaamisesta ja muovattavuudesta. ISF on lyhenne sanoista Incremental Sheet Forming. Kyseessä on muotoa kerros kerrokselta lisäävä menetelmä. Muovausperiaate tapahtuu kuitenkin kerros kerrokselta ja tietokoneohjauksella.

6.1 Laitteisto

Tutkittavien metallilevyjen muovaamista varten tarvittiin levynkiinnitysteline ja CNC-kone ja muovauskärkiä. Muovauskärki on kovametallitappi, jonka päässä on puolipallon muotoinen kärki. Teline koostuu alumiiniprofiileista tehdystä kahdesta kehikosta, joiden väliin levy voidaan kiinnittää puristimilla. Levy on siis kiinnitetty neljältä sivulta. Levyn alla ei ole tukia, vaan telineen alumiiniprofiilit toimivat tukipisteinä. Kitkan vähentämiseksi levylle levitettiin voitelu öljyä.

Aluksi suunnitellaan CAD-malli siitä muodosta, joka halutaan muovata metallilevyyn. Tämä malli käsitellään CAM-ohjelmalla, jotta CAD-malli saadaan muutettua G-koodiksi. G-koodi on komentokieli, jota käytetään CNC-koneen ohjaamiseen. CAD-malli siis muutetaan CNC-koneen ymmärtämiksi liikkumiskomennoiksi. G-koodi ladataan CNC-konetta ohjaavaan Mach-ohjelmaan, jolla voidaan hallita koneen liikkeitä ja käynnistää muovausprosessi. CNC koneena käytettiin KX3-Mach merkkistä konetta. Kuvassa 14 on esitetty kyseinen kone, telinemetallilevyn kiinnitykselle, sekä lähikuva muovauskärjestä ja voiteluöljystä.

Kuva 14. CNC-kone KX3-Mach ja telinemetallilevyn kiinnitystä varten, sekä lähikuva muovauskärjestä.

6.2 Materiaalit ja parametrit

Prosessiin vaikuttavat monet parametrit. Muovattavan radan muoto vaikuttaa merkittävästi lopputulokseen. Terävät kulmat ovat usein vaikeampia valmistaa onnistuneesti kuin pyöreät muodot. Muovauskärjen koko rajoittaa kulmien terävyyttä ja yksityiskohtien tarkkuutta. Myös muovauskärjen varren pituudella, pyörimisellä ja kärjellä on merkitystä. Pitkä varsi on joustava, jolloin muodot pyöristyvät. Pyöriminen puolestaan hioo levyn pintaa samalla kun kärki piirtää haluttua kuviota levyyn. Kokeissa selvitettiin myös miten kuulakärkikynämäinen ratkaisu toimii muovausprosessissa. Muovausnopeuden kasvattaminen pyöristää kulmia, mutta nopeuttaa valmistusprosessia. Kerrosten välinen z-askel vaikuttaa pinnan laatuun, sillä pieni z- askel vähentää pinnan aaltoisuutta, joka muodostuu kerrosten välisestä askeleesta. Askeleen suurentaminen nopeuttaa prosessia, mutta kärjen liikuttamiseen tarvittava voima kasvaa huomattavasti. Muovaus tapahtuu käyttämällä levyn materiaalia joten erittäin syvät ja jyrkkäseinäiset muodot eivät ole mahdollisia. Levyn materiaali ja paksuus ovat tärkeitä parametreja, jotka tulee ottaa huomioon muodon suunnittelussa. Jäykkä materiaali hajoaa helpommin kuin joustava materiaali. Paksuus puolestaan lisää materiaalin määrää, jolloin murtumat ovat epätodennäköisempiä, mutta samalla levyn jäykkyys kasvaa.

Tässä projektissa käytettiin seuraavia materiaaleja: alumiini, kupari, teräs (kylmävalssattu), syvävetoteräs (DC04) ja duralumiini. Näiden materiaalien levyjen paksuudet vaihtelivat pääsääntöisesti välillä 0,5 mm ja 1 mm. Muovauskärkenä toimi kiinteä puolipallo tai kuulakärkikynän tapainen pallo. Pallon halkaisija vaihteli välillä 3 mm ja 10 mm. Muovaus- nopeus valittiin väliltä 500 mm/min ja 2000 mm/min. Muovattavia muotoja oli kattavasti erilaisia. Pääsääntöisesti kuviot olivat erikokoisia kartiomaisia syvennyksiä, joilla oli vaihteleva pohjan muoto ja seinän jyrkkyys. Seinän kaltevuus on mitattu asteina siten että 0◦ on tasainen levy ja 90◦ on pystysuora seinä.

6.3Tulokset

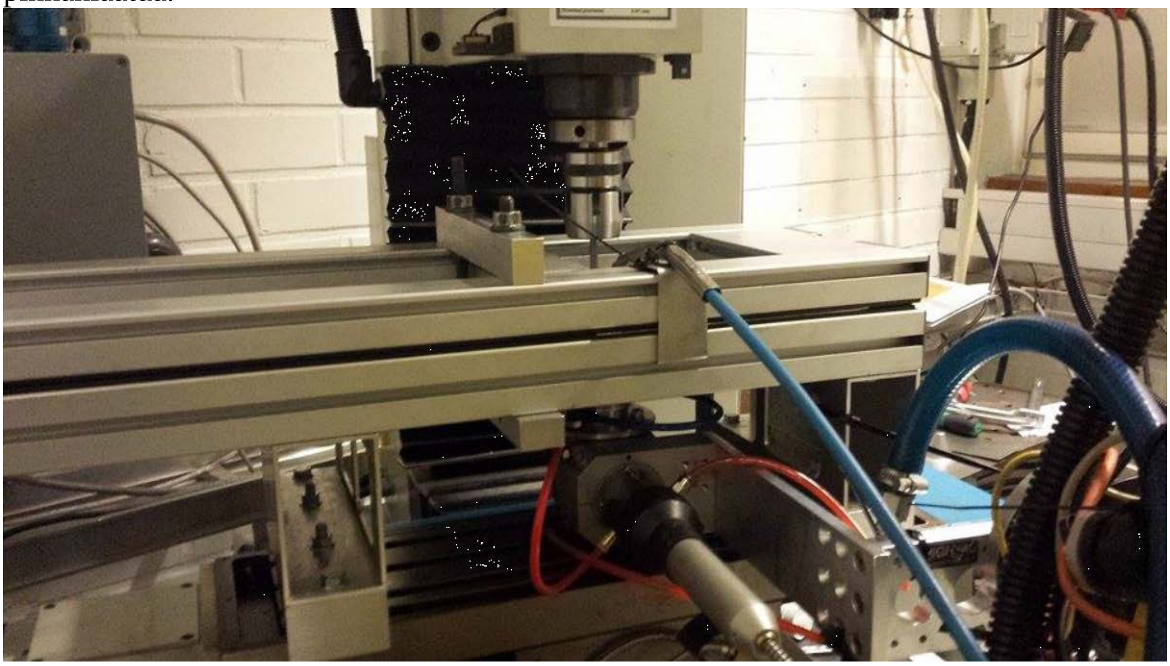
Taulukkoon 6 on koottu useimmiten käytettyjen materiaalien osalta suositeltavat parametrit ja rajoitteet. Parhaat testitulokset saatiin 0,5 mm paksuilla alumiini-, kupari- ja teräslevyillä. Kokeiden kannalta huonoin materiaali oli duralumiini, sillä se murtui hyvin herkästi. Suurta eroa ei huomattu syvävetoteräksen ja kylmävalssatun teräksen välillä, vaikka syvävetoteräksellä on alhainen myötölujuus ja se on suunniteltu juuri muovausprosesseja varten.

Taulukko 6. Muovauksessa hyvin toimivat parametrit

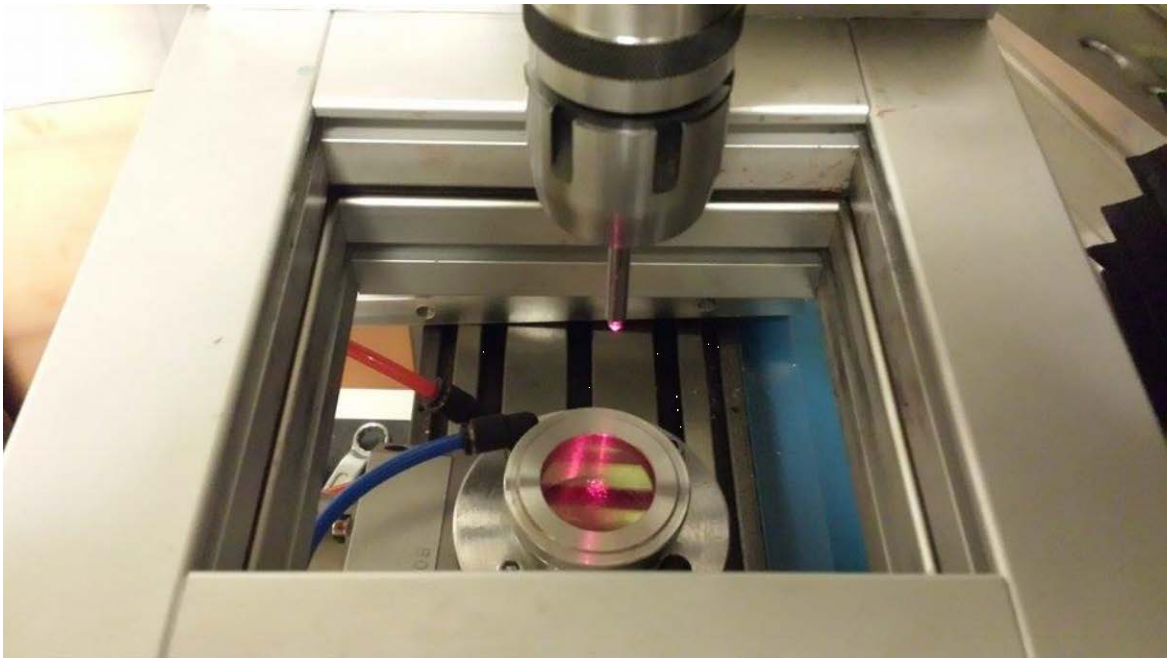
Materiaalit	Parametreja
Alumiini 0,5 mm	Muovauskärjen halkaisija 4 - 6 mm
Kupari 0,5 mm	z-askel 0,5 mm
Teräs 0,5 mm	Nopeus 500 - 1 000 mm/min
Syvävetoteräs 0,75 mm	Seinän kaltevuus alumiinille < 65°
	Seinän kaltevuus kuparille ja teräkselle < 68°

6.4 Laserin vaikutus muovaamiseen

Laserin vaikutusta muovaamiseen tutkittiin kuvan 15 mukaisella koelaitteistolla. Työstörataa ohjattiin samoilla NC-ohjelmilla kuin ilman laseria tehdyissä kokeissa. Robotti kannatteli laserpäätä muovattavan levyn alla siten, että lasersäde osoitti ylöspäin. Teräkseen tehdyissä kokeissa säde asetettiin kohtisuoraan muovattavan levyn pintaa vastaan. Alumiinilla ja kuparilla säde asetettiin pieneen, noin 5 asteen kulmaan levyn pintaan nähden takaisinheijastuksen minimoimiseksi. Laserina käytettiin 1 kW kuitulaseria ja fokusoimattoman lasersäteen halkaisija oli noin 5 mm. Säteen keskipiste kohdistettiin mahdollisimman tarkasti työkalun keskipisteen kohdalle (kuva 16). Laserin tehona kokeissa käytettiin arvoja väliltä 70-350 W. Koekappaletta jäähdytettiin kokeen aikana paineilmalla, jotta kappale ei ylikuumenisi. Alumiinilla ja kuparilla kokeita tehtiin myös ilman jäähdytystä. Kappaleen lämpötilan vaikutusta muovaukseen testattiin myös lämmittämällä kappaletta kuumailmapuhaltimella laserin sijaan. Voiteluaineena käytettiin korkeita lämpötiloja kestävää kuparitahnaa. Kaikki kokeet tehtiin pyöreälle kartiomuodolle. Kokeissa tutkittiin lähinnä muovautuvuutta, jossa mittarina käytettiin maksimi kartiokulmaa (vaakatason ja kartion seinän välinen kulma), mikä pystyttiin tekemään ilman kappaleen rikkoutumista. Tämän lisäksi havainnoitiin myös syntyvää pinnanlaatua.



Kuva 15. Koelaitteisto. Alhaalla laserpää ja kiinnittimen kyljessä näkyy paineilmajäähdytyksen sininen letku.



Kuva 16. Säteen kohdistus työkaluun.

Tavalliselle, että syvävetoteräkselle laserin käyttö osoittautui pikemminkin haitaksi kuin hyödyksi. Muodot, jotka onnistuivat ilman lämmitystä, eivät onnistuneet laserin kanssa. Lisäksi työkalun puoleisesta pinnasta tuli karkea (kuva 17). Kokeita tehtiin myös lämmittäen kappaletta kuumailma-puhaltimella ja tulokset olivat vastaavat kuin laserilla lämmitettäessä.

Kuva 17. Laserin käytön vaikutus pinnanlaatuun. Vasemmalla esimerkki laserin käytöstä, oikealla ilman lämmitystä muovattu pinta.

Alumiinilla havaittiin lievä muovautuvuuden paraneminen. Alumiinilla onnistuttiin tekemään 61° kartiokulman kappale Ilman lämmitystä suurin onnistunut kartiokulma oli 59°. Kartion sisäpinnan laatu oli laseravusteisessa muovauksessa huonompi kuin ilman lämmitystä muovattaessa. Parhaimmat laseravusteisen muovauksen tulokset saavutettiin kuparilla. Kartiokulmat 68,2° (laserteho 250 W) ja 70,1° (laserteho 350 W) onnistuivat molemmat. Ilman laseria maksimi kartiokulma oli 65,8°. Kokeita ei tehty enää suuremmille kartiokulmille, koska suuri laserteho altistaa laitteen takaisinheijastusvaaraan. Laseravusteinen muovaus ei vaikuttanut heikentävästi kartion pinnanlaatuun (kuva 18).

Kuva 18. Laseravusteisesti painomuovatun kuparikartion pinta

Laseravusteisesta painomuovauksen hyödyt ovat riippuvaisia muovattavasta materiaalista. Tehdyissä kokeissa teräksille ei saavutettu hyötyjä. Sen sijaan alumiinin ja kuparin muovattavuus parantui. Pinnankarheus heikentyi teräksillä ja alumiinilla. Löytämällä parempi voitelumenetelmä/-aine tai työkalumateriaali voisi ratkaista pinnanlaatuongelman. Työkalun ja kappaleen välisen kitkan pienentäminen parantaisi todennäköisesti myös muovattavuutta. Epäonnistuneissa kokeissa kappale rikkoontui lähes aina noin 13 mm syvyydessä. Tällöin ilmeisesti saavutetaan lopullinen kartiokulma ja jos kappale kestää tämän, se kestää saman kulman loppuun asti. Vain parissa kokeessa rikkoontuminen tapahtui vasta kokeen loppupuolella.

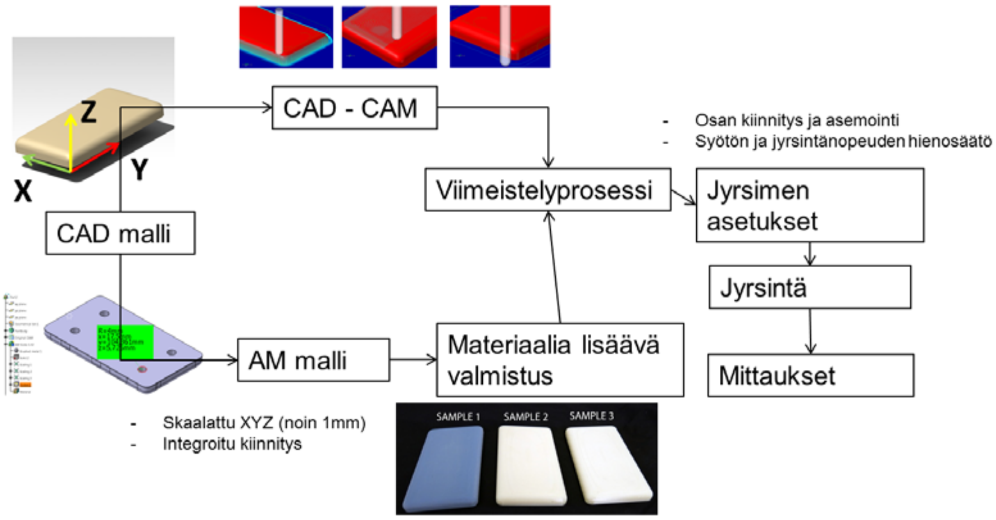
Koelaitteisto asetti kokeille seuraavat rajoitukset. Lasersäteelle ei voitu määrittää ns. offsettia eli osoittamaan hieman työkalun etupuolelle kulkusuuntaan nähden. Lisäksi lasersäteen halkaisija oli vakio, noin 5 mm. Offset ja suurempi lasersäteen koko ovat lähdekirjallisuuden mukaan optimaalisempia parametreja laseravusteisessa painomuovauksessa. Lisäksi kaikkiin koetuloksiin (myös ilman laseria tehtyihin kokeisiin) vaikutti työkalun muoto. Työkalussa oleva olake osui kappaleen pintaan naarmuttaen sitä, kun kartiokulma oli riittävän suuri (> n. 65°).

7. AM kappaleiden viimeistelykoneistus

AM kappaleiden viimeistelykoneistus tutkimuksen tavoitteena oli kehittää pikavalmistettaviin kappaleisiin integroituja kiinnitysratkaisuja, joita voidaan hyödyntää koneistuksessa kappaleiden viimeistelyssä ja näin ollen parantaa kappaleiden jälkikäsittelyä ja tarkkuutta huomioimalla kiinnitykset ja koneistus jo pikavalmistettavan kappaleen suunnitteluvaiheessa. Samalla huomattiin myös tarve erityisesti metallikappaleiden pinnanlaadun parantamiselle ja näin ollen tutkittiin myös kappaleiden automaattista hiontaa.

7.1Muovin koneistus

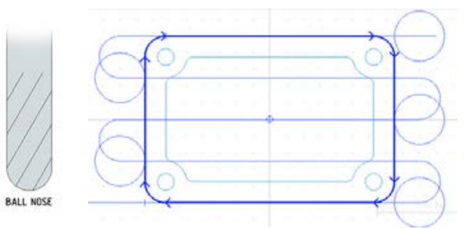
Muovikappaleiden koneistuksen tavoitteena oli tutkia integroituja kiinnittimiä AM osille 3-akseliselle jyrsimelle. Samalla tutkittiin kappaleiden postprosessointia, pinnanlaatua ja mittatarkkuutta AM kappaleiden viimeistelyssä jyrsimällä. Ensimmäisenä testikappaleena käytettiin vapaasti saatavilla olevan Lumia 820 puhelimen takakuoren 3D mallia. Valmistusprosessin vaiheet käyvät ilmi kuvasta 19 Testikappaleet valmistettiin Objet 30 material jetting ja Uprint SE plus materia extrusion laitteilla ja teknologioilla. CAM ohjelmoinnissa käytettiin MasterCAM X7 ohjelmaa. Taulukossa 7 on jyrsintäarvot ja kuvassa 20 integroitu kiinnitysratkaisu. Taulukkoon 8 on kerätty testauksessa saadut kappaleiden mitat ja pinnalaadut.



Kuva 19. AM kappaleiden viimeistelykoneistuksen prosessi

Taulukko 7. Jyrsintäarvot ja –rata.

Jyrsinkone	Modig MD7200 CNC-mill
Lastunpaksuus	0.25 mm
Toleranssi	0.01 mm
Syöttö	1100 mm / min
Karanopeus	18500 rpm
Työkalu	8 mm – BR4 – 2z

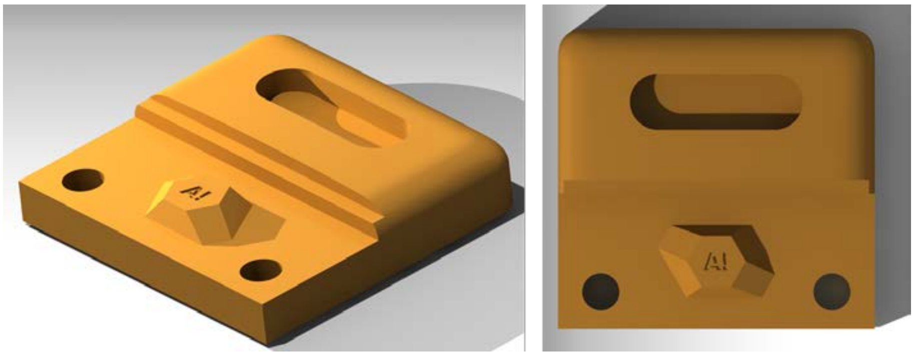


Kuva 20. Integroitu kiinnitysratkaisu.

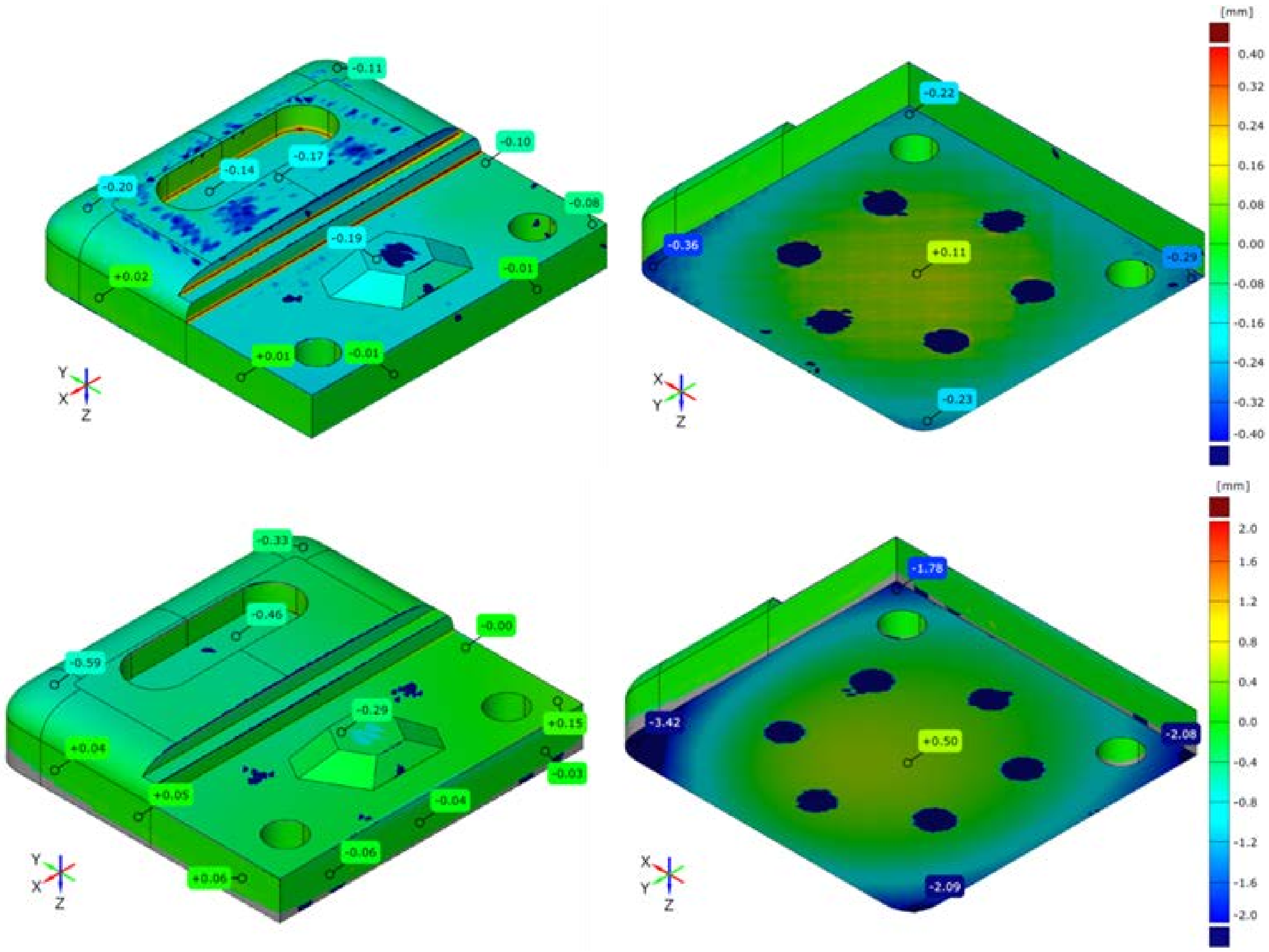
Taulukko 8. Kappaleiden mitat ja pinnalaadut

	Nimellinen	Skaalaus	CAD (mm)	AM (mm)	Jyrsintä (mm)	AM (Ra)	Jyrsintä (Ra)
Objet 30 VeroBlue	X – 68.5 mm	1.015 (1.5%)	69.53	69.65	68.46	1.09	0.77 – 1.59
	Y – 123.8 mm	1.008 (0.8%)	124.79	125	123.78	2.94	2.05 – 2.09
	Z – 10.61 mm	1.1 (10%)	11	11.7	10.62	N/A	0.26 - 0.3
U Print SE Plus ABS - Low Density	X – 68.5 mm	1.015 (1.5%)	69.53	69.50	68.48	N/A	2.16 – 2.57
	Y – 123.8 mm	1.008 (0.8%)	124.79	124.65	123.79	N/A	N/A
	Z – 10.61 mm	1.1 (10%)	11	11.8	10.65	N/A	4.8 – 6.44
U Print SE Plus ABS - Solid	X – 68.5 mm	1.015 (1.5%)	69.53	69.50	68.47	N/A	0.52 – 2.08
	Y – 123.8 mm	1.008 (0.8%)	124.79	124.6	123.82	N/A	4.8
	Z – 10.61 mm	1.1 (10%)	11	12.1	10.62	N/A	0.31 - 082

Toisena testigeometriana käytettiin hieman monimutkaisempaa osaa (Kuva 21.) Toisessa testissä verrattiin kotikäyttöön tarkoitetuilla FDM laitteilla ja teollisuuden käyttöön tarkoitettujen FDM laitteilla valmistettujen kappaleiden viimeistelyä jyrsimällä. Valitut laitteet olivat UPrint SE Plus, sekä Ultimaker 2. Kappaleeseen sijoitettiin kaarevia pintoja, jotta voidaan verrata kerrospaksuuksista johtuvaa porras efektiä. Kappaleeseen lisättiin myös teräviä kulmia, reikiä ja taskuja jotta voidaan arvioida kappaleen dimensionaalista stabiliteettia. Jyrsinnän jälkeen kappaleet mitattiin optisella mittalaitteella. Mittoja verrattiin CAD mallin mittoihin (Kuva 22). Kotilaitteessa oli selvästi suuremmat poikkeamat päällyspinnalla (max n. 0.6 mm), vaikka pinta oli viimeistelty koneistamalla. Viimeistelemättömässä pohjassa virhe oli n. 2 mm luokkaa kappaleen käyristymisen takia. Teollisessa laitteessa suurin virhe oli noin 0.2 mm luokkaa viimeistellyssä pinnassa ja 0.4 mm luokkaa ei viimeistellyssä alapinnassa.

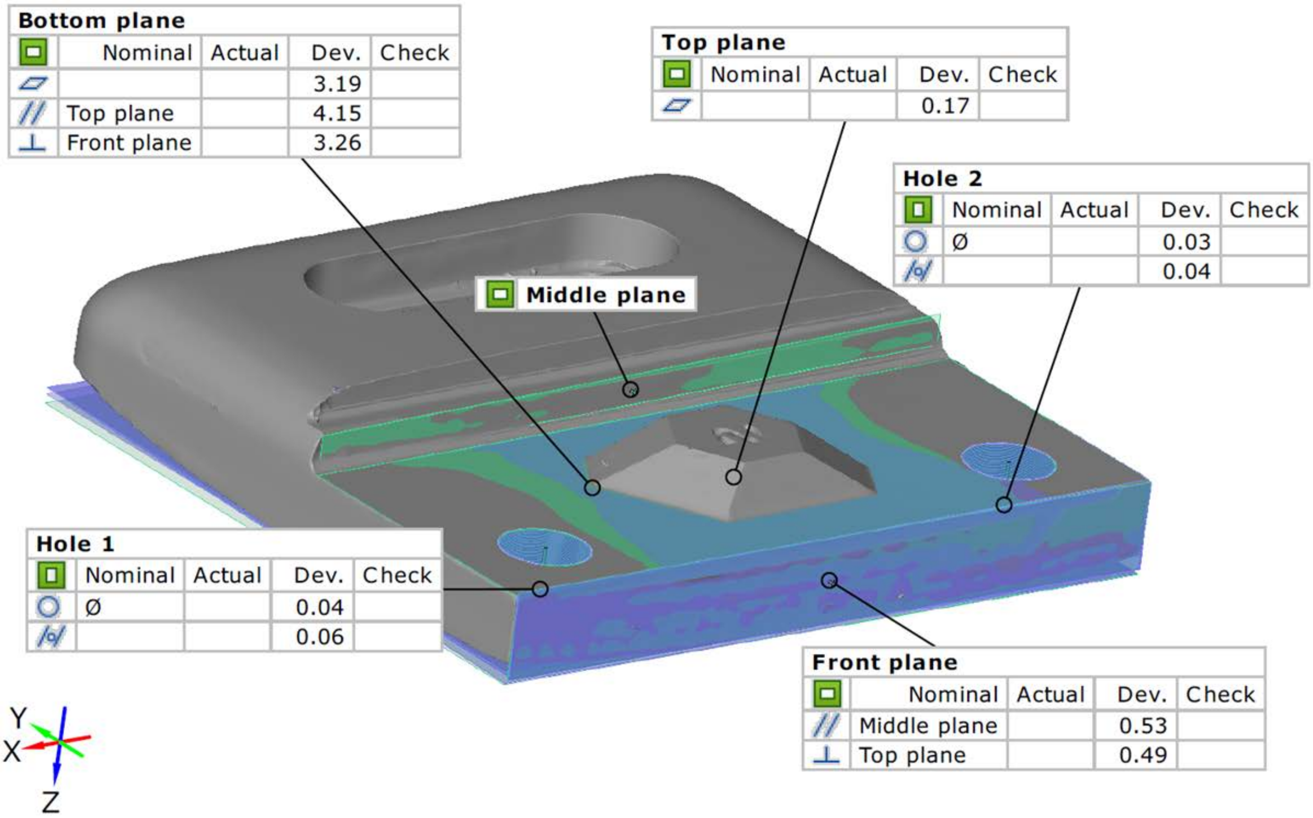


Kuva 21. Toinen testigeometria.



Kuva 22. Yllä teollisella laitteella tehty ja alla kotilaitteella tehty kappale poikkeamineen CAD malliin verrattuna.

Kappaleille suoritettiin myös geometristen toleranssien tarkastelu, jossa tutkittiin sylinterimäisyyttä, pyöreyttä, tasomaisuutta, tasojen yhden suuntaisuutta ja tasojen kohtisuoruutta. Kuvassa 23 on esitetty mitatut ominaisuudet ja tulokset ovat taulukossa 9.

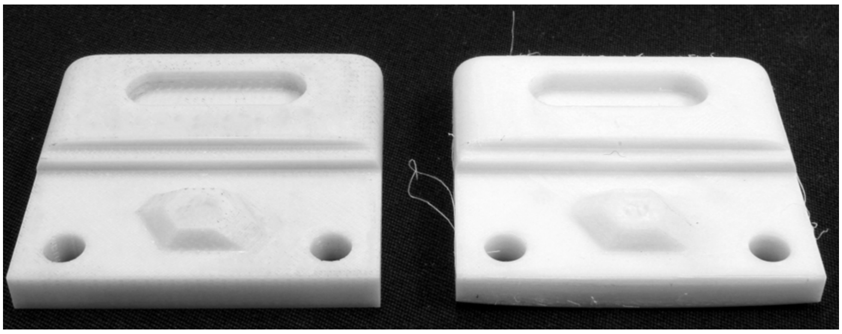


Kuva 23. Geometriset toleranssit.

Taulukko 9. Geometriset toleranssit ja mittaustulokset

			Teollinen		Kotilaite	
	Nimi	Ominaisuus	Keskiarvo	Keskihajonta	Keskiarvo	Keskihajonta
1	Hole 1	Cylindricity	0.08	0.03	0.09	0.03
2	Hole 2	Cylindricity	0.05	0.01	0.09	0.08
3	Hole 1	Roundness	0.07	0.02	0.07	0.03
4	Hole 2	Roundness	0.04	0.01	0.09	0.10
5	Top plane - Front plane	Perpendicularity	0.12	0.08	0.32	0.14
6	Front plane - Middle plane	Parallelism	0.16	0.08	0.34	0.20
7	Top plane	Flatness	0.11	0.05	0.20	0.03
8	Bottom plane -Top plane	Parallelism	0.62	0.02	3.18	1.23
9	Bottom plane - Front plane	Perpendicularity	0.55	0.06	2.90	1.05
10	Bottom plane	Flatness	0.52	0.06	2.64	0.81

Yhdistämällä materiaali lisäävä ja poistava prosessi voidaan merkittävästi parantaa kappaleiden mittatarkkuutta. Yhdistämällä viimeistely jyrsintä materiaalia lisäävään valmistukseen voidaan saavuttaa avainmitoille riittävä tarkkuus, hyvät liityntäpinnat kokoonpanoissa ja tarkat geometriat funktionaalisille pinnoille. Suurimmat mittatarkkuusongelmat ovat Z-akselin suuntaisia ja ne johtuvat lämpötila gradienteista ja jännityksistä, jotka aiheuttavat kappaleeseen vääntymiä. Kotilaitteet ovat selvästi epäluotettavampia, mittatarkkuus vaihtelee enemmän ja kappaleen kerrokset eivät välttämättä ole sitoutuneet toisiinsa yhtä hyvin kuin teollisissa laitteissa. Kuvassa 24 on koneistamalla viimeistellyt kappaleet, sekä teollisella laitteella, että kotitulostimella tehtynä.



Kuva 24. Vasemmalla teollisella laitteella tehty viimeistelty kappale ja oikealla kotilaitteella tehty vastaava kappale.

7.2 Kappaleiden automaattinen hionta

Kappaleiden autotomaattisen hionnan osaprojektissa selvitettiin materiaalia lisäävien menetelmien metallikappaleiden pinnanlaadun parantamista pyörittämällä tai täristämällä niitä hionta-aineiden seassa. Tutkimuksessa käytettiin kahta erilaista laitetta: vibraa, joka värisee ja tumbleria, joka pyörii akselinsa ympäri (Kuva 25). Hionta-aineena käytettiin keraamisia kolmioita, piikarbidia ja teräshauleja (kuva 26). Keraamiset kolmioiden malliset hiontakappaleet eivät viikon hiomisen aikana saaneet kappaleisiin silmin nähtävää vaikutusta, joten niitä ei testattu sen pidemmälle. Muovisille kappaleille parhaan tulokset antoivat teräshaulit, mutta varsinkin huokoisten kappaleiden osalta ongelmaksi muodostui hiomapölyn imeytyminen ja jämähtäminen kappaleeseen.

Kuva 25. Vasemmalla vibratyyppinen kappaleiden viimeistelijä ja oikealla pyörivä tumbler.

Kuva 26. Hionta-aineet: keraamiset kolmiot, piikarbidi ja teräshaulit.

Viikon hionnan jälkeen kappaleille tehtiin pinnankarheusmittaukset. Hiotut kappaleet olivat kolikon mallisia ja niistä mitattiin molemmat puolet 5 kertaa ja laskettiin niistä keskiarvo. EBM kappaleet ovat karkeampia kuin DMLS kappaleet. Jälkikäsittelyn vaikutukset ovat suuremmat DMLS kappaleilla. Paras tulos EBM-kappaleille oli pinnankarheuden Ra arvon paraneminen 11,16 µm -> 9,08 µm kun hionta-aineena olivat teräshaulit ja laitteena vibra. Vastaavasti paras tulos DMLS-kappaleille oli Ra arvon paraneminen 7,23 µm -> 2,96 µm, kun kun hionta-aineena olivat teräshaulit ja laitteena tumbler. Kooste mittaustuloksista on esitetty taulukossa 10.

Taulukko 10. Kappaleiden automaattisen hionnan mittaustulokset.

AM Menetelmä	materiaali	Hioma-aine	Laite	Aika	Ra AVG Puoli A (µm)	Ra AVG Puoli B (µm)	STDEV Puoli A (µm)	STDEV Puoli B (µm)
DMLS	Titaani	-	-	-	7,23	6,42	1,48	0,71
DMLS	Titaani	Piikarbidi	Vibra	1 viikko	6,29	5,72	0,85	0,91
DMLS	Titaani	Piikarbidi	Tumbler	1 viikko	5,69	5,56	0,21	0,83
DMLS	Titaani	Ruostumaton teräs	Tumbler	1 viikko	2,96	3,73	0,53	0,35
DMLS	Titaani	Ruostumaton teräs	Vibra	1 viikko	4,35	4,1	0,41	0,76
EBM	Titaani	-	-	-	10,81	11,22	0,92	1,24
EBM	Titaani	Piikarbidi	Tumbler	1 viikko	11,16	10,87	0,63	1,65
EBM	Titaani	Ruostumaton teräs	Vibra	1 viikko	9,08	9,03	1,19	1,96
EBM	Titaani	Ruostumaton teräs + vesi	Tumbler	1 viikko	9,89	9,64	0,84	2,48

8. Esitelmät projektin puitteissa

Jukka Tuomi. Possibilities That Addive Manufacturing Offers for Manufacturing Industries in Finnish; the original title is Materiaalia lisäävän valmistuksen tarjoamat mahdollisuudet valmistavalle teollisuudelle. Addite Manufacturing (3D-tulostus) seminaari, Jyväskylä Regional Development Company Jykes Oy. August 19, 2014, Jyväskylä, Finland.

Jukka Tuomi. 3D Printing Technology, Applications and Future Foresights in Finnish; the original title is 3D-tulostamisen teknologia, sovellukset ja tulevaisuuden näkymät. Sesearch foundation of communication, 3D Printing Workshop, August 28, 2014, Turku, Finland.

Jukka Tuomi. Invited presentation. Extended Classification System for Medical Applications of Additive Manufacturing. Medical Manufacturing Asia Conference. September 9-11, 2014, Singapore.

Jukka Tuomi. 3D Printing in Industry – Introduction and Market Review in Finnish; the original title 3D-tulostus teollisuudessa – johdanto ja katsaus alan markkinatilanteeseen. 3D printing workshop, Tampere subcontracting trade fair, September 17, 2014, Tampere Finland.

Jukka Tuomi. Robotics and 3D Printing in Finnish; the original title Robotiikka ja 3D-tulostus. Technology Industries' Anticipation Seminar. Helsinki Chamber, November 6, 2014, Espoo, Finland.

Jukka Tuomi. 3D-tulostuksen/Pikavalmistuksen kehitysnäkymät. CAD harjoituskurssi, Primetieto, 6.5.2014, Helsinki

Jukka Tuomi. Materiaalia lisäävän valmistuksen tarjoamat mahdollisuudet valmistavalle teollisuudelle. 3D-tulostus seminaari, Jyväskylän Seudun Kehittämisyhtiö Jykes Oy 19.8.2014 Jyväskylä

Pekka Lehtinen & Jouni Partanen. Controlling penetration depth in projection stereolithography by adjusting the operation wavelength. ESAFORM konferenssi, 8.5.2014, Espoo.

Jouni Partanen. 3D-tulostuksen teknologiat. Konepajamiehet vuosikokous, 8.5.2014, Helsinki

Mika Salmi. 3D-tulostus lääketieteessä. Suomen Pikavalmistusyhdistyksen vuosiseminaari, 13.05.2014, Lappeenranta.

Jukka Tuomi. Future Trends of 3D Printing/Additive Manufacturing in Finnish; the original title is 3D-tulostuksen/Pikavalmistuksen kehitysnäkymät. CAD specialist training course, Primetieto Oy, January 3, 2014, Helsinki, Finland.

Jukka Tuomi. Newest Applications of Metals 3D Printing in Finnish; the original title is Metallien 3D-tulostuksen tuoreimmat menetelmät ja esimerkit. 3D Printing innovations workshop, Ideascout Oy, March 11, 2014, Tampere, Finland.

Jukka Tuomi. 3D Printing on the Point of View of Companies in Finnish; the original title is 3D-tulostus yritysten näkökulmasta. Kasvuinno project workshop. April 2, 2014, Kokkola, Finland.

Jukka Tuomi. 3D Printing. 3D Printing and IPR seminar. IPR University Center. April 3, Helsinki, Finland.

Jukka Tuomi. 3D Printing and IPR Panelist. World IP Day 2014 – Finnish Main Event. April 25, Helsinki, Finland.

Jukka Tuomi. 3D Printing Principles in Finnish; the original title is Johdanto 3D-tulostukseen. Suomen Messut, 3D printing special program, September 3-4, 2013, Helsinki, Finland.

Mika Salmi, Jukka Tuomi, Roy Björkstrand. Industrial Applications of Additive Manufacturing. Educational overview lecture and workshop for company Wärtsila, September 10, Vaasa, Finland.

Jukka Tuomi. 3D Printing. Educational overview lecture for company ZenRobotics, November 29, 2013, Helsinki, Finland.

Jukka Tuomi. Future Trends of 3D Printing/Additive Manufacturing in Finnish; the original title is 3D-tulostuksen/Pikavalmistuksen kehitysnäkymät. CAD specialist training course, Primetieto, July 30, 2013, Helsinki, Finland.

Jukka Tuomi. 3D Printing Principles in Finnish; the original title is Johdanto 3D-tulostukseen. Suomen Messut, 3D printing special program, September 3-4, 2013, Helsinki, Finland.

Jukka Tuomi. 3D Printing in Finnish; the original title is 3D-tulostus. TIEKE The Finnish Information Society Development Centre, eBusiness Forum, May 21, 2013, Helsinki, Finland.

Jukka Tuomi. Part 6: Global Reports, Europe, Finland. Wohlers Report, Additive Manufacturing and 3D Printing State of the Industry, Annual Worldwide Progress Report. Wohlers Associates, OakRidge Business Park, 1511 River Oak Drive, Fort Collins, Colorado, USA, 2013, ISBN 0-9754429-9-6.

Jukka Tuomi. Keynote presentation. Extended Classification System for Medical Applications of Additive Manufacturing. 18th European Forum on Rapid Prototyping, French Rapid Prototyping Association, AFPR, June 24-27, 2013, Paris, France.

Jukka Tuomi. Cost model for industrial Additive Manufacturing applications Rapid Prototyping Conference - Driving 21st Century Innovation, European Plastics News, April 9-10, 2013, Amsterdam, Netherlands.

Jukka Tuomi. 3D Printing, in Finnish; the original title is 3D-tulostus. HAMK University of Applied Sciences, Management of customer oriented agile production course. January 18, 2013, Tampere, Finland.

Jukka Tuomi. 3D Printing Technology Survey, in Finnish; the original title is Katsaus 3D-tulostusteknologioihin. Print&media Magazine, 3D printing Seminar, February 12, 2013, Helsinki, Finland.

Jukka Tuomi. 3D Printing - technologies and practical applications in Finnish; the original title is 3D-tulostus - teknologiat ja käytännön sovellukset. HAMK University of Applied Sciences, 3D printing - State-of-the-art Seminar, March 19, 2013, Riihimäki, Finland.

Jukka Tuomi. 3D Printing, in Finnish; the original title is 3D-tulostus. HAMK University of Applied Sciences, Develop as a mechanical engineer course. March 20, 2013, Riihimäki, Finland.

Jukka Tuomi. Digital Manufacturing, +Studio, Digital Fashion Breakfast, April 12, 2013, Helsinki, Finland.

Salmi Mika. 2013 3D-tulostuksen trendit, 3D tulostus ajankohtaisseminaari, FirstRoundCenter, Hämeen AMK, Riihimäki, Suomi. 2013.

Salmi Mika. 2013 3D-tulostuksen mahdollisuuksia, 3D:n liiketoimintamahdollisuudet seminaari, Kuusio hanke – Kulttuurin uudet sisällöt ja oppimisympäristöt, Oulun seudun AMK, Oulu, Suomi. 2013.

9. Opinnäytteet

Doctoral dissertation 2013. Mika Salmi, Medical applications of additive manufacturing in surgery and dental care. AALTO UNIVERSITY School of Mechanical Engineering Department of Engineering Design and Production.

Master's thesis 2013. Iñigo Flores Ituarte, The role of Additive Manufacturing in modern product development: a case study for consumer electronic industry. AALTO UNIVERSITY School of Mechanical Engineering Department of Engineering Design and Production.

Master's thesis 2014. Sergei Chekurov, Additive Manufacturing Needs and Practices in the Finnish Industry. AALTO UNIVERSITY School of Mechanical Engineering Department of Engineering Design and Production.

Bachelor’s thesis 2014. Rui Chen, Incremental forming (test environment). HAMK University of Applied Sciences.

10. Tiivistelmä

Tutkimuksessa kerättiin best practice aineistoa ja kehitettiin internet alusta kerätyn aineiston tutkimiseen ja hakujen suorittamiseen. Aineisto löytyy internet osoitteesta: http://www.amcase.info/. Rekisteröitymällä kuka vain voi syöttää alustalle lisää aineistoa.

Kappaleiden suunnitteluohjeet on julkaistu Suomen pikavalmistusyhdistyksen sivuilla: http://firpa.fi/html/am-tietoa.html. Ohjeesta löytyy mm. suositeltu minimi seinämänvahvuus, suositellun pienimmän yksityiskohdan koko, tyypillinen markkinoilta löytyvä rakennuskammin koko, sekä tyypilliset materiaalit. Valmiiden kokoonpanojen ja mekanismien suunnitteluun muodostettiin Objet 30 ja UPrint SE+ laitteelle ohjeistus josta löytyy pienin radiaalinen välys, aksiaalinen välys, sekä pienin rako riippuen rakennussuunnasta.

Tutkimusprojektin aikana seurattiin alan teknologian kehitystä. Kahden vuoden aikana markkinoille ilmaantui noin. 50 uutta laitevalmistajaa, sekä noin 300 erilaista laitetta, sekä lukuisia materiaaleja. Merkittävimmät uudistukset listattiin ja pohdittiin mahdollisia kehityssuuntia. Kaikki uudet toimijat ja laitteet päivitettiin Firpan ylläpitämään tietokantaan: http://firpa.fi/html/am-tietoa.html. Markkinoilla on selvä suuntaus tuotantokomponenttien valmistamiseen, kotitulostimien hintojen laskemiseen, sekä isompien kappaleiden valmistamiseen.

Muovilevy komponenttien muovaamista tutkittiin laserin ja alipaineen avulla DDShape laitteella. Laitteella onnistuttiin tekemään testikappaleita ja laitetta saatiin kehitettyä eteenpäin. Laitteiston kehittämiseksi ja kaupallistamisen tueksi Tekes on myöntänyt "Tutkimusideoista uutta tietoa ja liiketoimintaa" (TUTLI) rahoituksen.

ISF mini projektissa onnistuttiin kehittämään edullinen pienten kappaleiden painomuovauskone. Samalla kartoitettiin laitteelle soveltuvat parametrit ja rajoitukset. Laseravusteisella muovaamisella päästään kuparilla isompaan seinämän kaltevuuteen ja pinnalaatu pysyy hyvänä. Teräksellä laserista ei ollut juuri hyötyä ja alumiinilla muovattavuus kyllä parani, mutta pinnalaatu huononi.

AM kappaleiden viimeistelykoneistuksessa tutkittiin muovisten kappaleiden viimeistely jyrsimällä, sekä metallikappaleiden automaattista hiontaa. Jyrsinnässä vertailtiin eri menetelmillä tehtyjä kappaleita, sekä mitattiin kappaleiden mittatarkkuutta ja geometrisia toleransseja. Huonosta kotitulostimella tehdystä kappaleesta on vaikea saada hyvää kappaletta vaikka se viimeisteltäisiin koneistamalla. Suurimmat ongelmat liittyvät kappaleiden vääntymiseen johtuen lämpöjännityksistä valmistusprosessin aikana. Kappaleiden automaattisessa hionnassa parhaat tulokset saatiin DMLS kappaleille käyttämällä hionta-aineena teräshauleja ja pyörittämällä niitä hiottavat kappaleen kanssa rummussa. Ra arvo parani tällöin noin seitsemästä mikrometristä kolmeen mikrometriin.

11. Viitteet

[1] Jukka Tuomi, Lotta Lamminen, Jussi Kanerva. Effects of the Latest Developments of the Rapid Tooling and Manufacturing Technologies on Companies' Product Development Processes. Proceedings of the2nd International Conference on Rapid Prototyping and manufacturing 2002, Beijing. Journal of Tsinghua University, Science and Technology 2002-08, Vol. 42 No. S2. ISSN 1000-0054, CODEN QDXKE8.

[2] Jukka Tuomi, Jouko Karjalainen. Cost Model for Rapid Manufacturing. Journal for New Generation Sciences, Central University of Technology, Free State, South Africa. Volume 4, No 1. 2006. ISSN 1684-4998.

[3] Jukka Tuomi, Lotta Vihtonen. Incremental Sheet Forming as Rapid Prototyping and Manufacturing Technology. International Conference on Manufacturing Automation, ICMA '07, CD-ROM ISBN 978-981-05-8089-6, National University of Singapore, May 28 – 30, 2007.

[4] Partanen J., Tuomi J., Vihtonen L. Toolless layer-wise production methods – Adaptable and fast way to customer. The 3rd International Conference on Additive Technologies, DAAAM Specialized Conference, September, 22th-24th, 2010 Nova Gorica, Slovenia. Proceedings CD ISBN 978-3-901509-75-9.

[8] Aamulehti 3.4.2011 - Tulostettu tulevaisuus.

[9] Talouselämä 29.4.2011 - Tulostaminen mullistaa maailman

[10] The Economist 10.2.2011 - Print me a Stradivarius, The manufacturing technology that will change the world.

[11] The Economist 10.2.2011 - The printed world

[12] The Guardian 17.11.2011 - Could 3D printing end our throwaway culture?

[13] Newscientist 1.8.2011 - 3D printing: The world's first printed plane

[14] The National Additive Manufacturing Innovation Institute (NAMII),n http://namii.org/

[15] ENGINEERING.com, UK to Invest an Additional £7 million in A.M.

[16] ASTM standard F2792. Standard terminology for additive manufacturing technologies. ASTM International. DOI: 10.1520/F2792-12, www.astm.org, 2012.

[17] Lehmhus, D., Busse, M., Herrmann, A., & Kayvantash, K. (Eds.). (2013). Structural materials and processes in transportation. John Wiley & Sons.

[18] China to invest $80M in 3D printing innovation center. 3Ders.org. 3D printer and 3D printing news. 5.2.2013. http://www.3ders.org/articles/20130205-china-to-invest-8m-in-3d-printing-innovation-center.html.

[19] Giving a lift to 3-D printing. Asia One News. 22.3.2013. http://news.asiaone.com/News/AsiaOne+News/Business/Story/A1Story20130319-409688.html.

[20] Gartner Says Consumer 3D Printing Is More Than Five Years Away. Gartner. 19.8.2014. http://www.gartner.com/newsroom/id/2825417.

[21] The 3D Printing Revolution You Have Not Heard About. Forbes. 7.8.2013. http://www.forbes.com/sites/rakeshsharma/2013/07/08/the-3d-printing-revolution-you-have-not-heard-about/.

12. Liitteet

Doctoral dissertation 2013. Mika Salmi, Medical applications of additive manufacturing in surgery and dental care. AALTO UNIVERSITY School of Mechanical Engineering Department of Engineering Design and Production.

Master's thesis 2013. Iñigo Flores Ituarte, The role of Additive Manufacturing in modern product development: a case study for consumer electronic industry. AALTO UNIVERSITY School of Mechanical Engineering Department of Engineering Design and Production.

Master's thesis 2014. Sergei Chekurov, Additive Manufacturing Needs and Practices in the Finnish Industry. AALTO UNIVERSITY School of Mechanical Engineering Department of Engineering Design and Production.

ISF mini loppuraportti 2014. Pekka Lehtinen. AALTO UNIVERSITY School of Mechanical Engineering Department of Engineering Design and Production.

Laseravusteinen numeerinen painomuovaus 2014, Tapio Väisänen. Hämeen ammattikorkeakoulu HAMK.

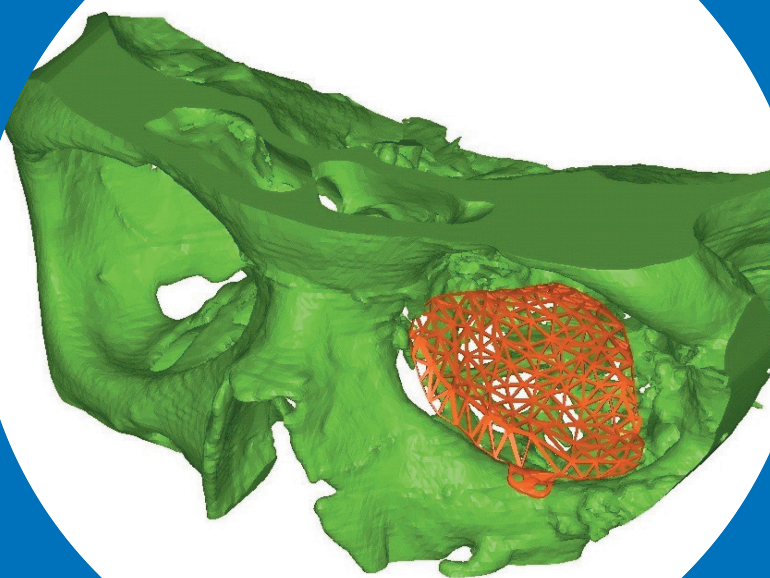
Bachelor’s thesis 2014. Rui Chen, Incremental forming (test environment). HAMK University of Applied Sciences.

Kokoonpantujen kappaleiden suunnitteluohjeet materiaalia lisäävää valmistusta varten 2014, Sergei Chekurov, AALTO UNIVERSITY.

Department of Engineering Design and Production

Medical applications of additive manufacturing in surgery and dental care

Mika Salmi



Aalto University

DOCTORAL DISSERTATIONS

Aalto University publication series
DOCTORAL DISSERTATIONS 213/2013

Medical applications of additive manufacturing in surgery and dental care

Mika Salmi

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall K216 of the School of Engineering on 20th December 2013 at 12.

Aalto University
School of Engineering
Department of Engineering Design and Production

Supervising professors
Professor Petri Kuosmanen
Department of Engineering Design and Production, Aalto University

Thesis advisors
Professor Antti Mäkitie MD PhD
Department of Otolaryngology – Head & Neck Surgery,
Helsinki University Central Hospital and University of Helsinki
& Department of Industrial Engineering and Management,
BIT Research Centre, Aalto University

Preliminary examiners
Professor Paulo Jorge da Silva Bártolo, Polytechnic Institute of Leiria, Portugal

Dr Richard Bibb, Loughborough University, United Kingdom

Opponent
Professor Antti Salminen, Lappeenranta University of Technology
LUT, Finland

Aalto University publication series
DOCTORAL DISSERTATIONS 213/2013

ISBN 978-952-60-5495-7
ISBN 978-952-60-5496-4 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934 (printed)
ISSN 1799-4942 (pdf)
http://urn.fi/URN:ISBN:978-952-60-5496-4

Unigrafia Oy
Helsinki 2013

Finland

441 697
Printed matter

Aalto University

Aalto University, P.O. Box 11000, FI-00076 Aalto www.aalto.fi

Abstract

Author
Mika Salmi

Name of the doctoral dissertation
Medical applications of additive manufacturing in surgery and dental care

Publisher School of Engineering

Unit Department of Engineering Design and Production

Series Aalto University publication series DOCTORAL DISSERTATIONS 213/2013

Field of research Medical applications of additive manufacturing

Manuscript submitted 19 August 2013 **Date of the defence** 20 December 2013

Permission to publish granted (date) 29 November 2013 **Language** English

☐ **Monograph** ☒ **Article dissertation (summary + original articles)**

Abstract

At present handcrafting is still common in surgery and dentistry. The majority of patient specific implants are handmade during surgery and oral appliances are handmade by a dental technician in a dental laboratory. Surgical procedures are usually designed according to medical imaging, but during the surgery, plans are often changed due to issues that were not detectable from the two dimensional images. By using the modern digital technology it is possible to reduce or completely avoid manual work phases, and thus achieve remarkable advantages related to accuracy and speed.

Additive manufacturing is a material adding fabrication process, which suits for manufacturing objects with complex geometric shapes for either one piece or small series production. The parts are produced automatically according to a digital 3D model. By digitalizing the medical processes of additive manufacturing can be easily and rapidly performed. Therefore, it is a suitable manufacturing method in both surgery and dentistry.

This research concentrated on medical models and patient specific implants made by additive manufacturing, as well as oral appliances used in dentistry. The subjects included (1) medical 3D modeling and design, (2) applying various additive manufacturing technologies and (3) estimating the usability and dimensional accuracy of these processes. As a result a patient specific orbital floor implant and different oral appliances were produced using additive manufacturing and digital design. In addition the effects of different additive manufacturing methods for accuracy of medical models were studied. The results showed that additive manufacturing can be effectively utilized in surgery and dentistry, and patients' treatment results may improve when using the above methods.

Keywords 3D printing, rapid prototyping, rapid tooling, implants, medical models, occlusal splint, oral appliances

ISBN (printed) 978-952-60-5495-7 **ISBN (pdf)** 978-952-60-5496-4

ISSN-L 1799-4934 **ISSN (printed)** 1799-4934 **ISSN (pdf)** 1799-4942

Location of publisher Helsinki **Location of printing** Helsinki **Year** 2013

Pages 85 **urn** http://urn.fi/URN:ISBN:978-952-60-5496-4

Aalto-yliopisto

Aalto-yliopisto, PL 11000, 00076 Aalto www.aalto.fi

Tiivistelmä

Tekijä
Mika Salmi

Väitöskirjan nimi
Materiaalia lisäävän valmistuksen lääketieteelliset sovellutukset kirurgiassa ja hammashoidossa

Julkaisija Insinööritieteiden korkeakoulu

Yksikkö Koneenrakennustekniikan laitos

Sarja Aalto University publication series DOCTORAL DISSERTATIONS 213/2013

Tutkimusala Materiaalia lisäävän valmistuksen lääketieteelliset sovellutukset

Käsikirjoituksen pvm 19.08.2013 **Väitöspäivä** 20.12.2013

Julkaisuluvan myöntämispäivä 29.11.2013 **Kieli** Englanti

☐ **Monografia** ☒ **Yhdistelmäväitöskirja (yhteenveto-osa + erillisartikkelit)**

Tiivistelmä

Kirurgiassa ja hammaslääketieteessä pääasiallinen työskentelytapa on käsityö, eikä digitaalisuuden kaikkia mahdollisuuksia vielä hyödynnetä. Kehittyneempiä tekniikoita kuten leikkausnavigointia, leikkausrobotteja ja digitaalista kuvantamista kyllä käytetään, mutta esimerkiksi potilaskohtaiset implantit kirurgi yleensä muotoilee käsin leikkauksen aikana tai käyttää valmiita implantteja, joista potilaalle valitaan sopivimman kokoinen ja muotoinen. Myös hammaslääketieteessä käytetyt suukojeet valmistetaan tavallisesti hammasteknikon toimesta käsityönä hammaslaboratoriossa. Leikkaukset suunnitellaan yleensä kuvantamistutkimusten perusteella, mutta leikkauksen aikana tulee usein esiin asioita, joita kaksiulotteisista kuvista ei pystytä havaitsemaan, ja näin ollen leikkaussuunnitelma voi muuttua leikkauksen aikana. Käyttämällä hyväksi digitaalisuuden tuomia mahdollisuuksia voidaan tuottaa 3D-malleja ja fyysisiä malleja potilaan anatomiasta, sekä vähentää tai poistaa kokonaan käsityövaiheita. Tämä nopeuttaa leikkausta ja parantaa tarkkuutta.

Materiaalia lisäävä valmistus on valmistusmenetelmä, joka soveltuu erityisesti monimutkaisten kappaleiden yksittäis- tai piensarjatuotantoon. Kappaleet tuotetaan automaattisesti digitaalisen 3D-mallin perusteella. Digitalisoimalla lääketieteen prosesseja voidaan materiaalia lisäävää valmistusta nopeasti hyödyntää. Se on myös erityisen sopiva valmistusmenetelmä lääketieteeseen, koska potilaiden tarpeet ovat erilaisia eivätkä samanlaiset ratkaisut sovellu kaikille.

Tässä tutkimuksessa keskityttiin materiaalia lisäävillä valmistustekniikoilla toteutettuihin lääketieteellisiin malleihin ja potilaskohtaisiin implantteihin sekä hammaslääketieteessä käytettyihin suukojeisiin. Tutkittuja aiheita olivat lääketieteellisten 3D-mallien muodostus, lääketieteellinen 3D-mallintaminen, eri valmistusmenetelmien soveltaminen ja prosessien käyttökelpoisuuden ja mittatarkkuuden arviointi. Työn tuloksena saatiin valmistettua ainetta lisäämällä toimiva yksilöllinen silmänpohjaimplantti, sekä erilaisia suukojeita. Tutkimuksessa selvitettiin myös eri materiaalia lisäävien valmistusmenetelmien tarkkuutta lääketieteellisten mallien valmistamiseen. Tulokset osoittivat, että tutkitut menetelmät tuovat uusia mahdollisuuksia potilaiden hoitamiseen ja mahdollistavat näin parempia hoitotuloksia.

Avainsanat 3D tulostus, pikavalmistus, implantit, lääketieteelliset mallit, purentakisko, suukojeet

ISBN (painettu) 978-952-60-5495-7 **ISBN (pdf)** 978-952-60-5496-4

ISSN-L 1799-4934 **ISSN (painettu)** 1799-4934 **ISSN (pdf)** 1799-4942

Julkaisupaikka Helsinki **Painopaikka** Helsinki **Vuosi** 2013

Sivumäärä 85 **urn** http://urn.fi/URN:ISBN:978-952-60-5496-4

Preface

This study was carried out at the BIT Research Centre, Department of Industrial Engineering and Management, School of Science, Aalto University during the years 2009-2013. It was financed by the Finnish Funding Agency for Technology and Innovation (Tekes), DeskArtes Oy, EOS Finland Oy, Vektor Claims Administration, Planmeca Oy, Inion Oy and LM-Instruments Oy. I would like to express my sincere appreciation to all of these parties for financing and supporting this research.

I wish to thank Research Director Jukka Tuomi and former Director of BIT Research Centre Jouni Partanen, now Professor in the Department of Engineering Design and Production, for support and valuable discussions. I am especially grateful to my thesis advisor Professor Antti Mäkitie for guidance and aid during these years. I am also grateful to Professor Petri Kuosmanen for his encouragement and help during this project.

I wish to express my gratitude to the preliminary examiners Dr. Richard Bibb and Professor Paulo Bártolo for their valuable input in improving this thesis, and to Professor Antti Salminen for being the opponent. I thank Docent Vesa Saikko and Piritta Niemi for language checking as well as for their comments on the thesis.

I would like to thank all my co-authors: Jukka Tuomi, Kaija-Stiina Paloheimo, Roy Björkstrand, Risto Kontio, Karri Mesimäki, Antti Mäkitie, Rauno Sirkkanen, Tuula Ingman, Markku Paloheimo, Jari Salo and Jan Wolff. It has been a privilege to work with you all.

I wish to thank all my colleagues and co-workers, who have participated in this research. I'm especially thankful to the members of our research group, who have supported me in my work and created a pleasant working atmosphere: Eero Huotilainen, Roy Björkstrand, Kirsi Kukko, Pekka Lehtinen, Iñigo Flores Ituarte, Sergei Chekurov and Irina Pitkänen.

Finally, I thank my family and friends, who have always been there to support me and helped me keep my working life and private life in a balance. My parents, Katja, Harri, Piritta and Leo are all especially thanked.

Contents

List of original publications

This doctoral thesis is based on the following publications:

I Salmi M, Tuomi J, Paloheimo KS, Björkstrand R, Paloheimo M, Salo J, Kontio R, Mesimäki K, Mäkitie AA: Patient specific reconstruction with 3D modeling and DMLS additive manufacturing. Rapid Prototyping Journal 18:209-214, 2012.

II Salmi M, Tuomi J, Sirkkanen R, Ingman T, Mäkitie A: Rapid Tooling Method for Soft Customized Removable Oral Appliances. The Open Dentistry Journal, 6:85-89, 2012.

III Salmi M, Paloheimo KS, Tuomi J, Wolff J, Mäkitie A: Accuracy of medical models made by additive manufacturing (rapid manufacturing). Journal of Cranio-Maxillofacial Surgery, 41:603-609, 2013.

IV Salmi M, Paloheimo KS, Tuomi J, Ingman T, Mäkitie A: A digital process for additive manufacturing of occlusal splints: a clinical pilot study. Journal of the Royal Society Interface 10:20130203, 2013.

The publications are referred to in the text by their roman numerals.

Author´s contribution to the appended joint publications:

I-IV The design of the research plan was carried out by Mika Salmi in collaboration with the co-authors. Mika Salmi performed the experimental work and was responsible for investigating the patient data capturing, creating 3D models from the data, medical 3D modeling and selecting suitable AM technology and materials. He carried out the measuring method development as well as geometry evaluation with the help of co-authors. The results were interpreted together by the co-authors. Mika Salmi was the principal author and corresponding author of all the manuscripts.

Abbreviations

3D	Three dimensional
3DP	Three dimensional printing
AM	Additive manufacturing
CAD	Computer aided design
CAM	Computer aided manufacturing
CBCT	Cone beam computed tomography
CMM	Coordinate measuring machine
CT	Computed tomography
DICOM	Digital imaging and communications in medicine
DMLS	Direct metal laser sintering
EBM	Electron beam melting
ELI	Extra low interstitial
FDM	Fused deposition modeling
MRI	Magnetic resonance imaging
MSCT	Multi slice computed tomography
PEEK	Polyether ether ketone
PMMA	Poly(methyl methacrylate)
RP	Rapid prototyping
SL	Stereolithography
SLM	Selective laser melting
SLS	Selective laser sintering
STL-file	Stereolithography-file
Ti64 ELI	Titanium alloy Ti6Al4V with particularly low level of impurities
UV	Ultraviolet

1 Introduction

Traditionally medical devices are designed according to “an average person” because customized devices need to be specially handmade and are therefore costly. Currently, the majority of patient specific implants are handmade during surgery and oral appliances are handmade by a dental technician in a dental laboratory. The development of medical imaging, especially imaging software and digital three-dimensional (3D) scanning has made it possible to create various 3D models from medical images. These 3D models can be directly manufactured into physical objects using additive manufacturing (AM) or the 3D models can be used as a design template for personalized medical and dental devices. This obviates the handicraft and may result in more accurate and economical devices. Combining known techniques and novel design and manufacturing methods offers medical professionals new means to treat patients and to enhance their quality of life.

The increase of welfare in Western countries sets higher expectations for a better quality of life. But on the contrary, the ageing of the population sets its own challenges. The lifestyle of our Western society has dramatically reduced physical exercise and increased the amount of sedentary work. As a consequence, the physical condition of people is deteriorating causing various health issues, such as problems with back and joints, among many others. These challenges require new and improved medical devices and advanced manufacturing technologies. It is estimated that in the European Union the old-age dependency ratio will grow from 25 % in 2010 to 50% by 2050 (Eurostat 2013). Furthermore, in the US, China and India the old-age dependency is estimated to double during the next 40 years (United Nations 2012). Based on these figures, there is great potential for new technologies, such as AM.

Several terms are used for AM, for example rapid prototyping, layer manufacturing, freeform fabrication and rapid manufacturing. Since the inventing of first AM equipment in 1986, the development has been fast. In the field, there are at least 21 different technologies for AM such as stereolithography (SL), three dimensional printing (3DP), fused deposition modeling (FDM), PolyJet, electron beam melting (EBM), direct metal laser sintering (DMLS) among others and at least 36 systems manufacturers with different types of systems commercially available (Wohlers 2011). Accuracy of the AM processes and properties of material have significantly improved over the last 20 years, and due to these improvements, some materials in AM technologies nowadays meet the strict requirements set for material in medical devices. AM is superior in one-off production, since there is no need for tooling and objects are manufactured automatically. Thus AM has huge potential for the production of patient-specific medical devices. The newest, specific materials are biocompatible and some materials can be used for implantation purposes. However, most doctors and dentists are not even aware of this technology and the use of implants and devices produced with AM is not yet a standard clinical procedure.

In the present work an attempt is made to better understand the multidisciplinary process, which is needed to develop and evaluate digital manufacturing of medical and dental devices. It is a proof of concept that these processes and procedures are functioning on real patients with advantages compared to the standard processes used by hospitals and dentists. With more awareness and case studies this can be a major technical step in medical field development.

This research was carried out in Aalto University in two projects funded by Tekes (the Finnish Funding Agency for Technology). The projects Bioman II (2007–2010) and MedAMan (2010–2012) were carried out in cooperation with industry and hospitals, and the objective was to find new business opportunities for the Finnish industry and to solve problems arising from the clinical side. Papers I and II are based on the results of the Bioman II project and papers III and IV are based on the MedAMan project.

1.1 General aims of the study

The general aim of this Doctoral Thesis was to investigate the use of digital 3D modeling technology and AM to improve surgery and dental care processes. The processes were studied including all the phases from the beginning to the end. The use of AM technology can be divided into several steps, which were all investigated to obtain knowledge of the process:

i. Suitable software and hardware for digital imaging and data capturing were investigated to obtain data for patient-specific geometry. Communication with radiologists was essential to obtain high quality in imaging.
ii. Patient-specific data was transformed into a 3D model for the modeling phase. Suitable software and parameters were selected for each case.
iii. Medical 3D modeling was performed by utilizing a 3D model of a patient as a reference. Suitable software for each purpose is required. The 3D models were produced for AM without triangulating errors.
iv. The most suitable AM process and material were selected for each application.

1.2 Specific aims

The specific aims of this Doctoral Thesis can be divided in to the following sub-aims:

1. To develop a process to produce patient-specific implants using AM and data from computed tomography (CT) images. The process was tested from the beginning to the end with a patient in order to reduce manual work phases during surgery and operation time compared to the currently used methods to prepare patient-specific implants. Previously, cranial implants have been made using such a process (Poukens et al. 2008), but in this research the focus was in orbital implants requiring more accuracy. The geometry and macrostructure of the implant were optimized. The geometry included both the boundary surface to the bone and the functional form.

2. To study the accuracy of different AM methods in medical model production in order to understand the variations in different models, and to develop a suitable measuring method by taking into account special characteristics of AM. The accuracy has been previously investigated, but often using manual measuring equipment and repeatability has not been estimated (El-Katatny et al. 2010, Ibrahim et al. 2009, Silva et al. 2008). Therefore, the aim was to develop an automatic measuring method with high repeatability.

3. To investigate the use of a rapid tooling technique in order to produce soft orthodontic appliances utilizing a plaster model from a patient's teeth as a starting geometry and silicone as a material for the appliance. Hard aligners made by rapid tooling (Joffe 2003) are commercially available. Soft material may allow using fewer aligners and therefore reducing costs. And they have not been previously produced using rapid tooling. Therefore, the aim was to prove the concept for making soft aligners by rapid tooling.

4. To study the use of AM as a direct fabrication method for an occlusal splint by capturing data from a patient's plaster model, and to find a suitable material for the application. Computer-assisted method for design and milling of splints has been presented earlier (Lauren et al. 2008). Using AM for occlusal splint manufacturing has not been reported or studied. The aim was to reduce manual work phases for a more accurate and efficient production of occlusal splints.

1.3 Scientific contribution

This work showed that it is possible to utilize AM in surgery and dental care. Aa patient-specific orbital implant was produced using digital design and AM. There are some studies, which report the manufacturing of implants using AM, but that is still rare and the implant prepared in this study was one of the first orbital implants. The automatically generated and adjustable macrostructure of the implant was designed to allow cells and tissues to grow through the implant. The accuracy of three different AM technologies for medical model production was measured with the method developed as a part of this study. The previous accuracy studies did not discuss the repeatability of the measurements (El-Katatny et al. 2010, Ibrahim et al. 2009, Silva et al. 2008). The repeatability of the measuring method, which was developed in this study, was excellent with only minor variations in the repeated measurements.

Hard occlusion splints made by rapid tooling are commercially available, but it has not been used to manufacture soft occlusion splints. Individualized soft occlusion splints have not been published earlier. In this study a functional occlusion splint was made by AM and clinically tested on a patient with promising results. This was one of the first occlusion splints directly produced using AM and tested on a patient for a period of six months. No tooth wear, significant splint wear or other problems were detected during the test period. At the follow-up visits less grinding was needed compared to standard splints. Multidisciplinary cooperation with surgeons and dentists was established.

The author's scientific contribution during this research was to investigate the patient data capturing, to create 3D models from the patient data, to perform medical 3D modeling, to select the suitable AM technology and material for specific purposes and measure, and to evaluate geometry of the manufactured part.

2 Background

2.1 Classification of medical applications of additive manufacturing

During the recent years more and more medical applications of AM have been developed and reported. This research area is challenging because the development is always a multidisciplinary process and includes work related to medical imaging, 3D modeling, medical treatment and the actual AM technology. There is a number of requirements related to AM technology when applying it in the medical field. Therefore, an application-based classification system for medical applications is needed. Hopkinsson et al. (2006) categorized medical applications to: presurgery AM, orthodontics, drug delivery devices, limb prostheses and *in vivo* devices. Gibson et al. (2009) defined the categories as: surgical on diagnostic aids, prosthetics, manufacturing, tissue engineering and organ manufacturing. More and more new applications are emerging without belonging to these categories. Medical implants can be defined as devices placed either inside or on the surface of the body to accomplish a particular function, such as to replace, assist or enhance the functionality of some biological structures (Bartolo et al. 2012). These can be categorized to: external to body, temporally internal to body and permanently internal to body (Bartolo et al. 2012). One of the most recent attempts to classify the whole area of medical applications of AM uses the following five categories (Tuomi et al. 2010):

1. Medical models for preoperative planning, education and training.
   These models can be used for planning or simulating the surgery preoperatively. The models can be used for educating students as well as patients and families and for surgical training purposes. Depending on the application different qualities of the models such as anatomical accuracy, material characteristics and haptic response of the model are important.

2. Tools, instruments and medical device parts
   AM is used to create tools and hardware for medical applications. Drilling, sawing and cutting jigs belong to this class. Manufacturing of operation or patient-specific

instruments or preforms are included in this category (Kontio et al. 2012). Parts in this class can be invasive but not implantable.

3. Medical aids, supportive guides, splints and prostheses

   AM technologies are utilized for anatomic personalization of a device or corresponding element. For example prosthetic sockets, appliances for dental malocclusion and patient-specific external ankle support (Björkstrand et al. 2010) belong to this category. Drill-guiding microtables belong to this class and devices in this class are external to body and non-invasive.

4. Inert implants

   Implants in this group are usually made of an inert metal or alloys, such as titanium or cobalt-chrome alloy. The implants may be created based on medical imaging and 3D modeling. Inert implants can be manufactured directly or indirectly by manufacturing a mold with AM. This class includes dental crowns and bridges.

5. Biomanufacturing

   Biomanufacturing combines AM and tissue engineering to produce biologically active implants, tissues and organs. This group includes biologically compatible parts such as tissues and reactive implants. In addition, biocompatible scaffolds and culture media used for tissue growth belong to this class. Fox example, AM can be used to produce scaffolds from polylactic acid or polycaprolactone (Mäkitie et al. 2013). Tissues can be externally grown or they can be the patient’s own. Contrary to the inert implants, reactive implants react with the body, such as by dissolving over time or by releasing drug in a controlled manner. Scaffolds can be used as a skeleton, providing support for cell growth, protection from external physical forces and as an optimal medium for 3D culture of cells (Yan et al. 2003). Culture media with a desired shape or form can be manufactured with AM technologies. Research in the field of direct AM of tissues is rapidly increasing (Hutmacher et al. 2004; Wang et al. 2006; Xu et al. 2007). The development of an innovative biomedical system can be a major breakthrough in the healthcare industry (Mitsuishi et al. 2013).

Categories 1, 3 and 4 are discussed in more detail in the following chapters, as the model of the patient orbital (Paper I) and skull models (Paper III) belong to class 1, directly and undirectly manufactured oral applications (Paper II & IV) belong to class 3, and orbital implant (Paper I) belongs to class 4.

2.2 Medical models

Medical models are physical objects that can be cut or sawn. It is possible to draw on the model with pencil to visualize section plans. Medical scan data from CT, magnetic resonance imaging (MRI), ultrasound, optical or laser scanner can be transformed to 3D surface model using segmentation, and after that used to produce physical models with AM techniques for use in surgery or prosthetic rehabilitation (Bibb 2006). Medical models made by AM can be used to help planning or simulating difficult phases of surgical operations (McDonald et al. 2001). Because of this preoperative planning, the use of these medical models can significantly reduce the operating time (D'Urso et al. 1999). In cosmetic surgery, harmonious facial contour can be achieved by planning cutting lines of jawbone preoperatively (Jiang et al. 2012). The medical models can be used as a template for pre-bending reconstruction plates (Lethaus et al. 2012) or custom implant manufacturing by taking a silicone mold from it for casting (Eppley 2002). It is possible to preoperatively pre-shape a titanium mesh for orbital wall reconstruction over a medical model (Kozakiewicz 2009 & 2011). Customized reconstruction plates can be manufactured according to a medical model by forming a wax over it and applying a casting technique using a metal alloy (Klammert et al. 2009). Medical models can be used for communication with students, patients, and families in procedures such as a temporal bone dissection (Mäkitie et al. 2008). AM can improve students' understanding of human anatomy by bringing the anatomical variations from the clinics into preclinical studies (Rengier et al. 2010). Different properties of the models such as anatomical accuracy, material characteristics or haptic response depend on the application. A haptic response similar to a bone is especially desirable in surgical training models (Mäkitie et al. 2008).

The process of making medical models involves various steps, each of which can be a source of errors. The imaging, segmentation and manufacturing phases can all contribute to the errors. In each phase the size or the shape can go wrong. Medical skull models can vary markedly depending on the DICOM to STL conversion software and the parameters used (Huotilainen et al. 2013). Significant errors can arise from CT data import, CT gantry tilt distortion, model stair-step artefact, irregular surface from support structures and mathematical modeling, metal and movement artefacts as well as image threshold (Winder & Bibb 2005). Communication between surgeons, radiologists and engineers is crucial. For example, images are taken using a thin slice thickness, but when archived, only half of the slices are saved to save storage capacity (Huotilainen et al. 2013). Choi et al. (2002) measured the skull in three phases: dry cadaver skull, 3D model from CT images and SL model, and found that errors between the dry skull and the 3D model was greater than between the SL model and the dry skull. This means that the errors in the middle of the process are larger than in the end, which can be explained by that the errors in different phases are compensating each other's. Errors of several millimeters were found when using cadaver skulls with soft tissues (Chang et al. 2003). El-Katatny et al. (2010) used digital calibers to measure the margin between a 3D model of a skull and a mandible compared to physical models made using FDM. Errors were some tenths of millimeters. Substantially less accuracy was found when comparing a dry cadaver bone to a replica made by AM (Ibrahim et al. 2009; Silva et al. 2008). Nizam et al. (2006) found small differences but with high standard deviation when measuring distances between different anatomical landmarks from a dry cadaver skull and a SL model. Some studies state that such a high accuracy is not needed for AM because the data from the 3D imaging is less accurate (Gibson et al. 2006), but the fast development of imaging has changed this.

The imaging method and parameters affect the quality of images and therefore the accuracy of the medical model. The accuracy of five cone beam computed tomography (CBCT) devices and one multislice computed tomography (MSCT) device have been compared for the imaging of anatomical structures (Liang et al. 2009a, 2009b). CBCT image quality was comparable to those obtained using MSCT technology, but there were some variations between the CBCT devices in delicate structures. The accuracy of MSCT device was better (mean deviation 0.137 mm) compared to the CBCT devices (mean deviation ranged from 0.165 mm to 0.386 mm). The partial volume effect related to the limited resolution occurs during the imaging and can make 3D model from facial structures unreliable and the thin walls of the cavities in the skull tend to disappear from the image (Lamecker et al. 2007). When measuring linear distances between anatomical landmarks from a dry skull and a 3D virtual model made using CBCT images, the measurement uncertainty was much higher for the 3D model (Periago et al. 2008). This may be explained by that it is difficult to select an exact point from the 3D model without a special software. The accuracy of combining helical CT and the 3DP method by changing the threshold value of the segmentation process produces a difference in the range of tenths of millimeters (Naitoh et al. 2006). The accuracy of a conversion from CT images to 3D reconstruction varies between conversion parameters (Mallepree and Bergers 2009).

2.3 Medical aids, supportive guides, splints, and prostheses

AM is utilized for anatomic personalization of a device or a corresponding element. Making prosthetic sockets has traditionally been labor intensive, taking two to three days per socket. By using computer aided manufacturing systems and AM technologies the time is reduced to less than 4 hours (Ng et al. 2002). Microtable drill guides made by AM were used in five cochlear implant surgeries and they reduced the operation time and overall costs (Labadie et al. 2008).

Wax patterns for facial prostheses produced by AM have been found to be more accurate than a conventional duplication (Sykes et al. 2004). An obturator prosthesis made from poly(methyl methacrylate) (PMMA) has been manufactured by using an AM model as a mock up (Lethaus et al. 2010). In addition, for facial prostheses laser surface digitizing with computer-aided design (CAD) and computer aided manufacturing (CAM) technologies has been successfully used (Cheah et al. 2003a&b). Facial prostheses can be fabricated more precisely using optical 3D imaging and CAD/CAM systems than conventional manual sculpturing techniques (Feng et al. 2010). Photography-based 3D imaging system has been found sufficiently accurate for clinical description of the mid-face structures and potentially useful for AM of facial prostheses (Kimoto et al. 2007). AM and 3D reconstruction from CT images have been used for fabricating dental splints for orthognathic surgery (Yanping et al. 2006). It has been considered that after CAD/CAM systems AM is the next revolution in dental device manufacturing (Van Noort 2012).

Occlusion splints and oral appliances are categorized in this group. The traditional protocol to fabricate oral appliances includes alginate impressions and wax registrations taken by a dentist and the appliance is made by a dental technician. 3D-CAD allows a greater use of industrially manufactured appliances while taking into account the biomechanics (Vassura et al. 2010). The prenatal development of the human temporomandibular joint has been monitored using computer-aided graphical 3D-reconstruction (Radlanski et al. 1999). Geometric copies of tooth roots have been manufactured using a combination of CT and AM (Lee et al. 2006). The first and the best known combination of CAD/CAM technologies in odontology is Cerec (Siemens, Germany) to produce ceramic inlays (Pallasen and Van Dijken 2000). Clear and hard tooth aligners can be digitally manufactured by first digitizing the teeth, then straightening them virtually by a computer, and further producing a mold by AM for pressure forming (Lin 2005). Lauren et al. (2008) digitalized the teeth from stone casts and virtually adjusted them by a computer. They used milling as the manufacturing method for these hard occlusal splints. AM can be used in a treatment of dental malocclusion by making a mold for a series of transparent and removable appliances (Miller et al. 2002). Hard appliances are made by the following method: digitalizing the tooth, virtually straightening the tooth, making a mold by AM, pressure forming and finishing the appliance (Joffe 2003). On the other hand, a soft appliance, which guides the eruption of the teeth, has been found an effective method to achieve normal occlusion for children and to eliminate the need for further orthodontic treatment (Keski-Nisula et al. 2008).

The accuracy of different CAM systems varies from the best mean value 58 μm to the worst ones 183 and 206 μm (Kohorst et al. 2009). The accuracy of a plaster model scanning and producing plaster replica by AM have been tested with four different digitizing systems and eight different combinations of AM technology with various materials, but since there is no reference models for non-standard shapes, an absolute accuracy value for the scanning process cannot be stated (Germani et al. 2010). CT imaging has been combined with an optic plaster model scanning to obtain a virtual model with accurate teeth and jaws for occlusion control. Jaws can be repositioned virtually and according new position a splint for orthognathic surgery can be manufactured with a 3D printer or subtractive manufacturing (Metzger et al. 2008).

2.4 Inert implants

One method for manufacturing patient-specific implants is a preoperative fabrication of a wax pattern on a skull model and using conventional dental replication methods (D'Urso et al. 2000a; Al-Sukhun et al. 2006) A silicone mold can be formed over a preoperative model and used for casting (Eppley, 2002). A digitally designed implant can be used as a positive part for silicone rubber mold, which in turn can be used for creating an implant by casting (Singare et al. 2005) or as a pattern in investment casting (Singare et al. 2009).

A reconstruction of a skull has been performed successfully using digital design and AM (Poukens et al. 2008, Rouse 2009). Cranial plates for direct implantation have been digitally designed and made using AM (Janssens & Poukens 2007). Traditional machining methods can be used in digitally designed patient-specific implants manufacturing by using CT images as a design reference (Poukens et al. 2008). Implants can be manufactured directly from metal alloys using direct metal laser sintering (DMLS) or electron beam melting (EBM) (Lethaus et al. 2011, Ciocca et al. 2011). Machined polyether ether ketone (PEEK) plastic has been used in implants for humans (Lethaus et al. 2011) and laser sintered PEEK tested in pigs without complications (Von Wilmonsky et al. 2009). Customized porous scaffolds, in which bone tissues can grow, has been studied to be manufactured using selective laser melting (SLM) (Warnke et al. 2009).

An orbital prosthesis has been produced using digital design and creating a wax model by AM to produce a physical pattern that could be used in the conventional prosthesis manufacturing process (Evans et al. 2004). Custom-made titanium orbital floor prosthesis has been manufactured with the help of SL. First a medical model of an orbital fracture is made by SL and repaired in the medical model using wax. Second silicone mold is taken from SL model and the mold is used to replicate the repaired orbital floor from plaster material. And finally plaster model is covered a layer of titanium using pressure flask and trimmed, polished as well as sterilized (Hughes et al. 2003). A flow chart of the different routes to produce personalized implants from polymers, metals or ceramics is shown in Figure 1.

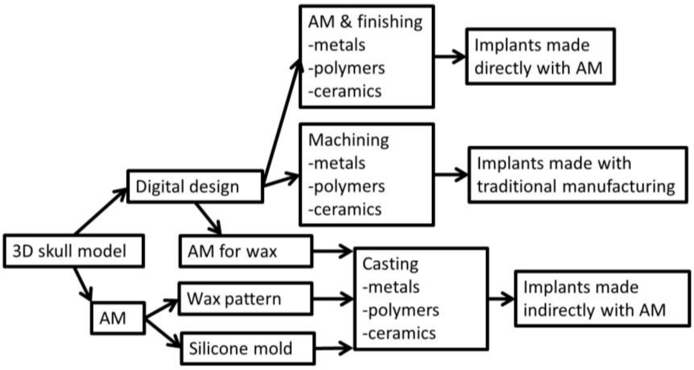


Figure 1 *Example of different routes to produce customized implants.*

2.5 Additive manufacturing

AM is a process, where parts are manufactured directly from a digital 3D model by adding material, usually on a layer by layer basis as opposed to subtractive manufacturing methods, such as traditional machining (ASTM 2012). According to ASTM, AM processes can be divided into the following categories: binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination and vat photopolymerization.

2.5.1 Binder jetting

In a binder jetting process a liquid bonding agent is selectively deposited to join powder materials (ASTM 2012). Additional support structures are not needed as the powder supports the part that is being built. Materials range from gypsum powder to metal powders. The process is not very costly, but material properties of the parts are not superior to other AM processes. Binder jetting is commercially used for example by Z Corporation and ExOne.

2.5.2 Directed energy deposition

In direct energy deposition process the focused thermal energy is used to fuse materials by melting as they are being deposited (ASTM 2012). Additional support structures are not needed because the building platform has four or five axial movement. Usually the produced parts need further processing, such as machining or polishing. Direct energy deposition is commonly used for repairing existing objects. Currently only metals are used as the materials. The process is expensive and the surface quality is low, but the material properties are excellent. Directed energy deposition is commercially used for example in Optomec's LENS process.

2.5.3 Material extrusion

In a material extrusion process the material is selectively dispensed through a nozzle (ASTM 2012). Additional support structures are needed for overhanging features. The produced objects need post-processing, at least the removal of the support structures. Thermoplastics are the most commonly materials. The process is not expensive but it is slow and the surface quality is low. On the other hand, the material properties are good. Material extrusion is commercially used for example in Stratasys's FDM process.

2.5.4 Material jetting

In the material jetting process droplets of build material are selectively deposited (ASTM 2012). If overhanging features are used, there is a need for support structures. The produced parts usually need post processing such as support removal or curing. Materials are commonly photopolymers or waxes. Process is moderate price and surface quality is good. Material properties are low. Commercially material jetting is used example Objet in Polyjet process.

2.5.5 Powder bed fusion

In powder bed fusion process thermal energy selectively fuses regions of a powder bed (ASTM 2012). For plastics there is no need for support structures since powder can support overhanging features, but metals need support structures because of thermal tensions. Metal parts need support removal and plastic parts can often use direct after cleaning from powder. Material ranges from technical plastis to metals. Process is expensive, but material properties of parts are excellent compared to other processes. Commercially powder bed fusion is used example in SLS and DMLS processes.

2.5.6 Sheet lamination

In sheet lamination sheets of material are bonded to form an object (ASTM 2012). There is no need for support structures but support removal may be troublesome. Material ranges from paper to plastic and to metal. Process is cheap, but material properties are poor in layer direction. Commercially sheet lamination is used example in Mcor paper printing process and in Fabrisonic metal printing process.

2.5.7 Vat photopolymerization

In vat photopolymerization liquid photopolymer in a vat is selectively cured by light-activated polymerization (ASTM 2012). There is need for support for overhanging features. Parts need post processing. Material ranges are photopolymers. Process is expensive, but very accurate. Material properties of parts are average compared to other processes. Commercially vat photopolymerization is used example 3D Systems SL equipments.

3 Materials and methods

3.1 Medical imaging and digital 3D scanning (Papers I-IV)

Medical imaging is used to noninvasively create images from the inside of a human body. The most commonly used imaging methods are ultrasound, X-ray, CT, MRI and nuclear medicine imaging. All these techniques produce digital imaging and communications in medicine (DICOM) images, which is a standard format in medical imaging. In implants, GE LightSpeed QX/I CT (General Electric Company, Fairfield, USA) was used with a slice thickness of 1.25 millimeters. Accuracy was studied with OsiriX DICOM sample Phenix image set (www.osirix-viewer.com/datasets/DATA/PHENIX.zip), with a slice thickness of 1.5 millimeters.

Digital 3D scanning is a method where the surface of an object is digitized. In medical or dental field this can be done directly or indirectly. Teeth can be scanned directly from the mouth using intraoral scanner or by taking a plaster model and scanning it. The used scanners, for dental models were GOM ATOS (GOM GmbH, Braunschweig, Germany) and 3Shape D710 Multi Die Scanning (3Shape A/S, Copenhagen, Denmark). GOM ATOS was used for geometry and accuracy verification of the occlusal splint and the oral appliance. The technologies used for geometry capturing are presented in Table 1. All of these methods produce triangulated 3D surface models, which contain triangulating errors.

Table 1 *The technologies used for geometry capturing.*

Technology / Source of data	Purpose
CT (slice thickness 1.25 mm) / patient	To determine patient's orbital geometry for reconstruction **(Paper I)**
CT (slice thickness 1.50 mm) / Phenix sample image set	To create a 3D skull model for accuracy measurements **(Paper III)**
GOM ATOS / plaster model from teeth	To capture tooth geometry to a mold for the manufacturing of a soft oral appliance **(Paper II)**
GOM ATOS / the soft oral appliance	To verify the geometry of the soft oral appliance **(Paper II)**
3Shape D710 Multi Die Scanning / plaster model from teeth	To capture tooth geometry to produce an occlusal splint **(Paper IV)**
GOM ATOS / the occlusal splint	To verify the geometry of the occlusal splint **(Paper IV)**

3.2 3D reconstruction and STL-file fixing (Papers I-IV)

DICOM images were reconstructed to 3D models in stereolithography format (STL format) using Osirix (open source, http://www.osirix-viewer.com) software. STL is a file format, where an unstructured, triangulated surface is described by the unit normal and vertices. 3D reconstruction was based on creating voxels (3D equivalent of a pixel) between image slices and using a selected value for the variation of density intensity. Each corner point of the voxels was examined. If the density of the voxel corner point was higher than the selected density intensity, the corner point was included in the 3D model, and vice versa. Based on the density of the corner points, surface triangles were created inside the voxel, and after all of the voxels were examined, the surface triangles covered the whole 3D model. In accuracy measurements and in the orbital reconstruction DICOM images were segmented to 3D models using 500 Hounsfield unit value.

3D models from medical imaging or digital scanning contain errors. These errors include gaps, flipped normals and triangulating errors. Before the 3D models can be manufactured using AM, errors must be repaired. These errors can be automatically or manually corrected using specified software. STL files were repaired using 3Data Expert

(DeskArtes Oy, Espoo, Finland) and Viscam RP 4.0 software (Marcam Engineering GmbH, Bremen, Germany).

3.3 Medical modeling (Papers I-IV)

Medical modeling includes creating and modifying geometry according to the data received from the 3D reconstruction. There is a need to perform different operations, such as surface modeling and Boolean operations, but so far no software includes all the needed features. Surface modeling is needed when a new geometry is created and Boolean operations are required for modifying this geometry to fit the patient. Minor editing of the triangulated surface is usually needed. There is a possibility to automatically transfer the surface to a volumetric net structure to allow tissue cells to grow through the structure. The software and purpose of the use are summarized in Table 2.

Table 2 *The used software for various purposes of medical modeling*

Software	Purpose of use
Rhinoceros 2.0 (McNeel Europe, Barcelone, Spain)	Surface modeling
3Data Expert beta version (DeskArtes Oy, Espoo, Finland)	STL-repair Convert surface to volumetric net Boolean operations Measurements
Pro Engineer Wildfire 4.0 (Parametric Technology Corp, Needham, USA)	Repositioning of teeth Placing the measurement balls
Viscam RP 4.0 (Marcam Engineering GmbH, Bremen, Germany)	STL-repair Cutting models, separating parts Smoothing, reduce triangles surface extruding Boolean operations Measurements

In accuracy measurements six measuring balls (Ø 10 mm) were attached to the 3D skull model, and the coordinates of the center points of these balls were determined. The distances between the balls were calculated from the coordinates. The locations of the balls are shown in Figure 2.

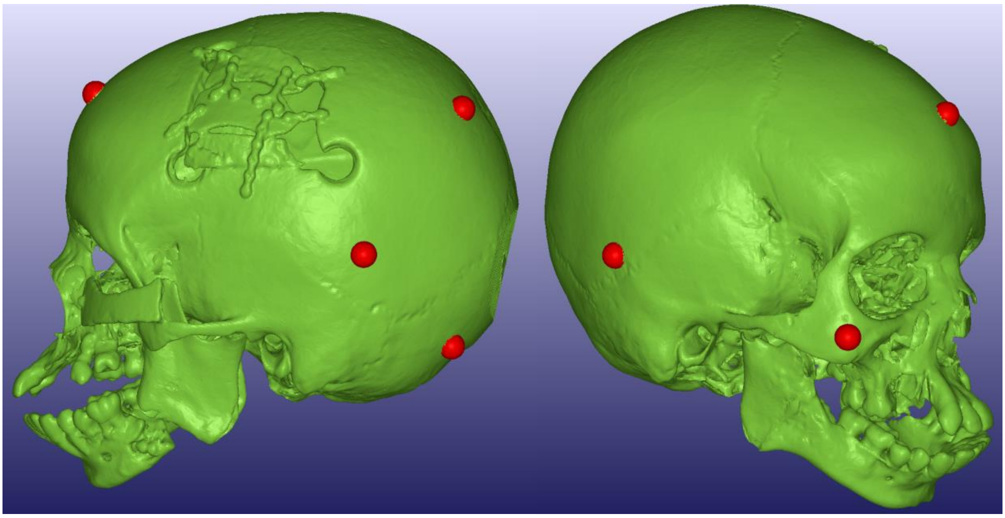


Figure 2 *The locations of measurement balls on a human 3D skull model (Paper III).*

Three versions of the 3D skull model were created for the accuracy experiments: “original”, “moderate” and “worse”. Moderate and worse models were created by reducing the accuracy of the original model by decreasing the tolerance of the STL model using Viscam RP 4.0 software (Marcam Engineering GmbH, Bremen, Germany). The tolerance is determined with the maximum distance and the angle between the new and the old triangle surface. For the moderate model, the tolerance was 3 millimeters, 10º and 50 steps and for the worse model millimeters, 15º and 50 steps. Angle deviation was dominating when decreasing tolerances.

3.4 Additive manufacturing (Papers I-IV)

AM technologies can be widely used in medical applications. In Table 3 the equipment, materials, technologies, purpose of use and parameters for AM used in the present study are shown.

Table 3 *The equipment, materials, technologies, purpose of use and parameters of AM technologies used in the present study.*

Equipment and material	Manufacturing technology	Purpose of use	Layer thickness (µm)
EOSINT M270 Ti and EOS Titanium Ti64 ELI (EOS GmbH - Electro Optical Systems, Krailling, Germany)	DMLS	Implant for orbital reconstruction **(Paper I)**	30
EOSINT P380 and SLS2200 (EOS GmbH - Electro Optical Systems, Krailling, Germany)	SLS	Preoperative medical model of the orbita **(Paper I)** SLS [models A & B] medical skull model for accuracy measurements **(Paper III)**	150
Objet Eden 350V and VeroWhite FullCure 830 (Objet Ltd, Rehovot, Israel)	PolyJet	Objet medical skull model for accuracy measurements **(Paper III)**	16
Zprinter 450 and ZP 150 (Z Corporation, Burlington, USA)	3DP	3DP (original, moderate, worse) three medical skull models for accuracy measurements **(Paper III)**	90
SLA 350 and Somos ProtoGen O-XT 18420 (3D Systems, Rock Hill, USA) and (DSM Functional Materials, Elgin, USA)	SL	Mold for soft oral appliance **(Paper II)**	50
SLA 350 and Somos WaterShed XC 11122 (3D Systems, Rock Hill, USA) and (DSM Functional Materials, Elgin, USA)	SL	Occlusal splint **(Paper IV)**	50

3.4.1 3D Printing (Paper III)

In 3DP an inkjet-like printing head moves over a powder bed and deposits a liquid binder material in the shape of the cross-section of the part being manufactured. After that a new layer of powder is spread over the previous one and new cross section printing starts. After manufacturing these parts need to be cleaned and post processed adding a hardener and drying in an oven. The systems used for medical skull models were Zprinter 450 (Z Corporation, Burlington, USA) with a layer thickness of 0.09 millimeters. ZP 150 powder (Z Corporation Burlington, USA) was used as the material. 3DP was selected to accuracy measurements since it is commonly used in medical models because of colors, no need for support structures and low cost as compared with other AM processes. 3DP does not have biocompatible material options.

3.4.2 Selective laser sintering (Papers I & III)

Selective laser sintering (SLS) uses a laser for sintering plastic powder layer by layer. At first, a layer of powder is spread on the building platform with a roller or a sweeper. In the next step, the laser sinters the powder to form the geometry of a specific layer. After these steps, the building platform is descended by one layer and the process starts over. The finished parts need to be cleaned from powder, but no other post-processing is needed.

The manufacturing system for preoperative orbita model and two medical skull models was EOSINT P380 (EOS GmbH - Electro Optical Systems, Krailling, Germany) and the material used was fine polyamide PA 2200 (EOS GmbH - Electro Optical Systems, Krailling, Germany). The layer thickness was 0.15 millimeters. SLS was selected for the preoperative orbita model because of the overhanging features in orbita bottom were thin. SLS is commonly used in medical models as it does not require post-processing or support structures, and therefore it was selected in accuracy measurements. There are biocompatible material options for SLS, such as PA 2200.

3.4.3 PolyJet (Paper III)

PolyJet is a method, which uses a jetting head to deposit UV light curable photopolymer at a desired place. After the layer has been deposited, the building platform is descended by one layer and a new layer can be deposited. UV light is used to cure the UV photopolymer. The parts need support structures and post processing.

The medical skull model was manufactured with Objet Eden 350V (Objet Ltd, Rehovot, Israel) from VeroWhite FullCure 830 (Objet Ltd, Rehovot, Israel). The layer thickness was 0.016 millimeters. Polyjet was selected because of its potential for greater accuracy with higher costs. Nowadays there are biocompatible material options such as MED610 (Objet Ltd, Rehovot, Israel).

3.4.3 Stereolithography (Papers II & IV)

SL is an AM technology, where parts are built layer by layer by curing a photopolymer with an UV laser. The shape of the cross-section is traced out on the surface of a liquid resin using a laser beam. After finishing the layer, the building platform is descended by one layer. A schematic figure of the SL process is shown in Figure 3. SL is one of the most accurate AM processes but more expensive than most others. The process requires support structures and post processing.

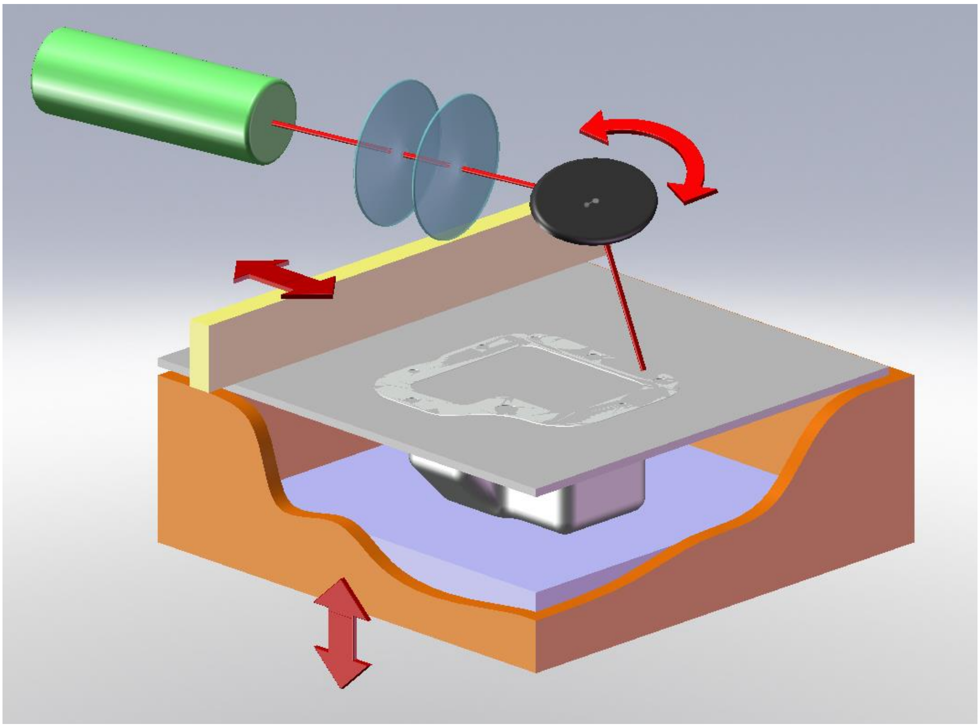


Figure 3 *A schematic presentation of a stereolithography process.*

SL was used for manufacturing a mold for the soft orthodontic appliance and as a direct fabrication method for occlusal splints because of the need for high accuracy. The device for both applications was SLA 350 (3D Systems, Rock Hill, USA). Somos ProtoGen O-XT 18420 (DSM Functional Materials, Elgin, USA) was chosen for the material for mold because it has a very low shrinkage and it can withstand the hot temperatures (80 ºC) needed in the casting phase. After manufacturing the mold was placed in a postcure apparatus for 60 min. The mold was heat treated and covered with a lacquer. Silicone was used as the casting material. The occlusal splint was made from the Somos WaterShed XC 11122 (DSM Functional Materials, Elgin, USA), because it fulfills the ISO 10993-5 Cytotoxicity, ISO 10993-10 Sensitization and ISO 10993-10 Irritation regulations and has USP Class VI approval. After the manufacturing, the splint was soaked in isopropanol for 20 min and any excess resin was scrubbed off. Dry, compressed air was used to blow excess solvent away from the surfaces. The splint was placed in a postcure apparatus for 60 min after cleaning. The layer thickness for both applications was 0.05 millimeters.

3.4.5 Direct metal laser sintering (Paper II)

DMLS is a layer by layer process that uses a laser for sintering metal powder. The process consists of three steps: (1) a layer of powder is spread on the building platform with a sweeper, (2) the laser sinters the powder at the desired places, and (3) the building platform is descended by one layer and then continues from the beginning. The manufacturing system for implant was EOSINT M270 Ti (EOS GmbH - Electro Optical Systems, Krailling, Germany) and selected material EOS Titanium Ti64 ELI (EOS GmbH - Electro Optical Systems, Krailling, Germany) because it fulfills mechanical and chemical requirements of ASTM F 136 standard for surgical implants. Ti64 ELI is a pre-alloyed Ti6AlV4 alloy with particularly low levels of impurities. The layer thickness was 30 µm. Laboratory results from test piece confirm compliance with ASTM F 136 requirements. After manufacturing the implant was polished and sterilized using an autoclave. DMLS was selected for implant manufacturing because of its accuracy compared to other metal AM processes.

3.5 Coordinate measuring machine (Paper III)

A coordinate measuring machine (CMM) ZEISS C 700 (Carl Zeiss AG, Oberkochen, Germany) was used for accuracy measurements. The measuring tip was a touching RENISHAW PH 1 (Renishaw Plc, New Mills, United Kingdom). The diameter of the ruby measuring head was 4 millimeters and the measuring force was 68.7 mN. The used measuring software was Calypso 4.4.04.01 (Carl Zeiss AG, Oberkochen, Germany). The resolution for CMM was 0.1 micrometers and the accuracy was ± 2 + L/200 micrometers, where L is the measured length. The measuring and the object attachment setting are shown in Figure 4. A measuring program for the CMM was used to repeat the same measurements automatically. This eliminates the error caused by the measurer, and therefore repetitions of the measurements by multiple persons are not needed. Before each measurement, each skull was positioned in nearly same position and the CMM was used to locate the exact position of the measured skull. When the exact position of the skull was known, the program performed the measurements. There was a ball-to-ball contact between the measuring balls and the measuring head and the exact location of this contact varied. However, the distance between the measuring balls and the measuring head was exactly determined. The center points of the measuring balls were determined with multiple measurements of the distance between the measuring balls and the accurate location of the measuring head. The location of each measuring ball was determined with 12 measurements. After the first measurements, the medical skull models with highest and lowest maximum error were remeasured to verify the repeatability of these measurements.

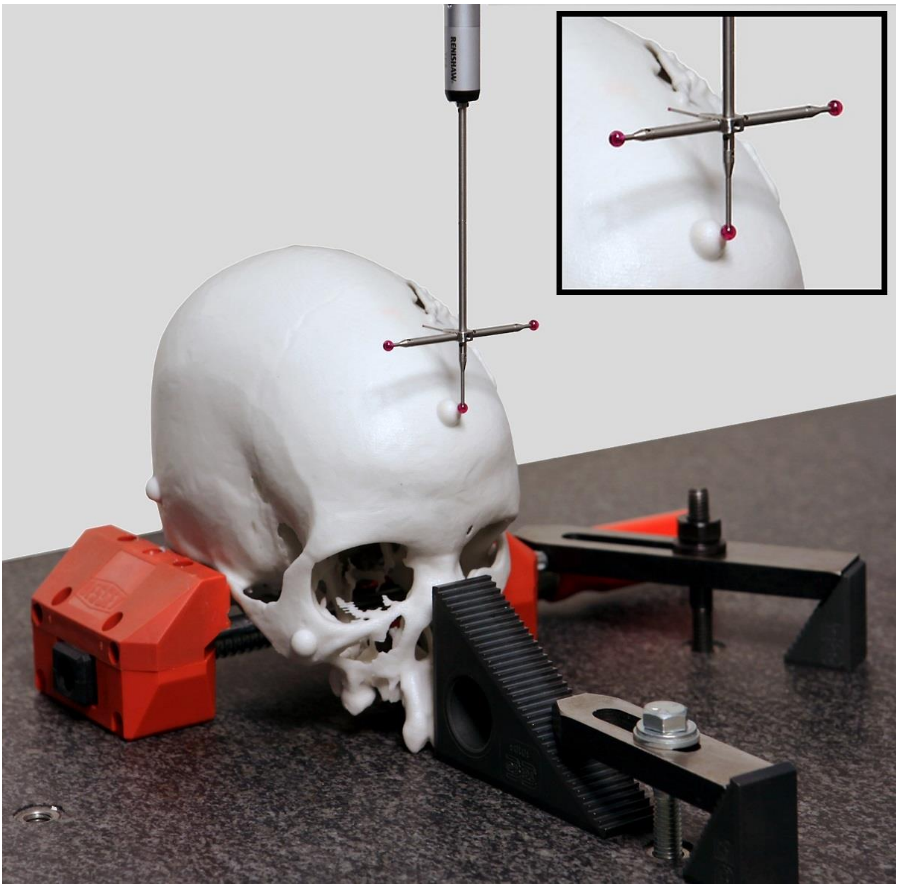


Figure 4 *Measuring attachment in accuracy measurements of medical models. (Paper III)*

As there were only two repeated observations, repeatability (Eq.1) was estimated by calculating the standard deviation of the obtained results and using a confident factor of 7 according to ISO/IEC 17025:2005.

$$repeatability\ (\%) = \overbrace{confident\ \ factor}^{=7} \times \sqrt{\sum_{i=1}^{n} \left(\frac{(measured\ value_i - average\ of\ \ measured\ values)^2}{(number\ of\ \ measurements - 1)}\right.} \qquad (1)$$

The diameters and center locations of the measurement balls were obtained from the measuring software. From the center locations of the measurement balls the distances between measuring balls were calculated. The calculations were compared to the distances measured from the 3D models. From the differences absolute value was taken and average error and standard deviation for error were calculated.

4 Results and discussion

4.1 Accuracy of medical skull models (Paper III)

When comparing the accuracy of PolyJet, 3DP and SLS for medical skull model fabrication, the dimensional error of the PolyJet model was the smallest: 0.18 ± 0.12% (average ± standard deviation) for the first measurement and 0.18 ± 0.13% for the repeated measurement. The error for SLS model was 0.79 ± 0.26% for the first model and 0.80 ± 0.32% for the second model. The error for 3DP was 0.67 ± 0.43% for the first measurement of the original model, 0.69 ± 0.44% for the repeated measurement of original model, 0.38 ± 0.22% for the moderate model and 0.55 ± 0.37% for the worse model. The repeatability of the used measurement method was 0.12% for the PolyJet and 0.08% for the 3DP. The repeatability of measurement for measuring ball diameters was 0.1 millimeters. The maximum, average and standard deviation for linear errors in the skull models are shown in Figure 5. The standard deviation represents the quality of the AM models, not the quality of the measuring method. In table 4, the results of this study are compared with the results obtained from the literature.

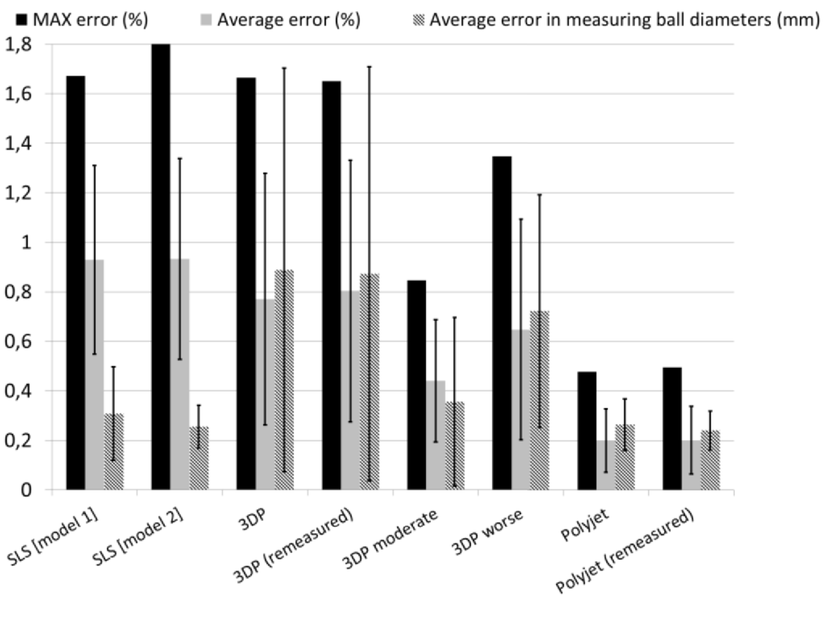


Figure 5 *Maximum, average and standard deviation errors in the skull models (%), and average error and standard deviation in the added measuring ball diameters (mm).*

Table 4 *Studies with accuracy measurement of AM models.*

Reference	Comparison	Mean difference (%)
(Paper III)	SLS - 3D model (original 1. & 2. model) 3DP - 3D model (original, 1. & 2. measurement) 3DP - 3D model (moderate) 3DP - 3D model (worse) PolyJet - 3D model (original 1. & 2. measurement)	0.79 ± 0.26 & 0.80 ± 0.32 0.67 ± 0.43 & 0.69 ± 0.44 0.38 ± 0.22 0.55 ± 0.37 0.18 ± 0.12 & 0.18 ± 0.13
El-Katatny et al. (2010)	FDM - 3D skull model FDM - 3D mandible model	0.24 ± 0.16 0.22 ± 0.11
Ibrahim et al. (2009)	SLS - dry cadaver mandible 3DP - dry cadaver mandible PolyJet - dry cadaver mandible	1.79 3.14 2.14
Silva et al. (2008)	SLS - dry cadaver skull 3DP - dry cadaver skull	2.10 2.67
Nizam et al. (2006)	SL – dry cadaver skull	0.08 ± 1.25
Chang et al. (2003)	3DP – fresh cadaver skull	2.1 - 4.7
Choi et al. (2002)	SL - dry cadaver skull SL - 3D skull model	0.56 ± 0.39 0.82 ± 0.52
Asaumi et al. (2001)	3D model - dry cadaver skull SL - dry cadaver skull	2.16 0.63
Berry et al. (1997)	SLS – 3D model	0.64
Barker et al. (1994)	SL - dry cadaver skull	0.6 - 3.6
Ono et al. (1994)	SL - dry cadaver skull	3
Waitzman et al. (1992)	3D CT - dry cadaver skull	0.9 (min 0.1, max 3.0)

Medical models can be widely used e.g. in vascular surgery, orthopedics surgery, pediatric surgery and common surgery field (Rengier et al. 2009, von Tengg-Kobligk et al. 2008). In cranio-maxillofacial surgery medical models have a critical role and their use is increasing. (Faber et al. 2006, D'Urso et al. 2000b, Muller et al. 2003, Wagner et al. 2004, Poukens et al. 2003, Mavili et al. 2007). However, the accuracy of these models has not been sufficiently investigated. In preoperative planning or surgical simulation there is a possibility of fatal errors to occur, if the medical model is not sufficiently accurate. Results from such research demonstrate that different manufacturing methods may cause significant errors. Previous studies have shown that imaging and segmentation together can cause even larger errors than AM (Table 4). The PolyJet technique was found to be more accurate than SLS or 3DP. The previous studies did not comment on the repeatability of the measurements (Table 4). Location of anatomic landmarks in the human body are hard to measure exactly, because forms are usually smooth and exact points are difficult to find with commonly used measuring equipment, such as a caliber rule. By using the measuring balls described earlier and determining their centers, the repeatability of the developed measuring method was found to be excellent, since there were only minor variations in the repeated measurements. In SLS and PolyJet skulls, the most measurement ball dimensions were over 10 millimeters. In models made with 3DP there were variations over and below 10 millimeters. 3DP skull from original model had the largest error, and one measurement ball was approximately 11 millimeters and one was 9 millimeters in diameter. This explains the large errors and a poor result for 3DP skull and may have been caused by the post processing, where the models are dipped into a hardener liquid and dried. 3DP skull from worse model had a large (11 mm) measurement ball. The hardener may leave droplets to the 3DP model. The repeatability of the SLS process was good. This can be explained by the fact that the process was fully automatic and post-processing usually requires only cleaning of the parts. The main reason for the observed errors was the post-processing. The more manual work it includes, the more errors can occur. This explains the large variation in 3DP accuracy, because manual post processing was needed. Different principles and physics of AM processes significantly affect the accuracy. Some processes are developed to be more accurate than others, and in some processes high manufacturing speed is achieved using low accuracy. It has an effect on the accuracy, if the AM equipment is aimed to prototyping, tooling or production. Taft et al. (2011) imaged a dry cadaver skull with stainless steel spheres using multi detector computed tomography, and they produced seven SL skull models based on those images. When measuring the SL skulls with a Faro Gage CMM (FARO Technologies Inc, Lake Mary, USA), they found a significance difference in the Z direction of the additive build, but did not detect the same difference in the X and Y directions.

There are early studies related to the accuracy of AM (Pham & Gault 1998, Ippolito et al. 1995), but the AM technologies and processes have developed so fast that more and more studies are needed. The medical field has set up its own requirements for accuracy and engineering structures are more angular and have straight surfaces when compared to the structures of nature. An enormous improvement in accuracy and material properties has been seen and the development is speeding up. However, there is a need for standardized method for measuring and verifying medical models made by AM.

4.2 Soft orthodontic appliances with rapid tooling (Papers III)

Orthodontic appliances are used to straighten teeth. Soft removable orthodontic appliances made by rapid tooling were studied in the mouth of the patient repeatedly for 2 min to understand various aspects regarding the use of the appliance such as comfort and convenience. Two soft appliances were tested, one causing a high force and one causing a low force onto the teeth. The appliance with the stronger force was more efficient but caused a slightly unpleasant sensation. The appliance with the weaker force did not create as much effect as version with high force, but was more comfortable to use. Both appliances were of exact fitting and the surface quality was user-friendly even without any finishing. The appliance between plaster model and the finished appliance are shown in Figure 6.

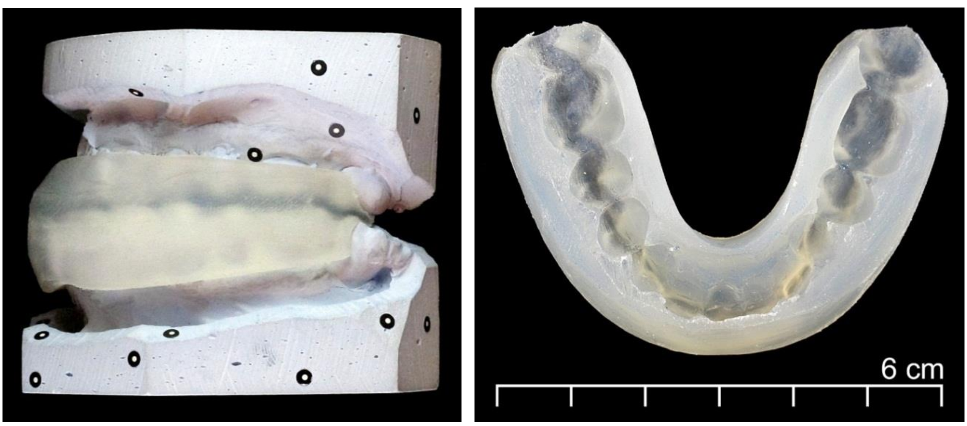


Figure 6 *The appliance between plaster models and the finished orthodontic appliance.*

The accuracy of soft orthodontic appliances is visualized in Figure 7. The maximum dimensional error of ca. 1 millimeter was observed at thin walls and sharp edges when comparing the physical appliance with the 3D model. The scale in Figure 7 varies from red (+1.0 mm) to blue (-1.0 mm). The geometry of the soft appliance was accurate when compared with the 3D model (Figure 7). Since the soft material is flexible, an accuracy ashigh as that in the hard appliances is not needed.

With soft appliances it may be possible to achieve a larger orthodontic tooth movement and therefore reduce the amount of aligners compared to hard ones. When using thermoplastic appliances tipping movements are predictable, but controlling of roots may cause trouble (Hahn et al. 2010). The material and the thickness of the appliance influence the tooth movement (Barbagallo et al. 2008, Hahn et al. 2009a, 2009b). When comparing the soft and hard appliance, no substantial difference in the completion rate was observed (Bollen at al. 2003). The soft occlusal splints have been used as treatment for migraine and other headaches (Quayle et al. 1990).

With Invisalign hard and clear orthodontic custom-made aligners over 100 000 patients had been successfully treated by 2004 (Beaman et al. 2004) and more than 80 million custom aligners have been produced (Wohlers & Caffrey 2013). The Invisalign process is such that a dentist takes a dental impression and sends it to a laboratory to be scanned. Based on the scan, the treatment is virtually designed and molds are manufactured with SL. By vacuum forming a set of aligners is created and sent to the patient. In the future, it is possible that the aligners are made by AM.

However, with these types of removable orthodontic appliances, treatments are limited to patients with mild orthodontic problems, and severe orthodontic problems cannot be treated with removable appliances. One manufacturing possibility for orthodontics appliances is thermoforming a soft slab of appliance over a straightened model made by AM.

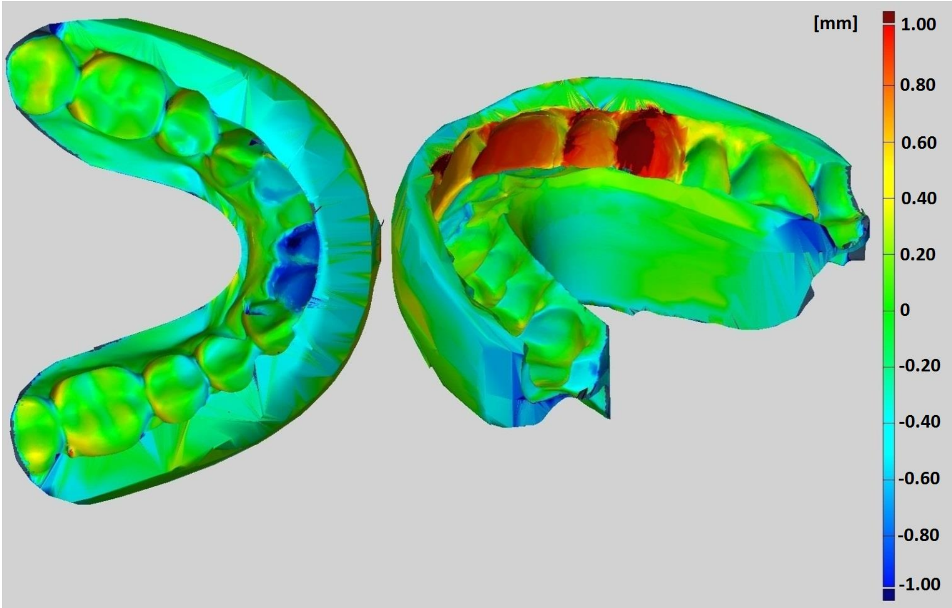


Figure 7 *Accuracy of orthodontic appliance compared with the designed 3D model.*

4.3 Occlusal splints with direct additive manufacturing (Paper IV)

Occlusal splints are used for the treatment of sleep apnea, temporomandibular disorder and bruxism. The occlusal splint made in this study by direct AM was used by a patient for six months nightly. After five days of use the splint was trimmed, because there was a slight pressure on the upper right canine and pressure between the upper and lower right premolars. The patient reported that the splint felt tight in the beginning of every use, but the pressure eased after a few minutes. This is typical of a conventional splint made in a dental laboratory. The patient adapted to the splint well and found it comfortable to use. The bite muscle tension of the patient was relieved by the use of the splint. At the follow-up visits (one, three and six months) only minor grinding was needed. No sign of tooth wearing, remarkable splint wear or other problems were detected after the six month test period. Minimal plaque deposits were noticed on the splint on a patient. The occlusal splint is shown in Figure 8.

Figure 8 *Occlusal splint made by additive manufacturing in use.*

After six months of use the splint was compared with the 3D model from which it was made (Figure 9). The maximum trim needed was approximately 1 millimeters and the wear can be estimated to be smaller than 0.2 millimeters. The wear can be estimated from occlusion plane in the areas without a need for trimming. The overall accuracy of the described system can be estimated from the areas with no trimming or wearing. Dimensional errors of approximately 1 millimeter were found at thin walls and sharp corners when comparing the splint with the 3D design. The accuracy in the others areas was better than 0.3 millimeters.

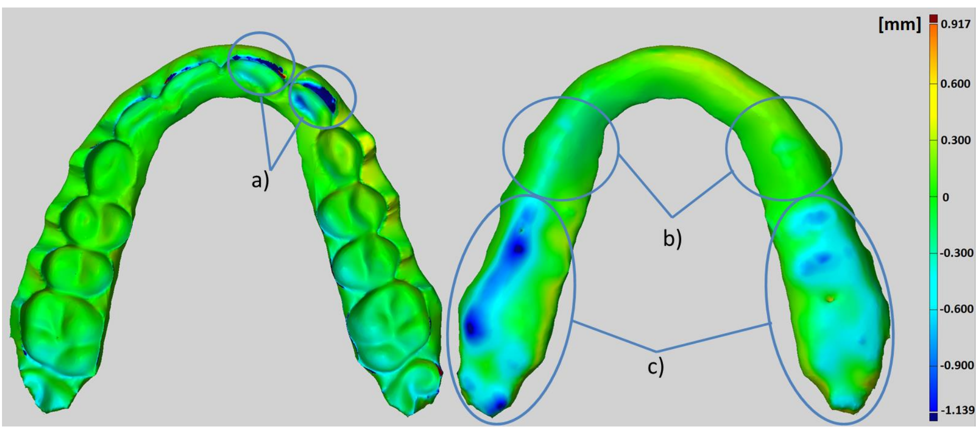


Figure 9 *The accuracy, wear (b) and the trim needed (a,c) when compared the used splint with the designed 3D model.*

In adults, temporomandibular disorder ranges from 25 to 50% (Carlsson 1999) and it is a common clinical observation (De Kanter et al. 1993, Kuttila et al. 1998). Therefore, the need of occlusal splints is increasing. Traditionally splints have been manufactured by hand in a dental laboratory. The lead time for traditional process is one week and handwork makes it expensive. AM and 3D scanning opens up new possibilities to manufacture splints more cost-efficiently by reducing the amount of handwork and the lead time. This may improve the accuracy of the splint and therefore reduce the time needed for a dentist to trim the splint. Digital technology is widely used and well-known for making ceramic inlays, such as Cerec (Siemens, Germany) (Pallasen et al. 2000). There are studies on the use of AM in the so called next generation dental device manufacturing (Van Noort. 2012). Using these next generation technologies it is possible to manufacture hard and clear removable orthodontic appliances directly with AM.

4.4 Inert implants (Paper II)

The digitally designed orbital wall implant made by AM was used in a surgical operation. The patient was pleased with the results on the 3 week follow-up visit. The displacement of the eyeball was dismissed. Some swelling and scars were observed after the surgery, but the eye ball was at its correct position (Figure 10, right). Later on, new artificial eye ball was made (not shown in Figure 10), because the old one was made for different height of orbital floor. Preoperative and postoperative photos of the patient are shown in Figure 10.

Figure 10 *The patient before surgery and 3 weeks after surgery. Reconstructed left eye floor raised eye back to normal position.*

After the surgery a new CT was performed and a new 3D model using the CT images was created. This model showed that the position of the implant was similar to the designed one. An exact fitting of the implant and clinical outcome were seen after only one surgical operation. No bleeding or infection complications were encountered. The designed 3D model with implant (left) and 3D model created from postoperative CT (right) are shown in Figure 11.

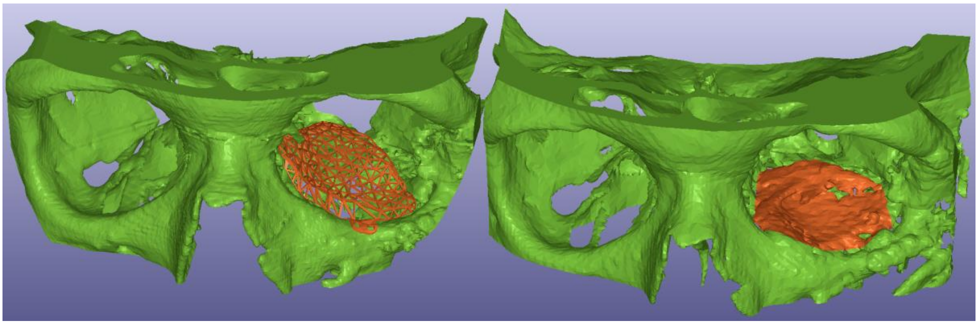


Figure 11 *The designed implant and 3D model from CT images after surgery.*

Traditionally implants are mass produced standard items with variable sizes or handcrafted individual implants made by a surgeon from implant slab before or during the surgery. Common fabrication methods for the implants or slabs are subtractive manufacturing methods. Titanium is one of the most commonly used material for dental and orthopedic applications (Lausmaa et al. 1990). For orthopedic implants metallic alloys based on iron, cobalt and titanium are commonly used (Galante et al. 2005). AM offers a new way to manufacture implants from the same materials that are already commonly used. It opens up a possibility to customize each implant for a specific patient, as there is no need for manufacturing tools such as molds or cutting tools.

Implants made by using AM are still relatively rarely used in surgical field. Recently, an accumulating amount of articles on metal implants has been published (Ciocca et al. 2011, Mangano et al. 2012, Figliuzzi 2012). The geometry and porosity of the implants are being intensively investigated. Stübinger et al. (2013) analyzed osseointegrative properties of porous titanium implants made by DMLS in a sheep. Witek et al. (2012) compared laser sintered metal surface with other commercially available surfaces from implants. They found higher bone-to-implant contact and bone area fraction occupancy for laser sintered surface than traditional ones after a week, whereas no differences were observed after three and six weeks. AM allows optimizing the geometry and topology of the implant if the optima can be somehow estimated or simulated. This may lead to better customized implants and treatment results.

An accumulating amount of research is carried out related to AM of tissues and organs (Melchels et al. 2012, Marga et al. 2012, Dean et al. 2012) and using AM possibilities combined with stem cells (Andersen et al. 2013, Sándor et al. 2013). In the future this may lead to more natural implants, which resorb away when they are no longer needed, or even AM of real living tissues and organs. There is already some research on fabricating miniaturized "walking" biological machines from hydrogels and cardiomyocytes using SL (Chan et al. 2012).

4.5 General discussion

Medical models can improve the communication between patients and surgeons. By using medical models it is more feasible and understandable to demonstrate to the patient what the surgeons are planning to do. Patient specific implants expedite the surgery and therefore improve the recovery, as the operation time affects the time needed for recovery. As scanning of the patient is possible also outside of the hospital, it may eliminate traveling costs. For example with occlusal splint, if digitalization of the occlusion is sufficient and the process well examined, the patient may have the splint mailed without a visit to a dentist. In facial prostheses digital workflow may reduce travelling and dependence on model storage and cataloguing (Eggbeer 2008). The cost of remakes is reduced because fewer models or molds are lost or damaged (Eggbeer 2008). Combining all this to robotics may in the future lead to virtual surgery performed in remote locations with experts from all over the world participating in the planning of the operation. The robot can perform the surgery in real time or at another point of time. These visions may enable surgeries in places as remote as space stations, or anywhere else where doctors are far away.

Using medical applications of AM requires a multidisciplinary team of experts. Problems may occur because usually people are experts only in their own area, and currently there is no common terminology between doctors and engineers. If the aspects are not clear and there is too much room for interpretation, misunderstandings may occur. This can be solved by further educating both doctors and engineers. In dentistry and at least in cranio-maxillofacial surgery there is a significant amount of craftsmanship involved. Digital processes may reduce the need for handcrafting. This change can be compared to mechanical design where drawing boards and pencils have been replaced with computers.

4.6 Future work

In the future we will try to open up and develop new applications in medicine by using AM. For medical implant manufacturing laboratory tests are needed to investigate the effect of the manufacturing method on surface quality. We are planning to carry out cytotoxicity test with DMLS and EBM parts to compare with commercially available standard implants.

In facial allotransplantation the donor receives significant visible disfigurement. There is ongoing work to solve this problem using 3D scanning, digital design and AM. It is possible to digitize the donor's face and then produce a replica using AM.

More and more allografts have been used in human knee joint operations. Since every person has different size joints, digital design and AM can be considered to expedite the surgery and improve the results. There is a possibility to use medical models, saw guides or jigs during the operation.

There is an ongoing project to develop a 3D-digitalization of ankle movement and a CAD-method for producing patient specific external ankle support by AM. By measuring the ankle movement, a personally designed ankle support can be made using AM and conventional manufacturing processes.

5 Conclusions

In the medical field, every patient is unique and therefore for certain purposes, mass production of products is not the optimal solution. AM technology is superior in applications involving single or only few parts, as when manufacturing these, only the 3D model will need to be changed. Digital design methods and AM offer the medical and dental professionals new tools to improve treatment results and therefore, to enhance the quality of life of patient.

The general conclusions of this research are:

i) CT, laser scanning and structured light scanners were successfully used to achieve data from patient-specific geometries. Communication with radiologist is crucial since usually there is no need for thin slice thickness that AM requires.

ii) Patient data from CT was successfully reconstructed to a 3D model and models from 3D scanners were fully repaired and fixed using three software. For reconstruction Osirix was found to be suitable. STL model repairing 3Data Expert and Viscam RP was found to be suitable.

iii) Medical modeling was performed, with four software using a 3D model of the patient as a geometric reference. Rhinoceros was suitable for surface modeling by referring patient geometry. 3Data Expert and Viscam RP were good in Boolean operations and measurements. Pro Engineer was suitable for repositioning of teeth and placing the measurement balls accurately.

iv) AM processes were investigated and the best suitable process was selected for each purpose. This forms a crucial principle of using AM for medical applications. For medical models 3DP, SLS, Polyjet was used. Rapid tooling and direct occlusal splint manufacturing was made using SL. AM process for inert implants was DMLS.

The specific conclusions of the research are:

1. In surgical procedures implants are usually handmade or modified from standard products during operation. By digitally designing and manufacturing implants before the operation will reduce operating time, improve accuracy, reduce morbidity and give

improved fitting of the implants. A process consisting four steps was successfully used. First the CT-images are taken from the patient and second step is to reconstruct those images to the 3D model. Third step is to perform medical modelling according patient geometry in 3D model. Final step is using AM method DMLS. Volumetric net allows tissues and cells to grow through to and from surrounding tissues and reduce sensitivity for hot and cold temperatures. By reducing manual work phases human errors decrease and final result improve. Accuracy of process is adequate for manufacturing oral appliances and occlusal splints where tight tolerances are ordinary. There is a need for standardization for implants made by AM. For example it is not clear where the 3D model of the patient and implant is stored and how long. It is a question how the mechanical durability is noticed in design or how to trace all the data of the implant if the starting point is only implant itself. If something goes wrong it is important to be able to track where it happened and why.

2. When using AM in medical model fabrication, surgeons should be aware of errors related to the AM technology, materials and the instance of machine use. The error sources should be noticed when making any medical devices by AM. The main errors were caused by the AM technology used. PolyJet was found the most accurate when comparing to SLS and 3DP. The second most important source of error was the quality of the STL model measured by the amount of triangles. The smallest error was caused by the instance of the machine used. This study did not include errors in medical imaging, which may be a major source of errors when compared to the imaged object. Post processing and handwork relating to models may cause significant errors. The measuring procedure for medical models is complicated. By using the proposed measuring method, which determines the center point of ball, an excellent repeatability was achieved. There is a need for a standard method for measuring and verifying medical models and devices fabricated by AM.

3. By making a mold with AM, the mold can be used indirectly to manufacture medical devices. The customized soft orthodontic appliances made from silicone were manufactured by making molds with SL. The appliance causing a higher force was more efficient but caused a slightly unpleasant sensation. The version with reduced force was more comfortable to use. Both appliances were well tolerated by the patient and

convenient to use. In the future the use of AM technology may reduce costs because the need for handicraft is reduced. Soft appliances require fewer versions of the appliance because the movements of teeth can be larger when compared to the hard ones. There is a need to investigate the force mechanism of the soft aligner to verify how much movement it can cause to teeth and what the limitations are.

4. AM was directly used to manufacture medical devices. Clinically functional occlusal splints can be manufactured by modern digital technology without manual working phases in a dental laboratory. In the future this may reduce costs, working time of dental technician and chair-side time of dentist. Accuracy can be improved, since one manual work phase is reduced. The material Somos WaterShed XC 11122 proved to be suitable for occlusal splint manufacturing. The mechanical properties could stand the forces from teeth and jaws, and the consistency of the material was fairly optimal. The accumulation of dental plaque on various splint materials used in the AM process should be investigated. Minimal plaque deposits were noticed on the splint on a patient after six months of testing. For commercial production more clinical studies are needed to verify how much the variation of forces from teeth and jaws affects the material.

References

Al-Sukhun J, Kontio R, Lindqvist C, Tornwall J. Use of a prefabricated titanium plate for accurate reconstruction of secondary orbital blowout fracture. Plast Reconstr Surg 117:1648-1651, 2006.

Andersen MØ, Le DQS, Chen M, Nygaard JV, Kassem M, Bünger C, Kjems J. Spatially controlled delivery of siRNAs to stem cells in implants generated by multi-component additive manufacturing. Adv Funct Mater, early view online, DOI: 10.1002/adfm.201300832, 2013.

Asaumi J, Kawai N, Honda Y, Shigehara H, Wakasa T, Kishi K. Comparison of three-dimensional computed tomography with rapid prototype models in the management of coronoid hyperplasia. Dentomaxillofac Radiol 30:330-335, 2001.

ASTM standard F2792. Standard terminology for additive manufacturing technologies. ASTM International. DOI: 10.1520/F2792-12, www.astm.org, 2012.

Barbagallo LJ, Shen G, Jones AS, Swain MV, Petocz P, Darendeliler MA. A novel pressure film approach for determining the force imparted by clear removable thermoplastic appliances. Ann Biomed Eng 36:335-341, 2008.

Barker TM, Earwaker WJS, Lisle DA. Accuracy of stereolithographic models of human anatomy. Australas Radiol 38:106-111, 1994.

Bartolo P, Kruth JP, Silva J, Levy G, Malshe A, Rajurkar K, Mitsuishi M, Leu M. Biomedical production of implants by additive electro-chemical and physical processes. CIRP Annals-Manufacturing Technology 61:635-655, 2012.

Beaman JJ, Atwood C, Bergman TL, Bourell D, Hollister S, Rosen D. Additive/subtractive manufacturing research and development in Europe. World Technology Evaluation Center Inc, Baltimore MD, 2004.

Berry E, Brown JM, Connell M, Craven CM, Efford ND, Radjenovic A, Smith MA. Preliminary experience with medical applications of rapid prototyping by selective laser sintering. Med Eng Phys 19:90-96, 1997.

Bibb R: Medical modeling: The application of advanced design and development techniques in medicine. Woodhead Publishing Limited, 2006.

Björkstrand R, Tuomi J, Paloheimo M, Lindahl J, Salo J. 3D-Digitalization of ankle movement and 3D-CAD-method for patient specific external ankle support development and rapid manufacturing. Bártolo PJ et al., Innovative developments in design and manufacturing: Advanced research in virtual and rapid prototyping, Leiden, CRC Press / Balkema, 199-204, 2010.

Bollen AM, Huang G, King G, Hujoel P, Ma T. Activation time and material stiffness of sequential removable orthodontic appliances. Part 1: Ability to complete treatment, Am J Orthod Dentofacial Orthop 124:496-501, 2003.

Carlsson GE. Epidemiology and treatment need for temporomandibular disorders. J Orofac Pain 13:232-237, 1999.

Chan V, Park K, Collens MB, Kong H, Saif TA, Bashir R. Development of miniaturized walking biological machines. Sci rep 2;857, 2012.

Chang PS, Parker TH, Patrick Jr CW, Miller MJ. The accuracy of stereolithography in planning craniofacial bone replacement. J Craniofac Surg 14:164-170, 2003.

Cheah CM, Chua CK, Tan KH, Teo CK. Integration of laser surface digitizing with CAD/CAM techniques for developing facial prostheses. Part 1: Design and fabrication of prosthesis replicas. Int J Prosthodont 16:435-441, 2003a.

Cheah CM, Chua CK, Tan KH. Integration of laser surface digitizing with CAD/CAM techniques for developing facial prostheses. Part 2: Development of molding techniques for casting prosthetic parts. Int J Prosthodont 16:543-548, 2003b.

Choi JY, Choi JH, Kim NK, Kim Y, Lee JK, Kim MK, Lee JH, Kim MJ. Analysis of errors in medical rapid prototyping models. Int J Oral Maxillofac Surg 31:23-32, 2002.

Ciocca L, Fantini M, De Crescenzio F, Corinaldesi G, Scotti R. Direct metal laser sintering (DMLS) of a customized titanium mesh for prosthetically guided bone regeneration of atrophic maxillary arches. Med Biol Eng Comput 49:1347-1352, 2011.

Dean D, Jonathan W, Siblani A, Wang MO, Kim K, Mikos AG, Fisher JP. Continuous digital light processing (cDLP): Highly accurate additive manufacturing of tissue engineered bone scaffolds. Virtual Phys Prototyp 7:13-24, 2012.

De Kanter RJ, Truin GJ, Burgersdijk RC, Van’t Hof MA, Battistuzzi PG, Kalsbeek H,Käyser AF. Prevalence in the Dutch adult population and a meta-analysis of signs and symptoms of temporomandibular disorder. J Dent Res 72:1509-1518, 1993.

D’Urso PS, Barker TM, Earwaker WJ, Bruce LJ, Atkinson RL, Lanigan MW, Arvier JF, Effeney DJ. Stereolithographic biomodelling in cranio-maxillofacial surgery: a prospective trial. J Craniomaxillofac Surg 27:30-37, 1999.

D'Urso PS, Effeney DJ, Earwaker WJ, Barker TM, Redmond MJ, Thompson RG, Tomlinson FH. Custom cranioplasty using stereolithography and acrylic. Brit J Plast Surg 53:200-204, 2000a.

D'Urso PS, Earwaker WJ, Barker TM, Redmond MJ, Thompson RG, Effeney DJ, Tomlinson FH. Custom cranioplasty using stereolithography and acrylic. Br J Plast Surg. 53:200-204, 2000b.

Eggbeer D. The Computer Aided Design and Fabrication of Facial Prostheses. PhD Thesis, University of Wales, 2008.

El-Katatny I, Masood SH, Morsi YS. Error analysis of FDM fabricated medical replicas. Rapid Prototyping J 16:36-43, 2010.

Eppley BL. Craniofacial reconstruction with computer-generated HTR patient-matched implants: Use in primary bony tumor excision. J Craniofac Surg 13:650-657, 2002.

Eurostat. Projected old-age dependency ratio. EUROPOP2010 Code: tsdde511, 2013.

Evans P, Eggbeer D, Bibb R. Orbital prosthesis wax pattern production using computer aided design and rapid prototyping techniques. J Maxill Prosthet & Technol 7: 11-15, 2004.

Faber J, Berto PM, Quaresma M. Rapid prototyping as a tool for diagnosis and treatment planning for maxillary canine impaction. Am J Orthod Dentofacial Orthop. 129:583-589, 2006.

Feng ZH, Dong Y, Bai SZ, Wu GF, Bi YP, Wang B, Zhao YM. Virtual transplantation in designing a facial prosthesis for extensive maxillofacial defects that cross the facial midline using computer-assisted technology. Int J Prosthodont 23:513-520, 2010.

Figliuzzi M, Mangano F, Mangano C. A novel root analogue dental implant using CT scan and CAD/CAM: selective laser melting technology. Int J Oral Maxillofac Surg 41: 858-862, 2012.

Galante JO, Lemons J, Spector M, Wilson PD, Wright TM. The biologic effects of implant materials. J Orthop Res 9: 760-775, 1991.

Germani M, Raffaeli R, Mazzolini A. A method for performance evalution of RE/RP systems in dentistry. Rapid Prototyping J 16:345-355, 2010.

Gibson I, Cheung LK, Chow SP, Cheung WL, Beh SL, Savalani M, Lee SH. The use of rapid prototyping to assist medical applications. Rapid Prototyping J 12:53-58, 2006.

Gibson I, Rosen DW, Stucker B. Additive manufacturing technologies: rapid prototyping to direct digital manufacturing. Springer, 2010.

Hahn W, Dathe H, Fialka-Fricke J, Fricke-Zech S, Zapf A, Kubein-Meesenburg D, Sadat-Khonsari R. Influence of thermoplastic appliance thickness on the magnitude of force delivered to a maxillary central incisor during tipping. Am J Orthod Dentofacial Orthop 136:1-7, 2009a.

Hahn W, Fialka-Fricke J, Dathe H, Fricke-Zech S, Zapf A, Gruber R, Kubein-Meesenburg D, Sadat-Khonsari R. Initial forces generated by three types of thermoplastic appliances on an upper central incisor during tipping. Eur J Orthod 31:625-31, 2009b.

Hahn W, Zapf A, Dathe H, Fialka-Fricke J, Fricke-Zech S, Gruber R, Kubein-Meesenburg D, Sadat-Khonsari R. Torquing an upper central incisor with aligners-acting forces and biomechanical principles. Eur J Orthod 32:607-13, 2010.

Hopkinson N, Hague R, Dickens P. Rapid manufacturing: an industrial revolution for the digital age. John Wiley & Sons, 2006.

Hughes CW, Page K, Bibb R, Taylor J, Revington P. The custom-made titanium orbital floor prosthesis in reconstruction for orbital floor fractures. Br J Oral Maxillofac Surg 41:50-53, 2003.

Huotilainen E, Jaanimets R, Valášek J, Marcián P, Salmi M, Tuomi J, Mäkitie A, Wolff J. Inaccuracies in Additive Manufactured Medical Skull Models Caused by the DICOM to STL Conversion Process. J Craniomaxillofac Surg Available online 1 November 2013, http://dx.doi.org/10.1016/j.jcms.2013.10.001, 2013.

Huotilainen E, Paloheimo M, Salmi M, Paloheimo KS, Björkstrand R, Tuomi J. Markola A, Mäkitie A. Imaging requirements for medical applications of additive manufacturing. Acta Radiologica 0284185113494198, 2013.

Hutmacher DW, Sittinger M, Risbud MV. Scaffold based tissue engineering: rationale for computer-aided design and solid free-form fabrication systems. Trends Biotechnol 22:354-362, 2004.

Ibrahim D, Broilo TL, Heitz C, de Oliveira MG, de Oliveira HW, Nobre SMW, dos Santos Filho JHG, Silva DN. Dimensional error of selective laser sintering, three-dimensional printing and polyjet models in the reproduction of mandibular anatomy. J Craniomaxillofac Surg 37:167-173, 2009.

Ippolitoa R, Iulianoa L, Gattob A. Benchmarking of rapid prototyping techniques in terms of dimensional accuracy and surface finish. CIRP Ann - Manuf Technol 44:157-160, 1995.

Janssens M, Poukens J. Rapid technologies in medicine: What can, can't be done and why. Proceedings of the international conference on competitive manufacturing, Stellenbosch, South Africa, 2007.

Jiang N, Hsu Y, Khadka A, Hu J, Wang D, Wang Q, Li J. Total or partial inferior border ostectomy for mandibular contouring: Indications and outcomes. J CranioMaxillofac Surg 40:277-284, 2012.

Joffe L. Current products and practice Invisalign: early experiences. J Orthod 30:348-352, 2003.

Keski-Nisula K, Hernesniemi R, Heiskanen M, Keski-Nisula L, Varrela J. Orthodontic intervention in the early mixed dentition: A prospective, controlled study on the effects of the eruption guidance appliance. Am J Orthod Dentofacial Orthop 133:254-260, 2008.

Kimoto K, Garrett NR. Evaluation of a 3D digital photographic imaging system of the human face. J Oral Rehabil 34:201-205, 2007.

Kohorst P, Brinkmann H, Li J, Borchers L, Stiesch M. Marginal accuracy of four-unit zirconia fixed dental prostheses fabricated using different computer aided desing/computed-aided manufacturing systems. Eur J Oral Sci 117:319-325, 2009.

Kontio R, Björkstrand R, Salmi M, Paloheimo M, Paloheimo K-S, Tuomi J, Mäkitie A. Designing and Additive Manufacturing A Prototype for A Novel Instrument for Mandible Fracture Reduction. Surg Curr Res, doi:10.4172/2161-1076.S1-002, 2012.

Klammert U, Böhm H, Schweitzer T, Würzler K, Gbureck U, Reuther J, Kübler A. Multi-directional Le Fort III midfacial distraction using an individual prefabricated device. J Craniomaxillofac Surg 37: 210-215, 2009.

Kozakiewicz M, Elgalal M, Loba P, Komuñski P, Arkuszewski P, Broniarczyk-Loba A, Stefañczyk L. Clinical application of 3D pre-bent titanium implants for orbital floor fractures. J Craniomaxillofac Surg 37: 229-234, 2009.

Kozakiewicz M, Elgalal M, Piotr L, Broniarczyk-Loba A, Stefanczyk L. Treatment with individual orbital wall implants in humans – 1-Year ophthalmologic evaluation. J CranioMaxillofac Surg 39: 30-36, 2011.

Kuttila M, Niemi PM, Kuttila S, Alanen P, Le Bell Y. TMD treatment need in relation to age, gender, stress, and diagnostic subgroup. J Orofac Pain 12:67-74, 1998.

Labadie RF, Noble JH, Dawant BM, Balachandran R, Majdani O, Fitzpatrick JM. Clinical validation of percutaneous cochlear implant surgery: Initial report. Laryngoscope 118: 1031-1039, 2008.

Lamecker H, Kamer L, Wittmers A, Zachow S, Kaup T, Schramm A, Noser H, Hammer B. A method for the three-dimensional statistical shape analysis of the bony orbit. Proc Computer Aided Surgery Around the Head :94-97, 2007.

Lauren M, McIntyre F. A new computer-assisted method for design and fabrication of occlusal splints. Am J Orthod Dentofacial Orthop 133:130-135, 2008.

Lausmaa J, Kasemo B, Mattsson H. Surface spectroscopic characterization of titanium implant materials. Applied Surface Science 44:133-146, 1990.

Lee SJ, Jang KH, Spangberg LS, Kim E, Jung IY, Lee CY, Kum KY. Three-dimensional visualization of a mandibular first molar with three distal roots using computer-aided rapid prototyping. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 101:668-674, 2006.

Lethaus B, Lie N, de Beer F, Kessler P, de Baat C, Verdonck HW. Surgical and prosthetic reconsiderations in patients with maxillectomy. J Oral Rehabil 37:138-42, 2010.

Lethaus B, Poort M, Laeven P, Beerens M, Koper D, Poukens J, Kessler P. A treatment algorithm for patients with large skull bone defects and first results. J Cranio Maxillofac Surg 39: 435 440, 2011.

Lethaus B, Poort L, Bockmann R, Smeets R, Tolba R, Kessler P. Additive manufacturing for microvascular reconstruction of the mandible in 20 patients. J Craniomaxillofac Surg 40:43-46, 2012.

Liang X, Jacobs R, Hassan B, Li L, Pauwels R, Corpas L, Souza PC, Martens W, Shahbazian M, Alonso A, Lambrichts I. A comparative evaluation of cone beam computed tomography (CBCT) and multi-slice CT (MSCT) Part I: On subjective image quality. Eur J Radiol 75:265-269, 2009a.

Liang X, Lambrichts I, Sun Y, Denis K, Hassan B, Li L, Pauwels R, Jacobs R. A comparative evaluation of cone beam computed tomography (CBCT) and multi-slice CT (MSCT). Part II: On 3D model accuracy. Eur J Radiol 75:270-274, 2009b.

Lin AC. Integration of 3D CAD, reverse engineering and rapid prototyping in fabrication of invisible tooth aligner. Systems, Man and Cybernetics, IEEE International Conference on 3:2431-2436, 2005.

Mangano FG, Cirotti B, Sammons RL, Mangano C. Custom-made, root-analogue direct laser metal forming implant: a case report. Lasers Med Sci 27:1241-1245, 2012.

Mallepree T, Bergers D. Accuracy of medical RP models. Rapid Prototyping J 15:325-332, 2009.

Marga F, Jakab K, Khatiwala C, Shepherd B, Dorfman S, Hubbard B, Colbert S, Gabor F. Toward engineering functional organ modules by additive manufacturing. Biofabrication 4: doi:10.1088/1758-5082/4/2/022001, 2012.

Mavili ME, Canter HI, Saglam-Aydinatay B, Kamaci S, Kocadereli I. Rapid prototyping as a tool for diagnosis and treatment planning for maxillary canine impaction. J Craniofac Surg 18:740-747, 2007.

McDonald JA, Ryall CJ, Wimpenny DI. Medical models, the ultimate representations of a patiet-specific anatomy. Wouters K, Rapid Prototyping Casebook, Trowbridge, Professional Engineering Publishing Limited, 177-182, 2001.

Melchels FP, Domingos MA, Klein TJ, Malda J, Bartolo PJ, Hutmacher DW. Additive manufacturing of tissues and organs. Prog Polym Sci 37:1079-1104, 2012.

Metzger MC, Hohlweg-Majert B, Schwarz U, Teschner M, Hammer B, Schmelzeisen R. Manufacturing splints for orthognathic surgery using a three-dimensional printer. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 105:1-7, 2008.

Miller JR, Derakhshan M. The Invisalign system: Case report of a patient with deep bite, upper incisor flaring, and severe curve of spee. Semin Orthod 8:43-50, 2002.

Mitsuishi M, Cao J, Bártolo P, Friedrich D, Shih AJ, Rajurkar K, Sugita N, Harada K. Biomanufacturing. CIRP Annals-Manufacturing Technology 62:585-606, 2013.

Müller A, Krishnan KG, Uhl E, Mast G. The application of rapid prototyping techniques in cranial reconstruction and preoperative planning in neurosurgery. J Craniofac Surg. 14:899-914, 2003.

Mäkitie AA, Korpela J, Elomaa L, Reivonen M, Kokkari A, Malin M, Korhonen H, Wang X, Salo J, Sihvo E, Salmi M, Partanen J, Paloheimo KS, Tuomi J, Närhi T, Seppälä J. Novel additive manufactured scaffolds for tissue engineered trachea research. Acta Otolaryngol. 133:412-417, 2013.

Mäkitie A, Paloheimo K-S, Paloheimo M, Kanerva J, Björkstrand R, Ramsay H, Tuomi J. Development of Rapid Prototype Models for Temporal Bone Dissection Simulation. 2nd International Conference on Additive Technologies, Ptuj, Slovenia, 2008.

Ng P, Lee PSV, Goh JCH. Prosthetic sockets fabrication using rapid prototyping technology. Rapid Prototyping J, 8:53-59, 2002.

Nizam A, Gopal RN, Naing L, Hakim AB, Samsudin AR. Dimensional Accuracy of the Skull Models Produced by Rapid Prototyping Technology Using Stereolithography Apparatus. Orofacial Sciences 1:60-66, 2006.

Ono I, Gunji H, Suda K, Kaneko F. Method for preparing an exact-size model using helical volume scan computed tomography. Plast Reconstr Surg 93:1363-1371, 1994.

Pallasen U, Van Dijken JWV. An 8-year evalution of sintered ceramic and glass ceramic inlays processed by the Cerec CAD/CAM system. Eur J Oral Sci 108:239-246, 2000.

Periago DR, Scarfe WC, Moshiri M, Scheetz JP, Silveira AM, Farman AG. Linear accuracy and reliability of cone beam CT derived 3-dimensional images constructed using an orthodontic volumetric rendering program. Angle Orthod 78:387-395, 2008.

Pham DT, Gault RS. A comparison of rapid prototyping technologies. Int J Mach Too Manu 38:1257-1287, 1998.

Poukens J, Haex J, Riediger D. The use of rapid prototyping in the preoperative planning of distraction osteogenesis of the cranio-maxillofacial skeleton. Comput Aided Surg 8:146-54, 2003.

Poukens J, Laeven P, Beerens M, Nijenhuis G, Sloten JV, Stoelinga P, Kessler P. A classification of cranial implants based on the degree of difficulty in computer design and manufacture. Int J Med Robot Comput Assist Surg 4:46-50, 2008.

Quayle AA, Gray RMJ, Metcalfe RJ, Guthriet R, Wastell D. Soft occlusal splint therapy in the treatment of migraine and other headaches. J Dent 18:123-129, 1990.

Radlanski RJ, Lieck S, Bontschev NE. Development of the human temporomandibular joint. Computer-aided 3D-reconstructions. Eur J Oral Sci 107:25-34, 1999.

Rengier F, Mehndiratta A, von Tengg-Kobligk H, Zechmann CM, Unterhinninghofen R, Kauczor HU, Giesel FL. 3D printing based on imaging data: review of medical applications. Int J Comput Assist Radiol Surg 5:335-341, 2010.

Rengier F, Weber TF, Giesel FL, Böckler D, Kauczor HU, von Tengg-Kobligk H. Centerline analysis of aortic CT angiographic examinations: Benefits and limitations, Am J Roentgenol 192:W255-W263, 2009.

Rouse S. At the speed of light – Additive manufacturing of custom medical implants. The TCT Magazine 17:47-50, 2009.

Sándor GK, Tuovinen VJ, Wolff J, Patrikoski M, Jokinen J, Nieminen E, Mannerström B, Lappalainen OP, Seppänen R, Miettinen S. Adipose stem cell tissue-engineered construct used to treat large anterior mandibular defect: a case report and review of the clinical application of good manufacturing practice-level adipose stem cells for bone regeneration. J Oral Maxillofac Surg 71:938-950, 2013.

Silva DN, Gerhardt de Oliveira M, Meurer E, Meurer MI, Lopes da Silva JV, Santa-Barbara A. Dimensional error in selective laser sintering and 3D-printing of models for craniomaxillary anatomy reconstruction. J Craniomaxillofac Surg 36:443-449, 2008.

Singare S, Dichen L, Bingheng L, Zhenyu G, Yaxiong L. Customized design and manufacturing of chin implant based on rapid prototyping. Rapid Prototyping J 11:113-118, 2005.

Singare S, Lian Q, Wang WP, Wang J, Liu Y, Li D, Lu D. Rapid prototyping assisted surgery planning and custom implant design. Rapid Prototyping J 15:19-23, 2009.

Stübinger S, Mosch I, Robotti P, Sidler M, Klein K, Ferguson SJ, Rechenberg Bv. Histological and biomechanical analysis of porous additive manufactured implants made by direct metal laser sintering: A pilot study in sheep. J Biomed Mater Res doi: 10.1002/jbm.b.32925, 2013.

Sykes LM, Parrott AM, Owen CP, Snaddon DR. Applications of rapid prototyping technology in maxillofacial prosthetics. Int J Prosthodont 17:454-459, 2004.

Tuomi J, Paloheimo KS, Björkstrand R, Salmi M, Paloheimo M, Mäkitie A. Medical Applications of Rapid Prototyping – from Applications to Classification. Bártolo PJ et al., Innovative Developments in Design and Manufacturing: Advanced Research in Virtual and Rapid Prototyping, Leiden, CRC Press / Balkema, 701-704, 2010.

United Nations. World Population Prospects: The 2012 Revision. Department of Economic and Social Affairs, Population Division (2013), 2012.

Van Noort R. The future of dental devices is digital. Den Mater 28:3-12, 2012.

Vassura G, Vassura M, Bazzacchi A, Gracco A. A shift of force vector from arm to brain: 3D computer technology in orthodontic treatment management. Int Orthod 8:46-63, 2010.

Von Tengg-Kobligk H, Weber TF, Rengier F, Kotelis D, Geisbüsch P, Böckler D, Schumacher H, Ley S. Imaging modalities for the thoracic aorta. J Cardiovasc Surg (Torino) 49:429-47, 2008.

Von Wilmonsky C, Lutz R, Meisel U, Srour S, Rupprecht S, Toyoshima T, Nkenke E, Schlegel KA, Pohle D, Münstedt H, Rechtenwald T, Schmidt M. In vivo evaluation of ß-TCP containing 3D laser sintered poly(ether ether ketone) composites in pigs. J Bioac Compat Pol 24:169-184, 2009.

Wagner JD, Baack B, Brown GA, Kelly J. Rapid 3-dimensional prototyping for surgical repair of maxillofacial fractures: a technical note. J Oral Maxillofac Surg 62:898-901, 2004.

Wang X, Yan Y, Pan Y, Xiong Z, Liu H, Cheng J, Liu F, Lin F, Wu R, Zhang R. Generation of three-dimensional hepatocyte/gelatin structures with rapid prototyping system. Tissue Eng 12:83-90, 2006.

Warnke PH, Douglas T, Wollny P, Sherry E, Steiner M, Galonska S, Becker ST, Springer IN, Wiltfang J, Sivananthan S. Rapid prototyping: porous titanium alloy scaffolds produced by selective laser melting for bone tissue engineering. Tissue Eng Part C Methods 15:115-24, 2009.

Waitzman AA, Posnick JC, Armstrong DC, Pron GE. Craniofacial skeletal measurements based on computed tomography: part I. Accuracy and reproducibility. Cleft Palate Craniofac J 29:112-117, 1992.

Winder J, Bibb R. Medical rapid prototyping technologies: state of the art and current limitations for application in oral and maxillofacial surgery. J Oral Maxillofac Surg 63:1006-15, 2005.

Witek L, Marin C, Granato R, Bonfante EA, Campos F, Bisinotto J, Suzuki M, Coelho PG. Characterization and in vivo evaluation of laser sintered dental endosseous implants in dogs. J Biomed Mater Res B Appl Biomater 100:1566-73, 2012.

Wohlers T. Appendix C: U.S. System specification and Appendix D: Systems manufactured outside the U.S., Wohlers Report 2010 Additive Manufacturing State of the Industry Annual Worldwide Progress Report, USA, Wohlers Associates, 234-245, 2010.

Wohlers T, Caffrey T. Part 10: Next frontier, Wohlers Report 2013 Additive Manufacturing State of the Industry Annual Worldwide Progress Report, USA, Wohlers Associates, 263-268, 2013.

Xu W, Wang X, Yan Y, Zheng W, Xiong Z, Lin F, Wu R, Zhang R. Rapid prototyping three-dimensional cell/gelatin/fibrinogen constructs for medical regeneration.

J Bioact and Compat Pol 22: 363-377, 2007.

Yan Y, Zhang R, Lin F. Research and application on bio-manufacturing. Internal conference on advanced research in virtual and rapid prototyping 2003, Leiria, Portugal, 2003.

Yanping L, Shilei Z, Xiaojun C, Chengtao W. A novel method in the design and fabrication of dental splints based on 3D simulation and rapid prototyping technology. Int J Adv Manuf Technol 28:919-922, 2006.

Aalto-DD 213/2013

ISBN 978-952-60-5495-7
ISBN 978-952-60-5496-4 (pdf)
ISSN-L 1799-4934
ISSN 1799-4934
ISSN 1799-4942 (pdf)

Aalto University
School of Engineering
Department of Engineering Design and Production
www.aalto.fi

AALTO UNIVERSITY

School of Mechanical Engineering

Department of Engineering Design and Production

Iñigo Flores Ituarte

The role of Additive Manufacturing in modern product development: a case study for consumer electronic industry.

A Master's Thesis

Espoo, 2th of December, 2013

Supervisor Professor Eric Coatanéa

Instructor Heikki Hakamäki, M.Arts

Abstract

Author: Iñigo Flores Ituarte Title of the Thesis: The role of Additive manufacturing in modern product development: A case study for consumer electronic industry Date: 3th of December, 2013	Number of pages: 89
School: School of Engineering and Architecture Department: Department of Engineering Design and Production Professorship: Kon-41 Product Development	
Supervisor: Professor Eric Coatanéa	
Instructor: Heikki Hakamaki, M. Arts	

This Master´s Thesis focuses on studying the State of Art of Additive Manufacturing (AM) systems and current industrial application to produce structural plastic parts for the prototyping and assembly of consumer electronic products. The work evaluates the potential implications of AM technology related to a case company which designs, manufactures and supplies consumer electronic products globally.

This work presents a framework of AM process categories depending upon the type of application in which the technology can be implemented. Furthermore, the link between the Case Company Product Development Process was performed to explain the capabilities of each AM process category.

During the research, three different AM machines have been studied in order to evaluate their technical and economic feasibility to produced structural plastic parts for the assembly of low and medium manufacturing batches of Alpha-Prototypes during pre-production series.

The result of the Design of Experiment (DOE) indicates that some AM systems can be economically viable and technically feasible to produce inner structural plastic parts for the assembly of technical prototypes. Therefore, temporary tooling and injection molding methods can be potentially replaced at initial stages of pre-production series. AM and toll-less manufacturing can be implemented to the product development process to gain design flexibility, reduce time-to-market and save cost during the assembly of technical prototypes.

Keywords: Additive Manufacturing, 3D Printing, Direct Manufacturing, Rapid Prototyping, Technical Prototyping, Product Development Process

Preface

The work presented in this Master's Thesis is part of a research project called "Super-Machines". It is carried out at Aalto University – in collaboration with the Business, Innovation and Technology (BIT) research center, within the group of Integrated Design and Manufacturing (IDM).

This applied research project has been funded by the Finnish Funding Agency for Technology and Innovation (TEKES) together with a private consortium of Finnish industry partners. The core structure of the research participants is formed by Finnish SME and big Corporations.

The main objective of this work is to study the State of Arts in Additive Manufacturing (AM) technologies to improve product development processes, prototyping and manufacturing methods, supply chain applications as well as to find out innovative business models looking at the case company processes, services and products.

Table of contents

Abbreviations

AM	Additive Manufacturing
RP	Rapid Prototyping
RT	Rapid Tooling
DM	Digital Manufacturing
DFM	Design for Manufacturing
CAD	Computer-aided Design
DOE	Design of Experiment
PDP	Product Development Process
CAE	Computer-aided Engineering
DFA	Design for Assembly
PLM	Product Lifecycle Management
ASTM	American Society for Testing and Materials
ISO	International Organization for Standardization
SLA	Stereolithography
SLS	Selective Laser Sintering
DMLS	Direct Metal Laser Sintering
FDM	Fused Deposition Modeling
DW	Direct Write
RTV	Room Temperature Vulcanization
IM	Injection Molding
PP	Polypropylene
ABS	Acrylonitrile Butadiene Styrene
PC	Polycarbonate
STL	Standard Tessellation Language or Stereolithography file
AHP	Analytic Hierarchy Process

1. Introduction

The interest around Additive Manufacturing (AM), commonly called “3D printing” or “Rapid Prototyping”, has increased vastly over the past few years. The expiration of some industrial patents and the commercialization of open-source and low cost AM systems has made this technology accessible to hobbyist, artists, researchers and non-expert users [1]. In addition, companies all around the globe are commercializing new and innovative AM solutions and offering a whole ecosystem of web-based digital manufacturing services associated with this technology. As a consequence, the concept of “3D printing” has been introduced into the common vocabulary of media, consumers, industry professionals, inventors as well as product developers.

The first AM equipment was commercialized approximately three decades ago [2]. Since then, its traditional use has been linked to the prototyping phase in the product development process. During this process, AM systems have contributed to the acceleration of design cycles, improved the dialogue between product designers, product engineers, model makers and manufacturers. It is currently used by industry professionals to rapidly evaluate and visualize the design solution, and to integrate accordingly new features or eliminate them from the product concept during the design reviews.

During the past years, the application scenario of AM technologies has grown exceptionally. The development and improvement of new materials along with new additive techniques, have created a new scenario in which AM can replace conventional manufacturing solutions and take a step forward in order to become a production technique. At the same time, the industry and academia have shown many case studies in which AM technologies have been used as a “bridge manufacturing” technique, filling the gap between prototyping and mass production stages in product development. AM systems are also used to create high end quality parts for demanding industrial applications, such as aerospace, aeronautic, automotive as well as the medical industry [3]. Within the manufacturing and engineering community, technical applications, such as Rapid Prototyping (RP), Rapid Manufacturing (RM), Rapid Tooling (RT), Digital Manufacturing (DM) or Distributed Manufacturing are ongoing trends. The industrial development in this field has been intrinsically linked with the advancement of digital tools and AM systems. [4]

However, in practice organizations still mostly use AM systems only at the early initial prototyping phase of product development. The manufacturing of medium and big volumes relies on conventional methods as AM is not considered as a production technique. In contrast to this, industry experts and academia believe that in the future AM systems can replace established conventional manufacturing methods, changing the picture of product commercialization systems and product distribution channels. [3] [5] [6]

The most relevant advantage of additive systems versus conventional mass production methods is the design freedom that the layer-by-layer manufacturing approach allows. Virtually any geometry can be produced directly from digital data without considering the constraints imposed by the manufacturing process. The designer does not need to conceive the model based on the manufactured technique needed to produce it. To some degree, the imagination of the designer is the only limit when designing a product. This approach to design is completely revolutionary and the Design for Manufacturing (DFM) traditional foundations radically change when using AM systems. [7] [8]

Another important advantage of additive technology is the manufacturing flexibility. AM systems do not require initial tool investment, whereas conventional production techniques do. Design modifications can be implemented incrementally only changing the original Computer-Aided Design (CAD) model and uploading the new file to the AM machine. In addition, it is possible to test many design solutions simultaneously without any additional tool investment. AM systems allow manufacturing on demand by means of automated processes in which the intervention of the operator is minimal and only needed during the initialization and finalization of the manufacturing process. [2]

However, industry and academia has identified the main drawbacks of AM systems in order to become a production technique. The first issue is linked to the limited characterization methods of the additive machines and manufacturing materials. Standardization of the technology and material characterization is not as mature as it is in most of the conventional manufacturing methods. [2] [3] [9]

The second drawback is related to the reliability and repeatability of the AM processes. The quality of the produced parts is strongly dependent on part geometry, machine and process parameters in which the final quality is subordinate to the specific machine technology, the type of material used in the manufacturing process as well as many process variables, such as the part orientation and part location during the build process. [10] [11] [12]

Finally, there is a lack of understanding of the technology from the practical application perspective. This is still vague among the industry professionals, partly because relevant standards define only AM technology depending on the nature of machine process and the technology involved [4] [13], not depending on the application area in which the technology can be used. Previous scientific papers already have indicated the lack of applied research in order to link the economic and technical impact of the technology for modern product development organizations. [14] [2]

From the technology adoption perspective, it is necessary to research case by case applications in which AM produced parts can potentially bring technical and economical improvements over the existing solutions. In general, there are not many publications about real-life company cases and the ones available do not link the technical and economic implications.

Therefore, this Master's Thesis aims to present a comprehensive classification of AM technologies and their application framework. At the same time, a connection to existing product development models is performed in order to help non-expert professionals to understand the potential benefits of the technology. In addition, a feasibility study of the manufacturing of a product part is presented, in which different AM systems are evaluated as an alternative production method. The geometry tested in this experiment serves as a proof on concept for the case company and the results obtained will be used to evaluate the maturity of the technology as a production system.

1.1. Scope of the work

This Master's Thesis presents AM technologies and their common industrial applications suitable for producing plastic parts, components or functions of consumer electronic product. The work takes into consideration and focusses primarily in the product development process, business activity and product portfolio of the case company involved in the research project.

The first goal is to create a comprehensive synthesis of AM technologies and applications suitable for the study case, as well as to organize them depending upon the stage of product development process in which the application can be used.

The second goal is to research the feasibility of AM systems as a production technique by means of a Design of Experiment (DOE). The result of this experiment is used to make a quantitative comparison of the economic and the technical parameters of AM produced part versus the common conventional manufacturing methods used in the industry.

Finally, this Master's Thesis makes a state of the industry analysis of AM technology, taking into account the business activity of the research partner. The work presented in this Master's Thesis identifies future development trends bearing in mind technical, economical and societal impacts of the technology.

2. The case study

This Master's Thesis is focused on studying the industrial and business implications of AM technologies from the perspective of the research industry partner. This organization designs, manufactures and commercializes products and services for consumer electronic business, primarily mobile communication devices and related electronic accessories.

Looking at the company stakeholders involved in this research, the most influential stakeholder was a team part of the industrial design department. The team was involved in the model making and functional prototyping of early stage product concepts. At the same time, participants from other departments such as, marketing, research and development, engineering and manufacturing department have influenced the thesis scope as well as the research focus taken in this Master's Thesis.

In the following chapter, an overview of the case company product development process (PDP) is described, the work follows on analyzing the conventional manufacturing methods used during their Product Development Process (PDP) and finally a presentation of current available AM technologies is exposed.

2.1. The product development process

In an international matrix organization, the PDP involves the concurrent work between different departments located globally. During a typical PDP, representatives from marketing, industrial design, prototyping lab, product engineering, quality, manufacturing, supply chain as well as research and development are involved in the process.

Figure 1 shows a simplified framework of the PDP and the interaction of the different business functions within the organization. The product development is carried out concurrently by means of virtual mock-ups or analytical prototyping tools, such as 3D representations of the product using Computer Aided Design (CAD) models, simulation and Computer Aided Engineering (CAE) models, design for manufacturability (DFM) and design for assembly (DFA) tools, as well as collaborative working environments or Product Life cycle Management (PLM) systems.

In a typical PDP, at the initial Planning stages, the marketing department needs to foresee the business opportunity. This opportunity is transferred to industrial design and engineering departments, at this stage the taxonomy of the product is defined in order to create alternative concepts. One or more product concepts can be selected simultaneously and prototyped for further development and testing. [15]

The initial role of prototyping is to obtain tangible models of the product concepts, these models are used to detect and anticipate the performance of the product concept. Prototyping activities are developed during all stages of the PDP. For instance, the marketing department can evaluate the feasibility of the product idea by surveying and conducting interviews using appearance models of the product. During more mature levels of the PDP, functional and technical prototypes are used to demonstrate that the product has achieved the desired level of functionality. [16]

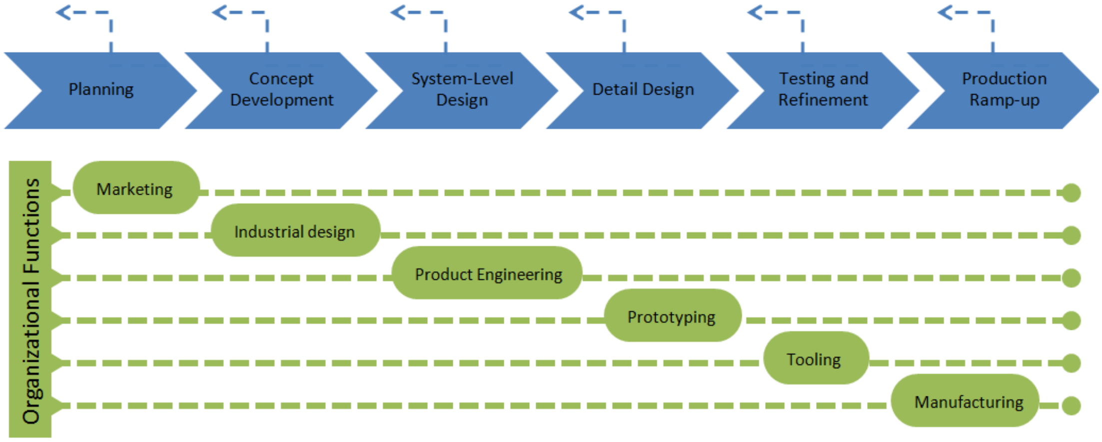


Figure 1 - Generic product development process and the typical organizational functions in concurrent engineering, adapted from [16] and [17].

During the System-Level Design, the product engineers define the architecture the product. At this phase, product portfolio management and project management activities play an important role by defining the organizational work flow diagrams and resources allocated to the specific projects. [18]

In this stage, the product is decomposed into manageable subsystem or product components. These subsystems can be seem as work packages to share within the engineering and design teams, the work is organized according to the resources available and the different teams are responsible to solve the related issues. The outcome of this stage is to define the initial topology and layout of the product and the top-level functional specification of each sub-system. [16]

During the Detail Design, industrial design, product engineering, tooling and manufacturing departments are responsible of creating a complete description and specifications of each sub-system. Generally, the work developed during this phase describes most of the final specifications and requirements of the product. Thus, geometry and functional parameters of the product as well as the material technical specifications are accurately defined.

In addition, a complete bill of materials, supplier tendering process, manufacturing, supply chain and product assembly planning are also executed. The outcome of this PDP phase is a complete and detailed documentation of the designed product that will be used for further testing and refinement.

During the testing and refinement stage of the selected product concepts, the case company needs to fabricate multiple pre-production versions of the intended product for internal testing and evaluation purposes.

In the initial phase of this stage, known as Alpha-prototyping, product engineers need to produce relatively low and medium volume batches of technical prototypes that have identical geometrical, functional and aesthetic properties of the intended product design. The difference is that during Alpha-prototyping the manufacturing methods are not necessarily the ones used during the final mass production. During Alpha-prototyping, the company uses preliminary mass production techniques such as, milling, silicon casting processes and injection molding using temporary tooling.

During the final stages of pre-production series, known as Beta-prototyping, the prototypes are built with the parts supplied and manufactured by the intended supplier and production processes respectively. The tooling and manufacturing methods used are identical or very similar to the ones used during the final production ramp up.

The PDP process of the case company is an iterative process that contains many interdependent activities between the different organizational functions. Although, the Figure 1 shows the PDP organized in a purely sequential other, the reality demonstrates that rarely the process behaves linearly and the stages of the PDP need to be iterated several times until the product concepts arrives to the ramp up phase. [16] [17]

The prototyping practices are also iterative. The PDP begins with purely visual prototypes and the complexity and requirements are included incrementally to the product prototype. Moreover, functionalities and performance features need to be tested several times during the PDP. During this process, industrial design and product engineering departments work concurrently and take advantage of AM technology to produce visual and semi-functional prototypes in low volume and only at initial stages of PDP. Commonly industrial design evaluates aesthetic using AM systems and product engineers are evaluating the performance of the product using more functional AM parts.

2.2. Manufacturing methods in product development

The manufacturing methods used currently to produce three-dimensional parts are classified in three conceptual groups. These manufacturing methods are known as subtractive, formative and additive methods.

The first group includes the production techniques that remove or cut the unnecessary material from an initial rough solid in order to obtain the desired geometry. For instance, this group is composed of conventional milling, turning, drilling or cutting processes. These techniques are grouped as the subtractive method.

The second group is known as the formative method. This method builds the part by means of external forces or topological constraints imposed by cavities, molds or tooling. Techniques, such as ancient forging and casting pertain to this group, as well as modern mass production techniques, such as injection molding or die casting.

The last group is known as Additive method, during this process the part is built directly using a CAD model and it manufactures the part in a sequential layering process by adding or binding material substrates layer by layer. Various types of technologies utilize this approach, such as Extrusion-Based Systems, Powder Bed Fusion Processes, Sheet Lamination Process or Direct Write technologies among others.

The use of subtractive or formative methods implies important geometrical constrains and limitations intrinsically related to the manufacturing process. For instance, during the milling process the machine and cutting tool geometry has an impact on the achievable morphology. In addition, while using formative methods, geometrical features, such as undercuts or draft angles need to be carefully designed. In some cases, the original geometry is not possible to achieve, thus the chosen manufacturing process has a big impact over the original design intent.

Subtractive and especially formative methods are widely used to manufacture plastic parts in electronic consumer products. These mentioned methods have more advantages for the mass production of plastic parts, due to the repeatability and the reliability of the process. However, subtractive and formative methods also have drawbacks that additive systems can potentially solve.

2.3. Conventional manufacturing methods

The most common conventional manufacturing methods used for producing structural plastic parts in a typical development process of consumer electronic products are displayed in the Table 1. The table also displays a description of the plastic used in common PDP and their production techniques depending upon the manufacturing volumes.

Table 1 - Manufacturing method used by the case company depending on the type of plastic and production volume

Production Volume (Units)	Plain plastic	Transparent plastic	Color plastic	Double shot plastic
1 to 20	AM, Silicon molding, CNC milling and Grinding			N/A
100 to 15.000	Temporary soft tooling and Injection molding process			
15.000 to 1.000.000	Hard tooling and Injection molding process			

During the PDP, initial volumes from 1 to 20 units of appearance models and semi-functional prototypes are produced by combining subtractive and formative techniques such as, milling and silicon molding techniques. When the volumes are higher than 100 units, injection molding and temporary tooling is normally used. Mass production relies on hard tooling and fully automated injection molding processes.

During the Alpha-prototyping in pre-production series, in which production volumes vary from 10 to 2000 units, an initial investment on temporary tooling or soft tooling is often required in order to produce structural parts for the final assembly of the pre-production series.

2.4. Additive manufacturing methods

Commercially available AM machines have very different architectures and material-processing capabilities. As mentioned before, the characterization of the machines and materials is not yet mature and the differences from one machine manufacturer to another are substantial. In addition, although the technical process used in the machine might be the same, in practice the terminology used to describe the AM system is different from supplier to supplier. [2]

This brings problems at many levels, for example the current standard development wanted to clarify what are the type of AM systems available in the market and what are the technical similarities and differences between them.

A current ASTM [4] standard has already identified seven AM process categories and in addition this Master´s thesis also presents a classification scheme based on the applications. Nevertheless, the list of the processes based on ASTM and there definition is listed below:

Material extrusion: *additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.*

Material jetting: *additive manufacturing process in which droplets of build materials are selectively deposited.*

Binder jetting: *additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.*

Sheet lamination: *additive manufacturing process in which sheets of material are bonded to form an object.*

Vat photo-polymerization: *additive manufacturing process in which liquid photopolymer in vat is selectively cured by light-activated polymerization.*

Powder bed fusion: *additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.*

Directed energy deposition: *additive manufacturing process in which focused thermal energy is used to fuse materials by melting as the material is being deposited.*

There are also other process subcategories which have not been included in this standard as such. The technical papers describe more AM processes, such as direct writing processes and hybrid processes. The definition adapted from existing literature defines these categories as:

Direct Writing: is a sub category of *directed energy deposition in which the materials is deposited to create functional structures on a substrate to form simple linear or complex conformal functional structures.* [19]

Hybrid processes: *additive manufacturing process in which a combination of different additive system or additive and subtractive methods are used simultaneously to produce parts with functional properties.* [3]

3. Additive manufacturing in the product development

3.1. State of the Arts in AM applications

The products commercialized by the case company are commonly defined and as consumer electronics products. Therefore, this type of product implies certain constrains coming from the type of materials, typical product size and production volumes used in the manufacturing.

The main limitation of the next chapter, 3.2 State of the Arts in AM applications, is that the review of AM applications is fundamentally focused on analyzing the processes to manufacture structural plastic parts and its use in prototyping, model making and product development activities. At the same time, some niche applications related to high performance metal tooling and manufacturing of functional components have been presented. The following State of the Arts does not take into account all the AM applications available in the industry, as they were not identified as the most relevant ones for the case study.

The State of the Arts of AM applications has been comprehensively divided in three chapters. These chapters have organized AM technology depending upon the type of applications in which an AM system is used in the industry. This Master's Thesis has identified basically three types of applications which are defined as: Physical Prototyping, Tooling and Manufacturing applications and Direct Part Manufacturing.

Physical Prototyping is the process in which additive methods are used to produce visual, functional or technical prototypes in order to test the form, fit and function of the product idea.

Tooling and manufacturing applications are the processes in which additive methods are used and combined with other manufacturing techniques in order to assist manufacturing processes.

Direct part manufacturing is the process in which additive methods are used to produce parts to be used as a final product.

3.2. Physical Prototyping

Physical prototyping is an essential process in every PDP. Its purpose is to create tangible early stage mock-ups in order to visualize the original design intent. A prototype helps to find answers to basic questions, such as "Will the designed solution meet customers requirement?" "Will this idea work out?" "How does this product fit and function together? "How does it look like?" or "What are the possible design alternatives?"

Physical prototypes are used as a communication tool during the iterative PDP. The developer uses tangible models that help to communicate the design solution to the organization. Moreover, the same physical model allows studying the strengths and weaknesses of the original design as well as to help the design teams in the conception of new possible alternatives to the same problem.

During all the stages of PDP, comprehensive physical prototypes are used to evaluate the degree of maturity of the product and ensure that components or subsystems of the product interface properly. By doing so, prototypes are tools for the design team to set milestones. Therefore, the concurrent work on the prototype helps to coordinate different departments and achieve the expected functionality out of the designed product.

As mentioned in chapter 2.1 Product Development Process, it is necessary to use virtual as well as physical prototypes simultaneously. The virtual prototype is generally a CAD model, the original design intent and further iterations are sketched by using a digital tool in an iterative process.

Consequently, the data of this CAD model can be used to produce physical appearance prototypes, for instance by using AM systems among other methods. The particularity of the AM process is its simplicity, from digital data to physical part in few steps. This advantage has made AM system good candidate process for physical prototyping. [3]

AM systems are potential manufacturing systems to produce parts for the three types of physical prototypes: visual prototypes, functional prototypes and technical prototypes. Visual prototypes are used to verify the dimensional and aesthetic requirements of the product. Functional prototypes are used to integrate functional features into the prototype, for instance preliminary hardware electronics or sensing technology can be assembled to test the performance of one product idea. Finally, technical prototypes are used to validate the product before high volume manufacturing, these types of prototypes are known as pre-production series. [20]

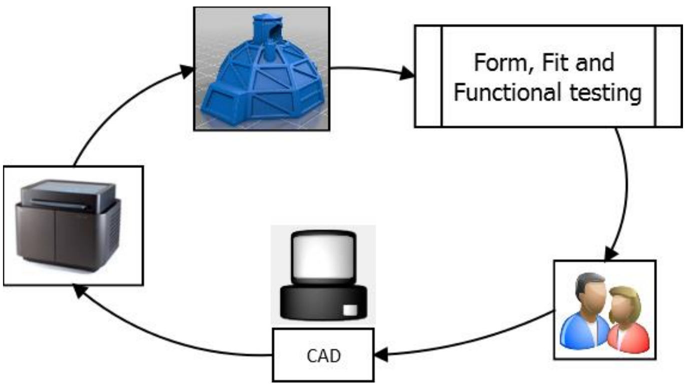


Figure 2 – Design and prototyping process using AM technology

During the PDP of consumer electronics products, the product engineers and the industrial designers work concurrently by using a collaborative PLM environment linked to the product CAD model. As an example of concurrent work during the PDP, the modification done by mechanical engineer in an inner structural part has an influence on the outer geometry of the product. The industrial designer needs to adapt the geometry to match the aesthetic requirement of the product. During this process, AM systems are used to manufacture appearance models to evaluate the changes and find the most suitable solution.

The Figure 2 above, shows the working process used in a typical industrial design studio. In this case, the AM system is used to create a quick visual prototype. The design team evaluates the result by analyzing form, fit and function of the solution and the following step is to implement the modifications into the CAD model and manufacture a new part. The process is iterated until the design matches the expectations of the industrial designers and product engineers.

3.2.1. Functional parts using AM

Current AM systems allow producing engineering plastics. AM systems have advanced in a way that additively produced parts are used to produce functional parts or functional readymade assemblies in a single process. Current AM produced material can be used in more demanding applications in which good mechanical properties and high dimensional stability of the produced part are a must. [21]

Improvement in material technology and AM system technology are making feasible the direct digital manufacturing of plastic part in prototyping stages. The flexibility of the manufacturing systems, together with the relative straightforward manufacturing process makes AM a solution for producing functional parts quickly at any stage of the PDP.

Functional plastics produced by AM may have similar mechanical properties than injection molded plastics. Therefore, they are used to test the performance of the product. Mechanism, such as snap fit, living hinges or more developed mechanical assemblies can be produced using functional plastics produced by AM systems. In addition, the flexibility of the manufacturing process allows iterating and modifying the design without high economic impact.

3.3. Tooling and Manufacturing

Production of tools and patterns used in the assembly lines, manufacturing ramp-up or prototyping phase have a substantial impact over the performance and economics of the product and the product development process respectively. The manufacturing of the tooling used during the final production ramp-up is considered as a milestone between the Design and Manufacturing departments. [22]

This milestone compromises the design perspective in order to meet the customer needs, and also the commitment from the manufacturing side to reduce the lead time and speed up the time-to-market. This relationship has been defined in previous studies as the design versus manufacturing conflict. [23]

The answer to this conflict seems to be easy to formulate, the sooner the product specifications and design features are frozen the faster manufacturing begins. However, the problem is not that trivial. The uncertainty of the business environment and the pressure imposed by the competition makes that the marketing and design departments find themselves with limited time to gather all the valuable information, therefore they have to incrementally adapt the product specifications along the development process to react to the changing environment.

At the same time, model-makers and manufactures need to be reactive to the design changes and they need to deliver the required quality and specifications on time. In addition, the manufacturing site needs to align their production systems so the cost of the process and lead time is decreased as much as possible to remain competitive and reduce time-to-market. [24]

AM and its applications as a bridge-manufacturing technique, to produce temporary tooling and patterns, have been in use for quite many years. In the past years, its popularity has grown because of the improvements shown in manufacturing speed, part quality and material properties of high-end commercially available systems. [3]

Nowadays, Rapid Tooling (RT) techniques using AM are another tool in the toolkit for model-makers and manufactures. It is used to fill the gap between the design and the mass production stages of the product development. The technology gives to the manufacturing site a higher degree of flexibility to align their production systems according to the changing environment. [25]

At initial phases of the product development, the case company needs to produce relatively low-volume manufacturing runs of plastic parts for its visual and physical evaluation. As the product concept matures, more functional prototypes need to be manufactured. At the same time, the preliminary mass manufacturing processes are also tested. Finally, when the production is up and running, factors such as production cycle time, scrap rate and other also needs to be optimized.

The following tooling and manufacturing applications have been identified as the most relevant for the case study.

3.3.1. Production of soft tooling

Indirect tooling

One of the most extended applications of AM in model making and RP is to use the 3D printed parts as a pattern or Master's for indirect tooling. The AM produced part can be used as a pattern to create silicone RTV (Room Temperature Vulcanization) molding, and fill the gap between stages of prototyping and metal tooling. [26]

Molding techniques are widely used during the initial stages of the PDP in order to produce small batches of plastic parts for the assembly of prototypes. AM is widely used to manufacture the master pattern in order to create silicone soft tooling. Generally, the process uses the CAD model directly to print the master by using for instance a Stereolithography (SLA) machine. The AM part is used as a pattern and this is suspended afterwards in a frame where the silicone or urethane is poured around it. After curing the mold in the vacuum chamber, this is split in half and the AM pattern is removed. Finally, the mold can be used to produce small batches of parts in order to replicate the initial topology of the pattern.

Direct tooling

AM manufactured parts are also used as a tool for vacuum casting applications. The tool is produced directly from the CAD models and manufactured using commercially available AM system. In this example, the mold is printed using Polyjet technology. After that, the silicone is injected to the mold. The following steps require closing the mold by clamping it before the silicone is cured and the air bubbles are removed using the vacuum chamber.

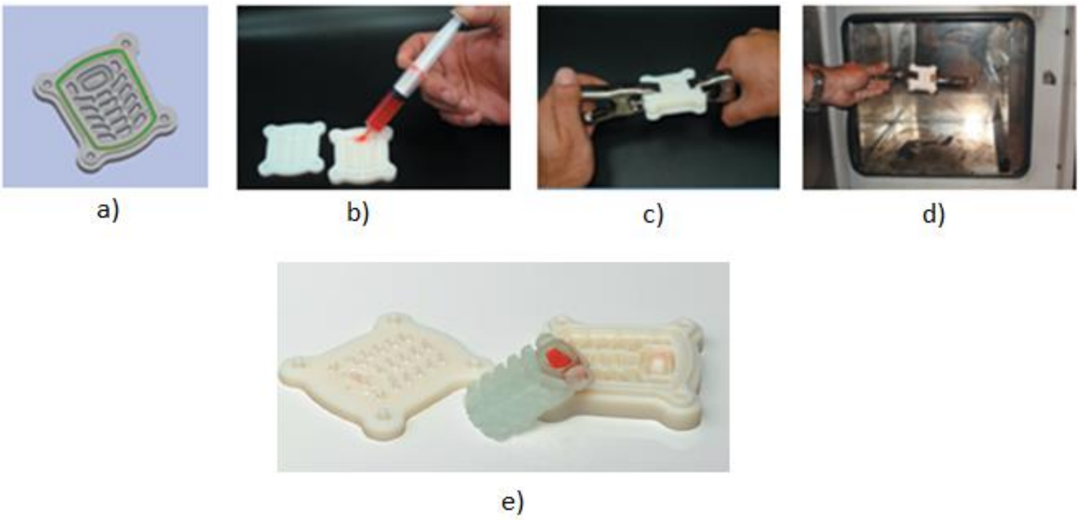


Figure 3 - Direct tooling application using Polyjet technology and vacuum casting, adapted from Stratasys. [27]

Figure 3 shows the pictures and schematic view of the direct tooling application using AM produced molds to prototype a keypad used in electronic devices. From left to right, a) is the CAD representation of the mold, b) shows the process of injecting the silicone into the mold, c) shows the mechanical clamping of the mold, d) illustrates the process of removing the bubbles and curing of the silicone using a vacuum chamber and finally, e) shows the final produced keypad prototype.

Some direct tooling applications also use AM parts as a tool for injection molding process [28]. The tools can be produced directly using a CAD model and assembled in injection molding machines produce small batches of plastic parts. This technique can be used to produce parts with features such as living hinges, holes, thin and thick walls, snap fits and logos.

The biggest difference compared to conventional injection molding metal tools is that polymers have low heat transmission. Thus, the cooling time has to be much longer between injection cycles. At the same time, the intended product geometry needs to be carefully analyzed in order to evaluate the feasibility of the process. Generally, the technique can be used to produce up to 100 parts using base materials with good flow ability.

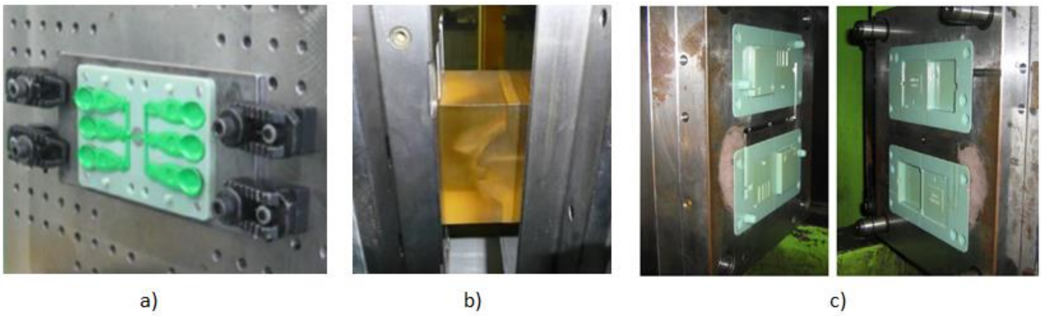


Figure 4 - AM produced polymeric tools used in injection molding applications, adapted from Stratasys. [27]

Figure 4 shows some real cases using injection molding and AM tools. From left to right, a) shows a Polypropylene (PP) injected material in a consumer goods application, b) shows a Stereolithography (SLA) printed tool to produce nylon parts and c) shows a case study used to produce injection molded parts with living hinges and snap fits using AM printed tools and injection molding. Other AM direct tooling applications have impact on manufacturing industry processes, such as thermoforming tooling for packaging applications.

3.3.2. Production of hard tooling

High-performance tooling

The manufacturing of injection molding tooling inserts with integrated conformal cooling channels is proved to be a technology that allows optimizing the injection molding process for plastic parts by using free-form design of the cooling chambers inside the tool insert. [29]

By means of the AM process called Selective Laser Sintering (SLS) or Direct Metal Laser sintering (DMLS), which belongs to the process category of powder bed fusion. It is possible to produce layer by layer metal injection molding tool inserts with integrated inner conformal cooling geometries which follow the contour of the mold cavity in order to optimize the cooling process during the manufacturing process. On the contrary, by using the traditional approach, the cooling system of the mold is constructed by drilling a matrix of straight channels as close as possible from the walls of the cavity. This generates non uniform offset distances between the cavity and the cooling systems and consequently uneven temperature gradients on the mold cavity.

During the production of engineering plastics by means of injection molding process, the mold temperature is a fundamental parameter to control. Uneven temperature levels on the cavity surface have substantial impact on mechanical properties of the produced parts, shrinkage behaviors, surface quality, production cycle time, economics of the production system as well as production scrap rates among others variables. [30]

Figure 5 - Mold inserts with integrated conformal cooling, adapted from [30]

Figure 5 shows the geometry of a high performance tooling used in injection molding, the picture in the right hand side allows visualizing the conformal cooling channels inside the tool. This application helped to the manufacturer to improve substantially the quality of the parts produced and reduce the injection molding cycle time by controlling more efficiently the temperature of the manufacturing process.

The optimal application area of conformal cooling is in complex geometries in which heat is difficult to remove by traditional cooling systems and the economics of the injection molding process are a fundamental parameter to consider. Ongoing research also has focused effort on creating automatic algorithms to design optimized conformal cooling channels and integrate this tool to commercial CAE software, these methods assist during the mold design process in order optimize the cooling process of the parts produced by injection molding. [31] [32] [33]

3.3.3. Assembly tooling

In manufacturing and assembly operations, the production in low quantities of jigs, fixtures, assembly tooling and many other types of manufacturing tools is required. Assembly tools are used in PDP from the very initial stage of development until mass production. The economic impact of assembly tooling is high as they are often custom made designs and the required quantities are low. In addition, the common processes to manufacture assembly tooling involves subtractive process like milling of metallic materials, such as steel and aluminum. [21]

Therefore, the waste in the form of energy and material associated to subtractive process, together with the fact that the tooling needs to be custom designed for every product variant, can make AM a competitive solution versus conventional methods. In addition, especially in prototyping stages, the number of copies of fixtures and assembly tooling is often quite low, and by using AM systems improved versions of the tooling can be tested rapidly.

In many ongoing industrial applications for automotive and manufacturing industries, thermoplastic materials, such as ABS and PC-ABS blends are used to produce assembly tooling by means of material extrusion processes, such as Fusion Deposition Modeling (FDM) processes [3].

3.3.4. Hybrid processes

Direct write technologies

There is tendency in the manufacturing of modern electronic communication devices to build more and more compact products with integrated conformal functionalities within the inner and outer structural geometries of the product. This is achieved in order to decrease material usage on the product, reduce the thickness of the product or simplify the manufacturing process as well as to improve existing functionalities, such as battery capacity, camera or sensing technology by adding more space in the inner topology of the product. [19]

Direct write (DW) technologies, also known as direct printing or digital writing is a technology capable of depositing various types of materials in a computer controlled manner following the topology of the substrate in which is going to be deposited. DW technology has the potential to change conventional manufacturing processes in many sectors - automotive, electronics manufacturing and biotechnology among others.

There are wide variety of technologies which are classified as DW and current commercially available five axis controlled machines are able to add functional material to existing product parts [34]. DW is a scalable manufacturing process that enables to manufacture electronic and mechanical elements, such as antenna structures, 3D electronic components, connectors and wiring solutions and can potentially help to reduce production cost and manufacturing times.

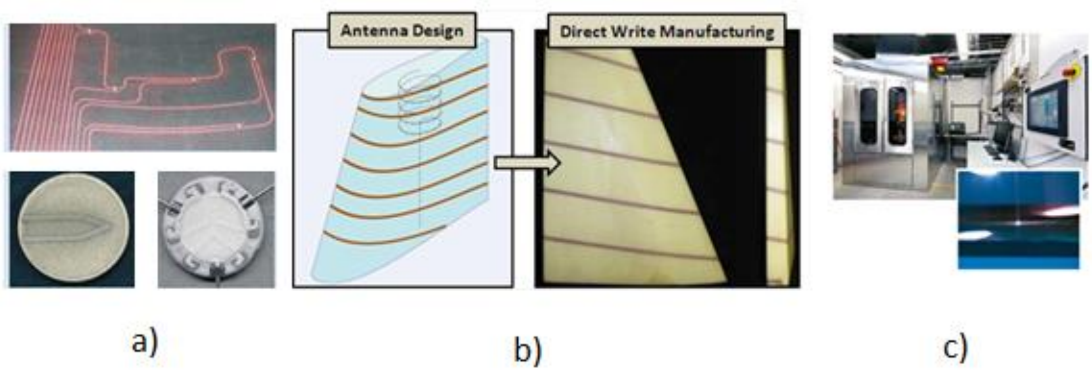


Figure 6 - Examples of DW produced functionalities, adapted from [35]

Figure 6 summarizes some of the ongoing industrial applications of DW technologies. From left to right, picture a) shows some DW manufactured components, such as copper conductors, thermal elements and heat flux sensors, picture b) shows a Cad model of a conformal antenna and the final manufactured component, the last picture c) show the manufacturing equipment in this case based on Direct Write Thermal Spray technology.

Hybrid processes

Hybrid processes are the ones that combine either different additive process in the same system or combine at the same time additive and subtractive systems. As an example of ongoing research in this field, two additive methods, such as SLA and DW are combined to develop fully integrated electronic system were the substrate and morphology of the object is deposit layer by layer using and SLA and simultaneously, conductive functional properties are added to the geometry by using DW technologies [36].

Figure 7 shows a benchmark application of this technology in which electronic functionalities are added by using DW technology that produces conformal conductive copper routing systems. At the same time, an SLA process is used to produce the substrate of the component. At this stage of the technology, the hybrid process is stopped in the middle of the build to manually assemble the semiconductor technology. In the future, this and similar kind manufacturing processes can be automated by using robots in the hybrid manufacturing process.

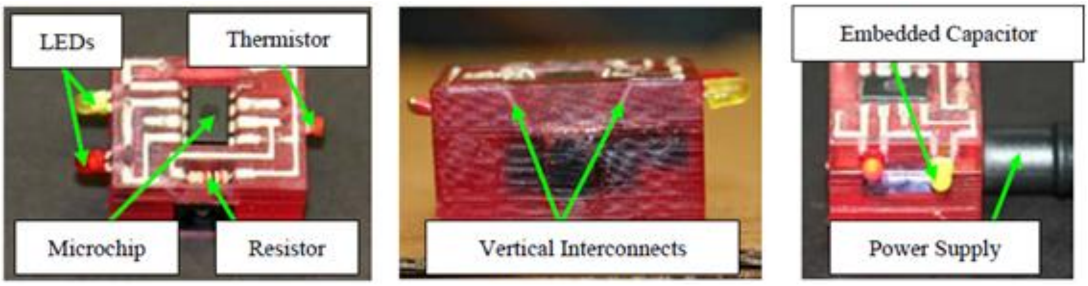


Figure 7 - An example of AM 3D structural electronic systems, adapted from [36]

Current commercially available solutions also combine a powder bed fusion metal sintering additive system with integrated high speed milling processes. Application niches of this technology are focused on producing high performance tooling, mold dies and similar equipment. The process is so that the initial geometry is sintered layer by layer and at some predefined step of the additive process, the milling process begins to improve the disadvantages related to sintering process, such as repeatability, dimensional stability and surface quality of the produced parts. These drawbacks are overtaken by combining a high speed milling process, at the same time there is an increase in efficiency because less waste is generated compared to fully subtractive processes. [3]

The concept of hybrid manufacturing can potentially drives to a new scenario in which machines are able to produce fully complex systems in one go by using digital data. The combination of additive and subtractive manufacturing systems will help to make products in a more efficient and productive way than current conventional systems.

3.4. Direct part manufacturing

Increasingly, product development organizations are using AM systems to produce parts that are assembled into final products. Experts in AM technology are forecasting that by 2017, the net sales of AM product and services will increase to $6 billion worldwide. AM is commonly used for producing fully ergonomic and custom made products, short-run production, and even series manufacturing. In the past years, another growth trend, related to personal low-end AM systems, indicates that in 2012 more than 35.000 of this type of machines were sold to hobbyist, inventors, young engineers and academia. [3]

Related to this industrial trend, research has introduced a new emerging manufacturing paradigm defined as mass personalization. Some experts believe that we are moving at some extent from a mass customization era towards a mass personalization era. Currently, firms are able to design products with multiple variants, allowing the consumer to select certain specification according to their criteria. Hence, the consumer is able to buy a product which is much more personal at some extent. Corporations are able to deliver, at low manufacturing cost, highly customizable goods by means of product family planning and customizable product architectures. [37] [38]

Mass personalization paradigm of manufacturing is conceptually a step ahead from mass customization. In practice, a personalization approach includes the customer in the PDP of the firm making the consumer part of the product design process. Customer input becomes essential and transforms the product completely according to their individual and personal needs. [39]

Current online web services and product retailers have created a disruptive new business model where the manufacturing of products and goods is done on demand. The customers can upload to the cloud his own product designs and get the parts manufactured in days or weeks. Moreover, they can also try to sell their own designs using the same web based platform. An emerging community of 3D makers is growing rapidly and taking advantage of the versatility of AM systems.

Additive technologies have the advantage to produce goods, at relatively low cost, without any type of initial investment in tools. Designs are directly manufactured on demand, without costly supply chains, inventories and stocks. The parts are directly manufactured from the digital data stored in the cloud and delivered to the end customer. Furthermore, during this process the customer can also choose what would be the printing material, what type of finishing needed or also influence in the type post-processing wanted, by selecting online the color and many other aesthetic variables.

AM systems are considered as enablers technologies towards mass personalization era and innovators and early adopters of the technology are moving fast on developing new and disruptive business models around AM systems in the era of digitalization.

3.5. Framework for Additive Manufacturing in Modern Product Development

The idea of this framework is to locate the different process categories of AM, which were explained in previous chapter 2.4, depending upon the PDP of the case company and the application in which each can be suitable. It should be noted that, this selection of applications is only based on the type of applications and necessities of the case company. In addition, the type of technology per application used by rapid prototype service suppliers has been taken into account.

The Table 2 tries to link the following three dimensions to improve the compression of non-expert professionals and explain the Product development process of the case company, the process categories of AM technologies and the State of the Arts in AM applications.

Table 2 - Framework for AM industrial application's, technological process categories and the PDP

<table>
<tr><th>AM Process Categories</th><th>Planning → Concept Development</th><th>System-Level Design → Detail Design</th><th>Testing and Refinement → Production Ramp-up</th></tr>
<tr><td>Material extrusion</td><td colspan="2">Visual and functional prototyping</td><td>Assembly tooling</td></tr>
<tr><td>Material jetting</td><td colspan="2">Visual and functional prototyping. Soft tooling, Indirect and direct tooling.</td><td>N/A</td></tr>
<tr><td>Binder jetting</td><td colspan="2">Visual and functional prototyping</td><td>N/A</td></tr>
<tr><td>Sheet lamination</td><td colspan="2">Visual and functional prototyping</td><td>N/A</td></tr>
<tr><td rowspan="2">Vat photo-polymerization</td><td>Visual and functional prototyping.</td><td>Technical prototyping</td><td rowspan="2">Technical prototyping and direct part manufacturing.</td></tr>
<tr><td colspan="2">Soft tooling, indirect and direct tooling.</td></tr>
<tr><td>Powder bed fusion</td><td>Visual and functional prototyping.</td><td>Technical prototyping.</td><td>High performance tooling. Technical prototyping and direct part manufacturing</td></tr>
<tr><td>Directed energy deposition (Direct Writing)</td><td>Functional prototyping</td><td>Technical prototyping</td><td>Technical prototyping and direct part manufacturing.</td></tr>
<tr><td>Hybrid processes</td><td>Functional prototyping</td><td>Technical prototyping</td><td>Technical prototyping and direct part manufacturing.</td></tr>
</table>

4. Research Design

The initial chapters of this Master's Thesis have shown most of the relevant application areas of AM systems. At the same time, technical and the economic implications of AM system were introduced.

During the following chapter, the experimental part of the Master's Thesis will be presented. The AM application chosen for this experiment has been framed as technical prototyping. In this case study, the additive manufacturing (AM) of a real product part will be evaluated from different perspectives in order to make a technical and economic feasibility study of AM to produce part for technical prototyping.

The following sub-chapters will introduce the methodology used in the experiment. Firstly, the engineering problem will be defined. Secondly, the research questions will be presented followed by a detailed explanation of the methodology and tools used in the experimental setup. At the same time, design variables and performance variables will be defined and finally, the measurement strategy taken in the DOE as well as the summary of the methodology are also introduced.

4.1. Introduction to the engineering problem

Research and empirical evidence show that AM technology can potentially replace some conventional manufacturing methods. Current commercially available AM systems are able to directly manufacture functional engineering plastic parts at relative low cost. Over the past years, mechanical properties of the materials as well as the reliability and repeatability of AM processes have improved significantly. Thus, available AM processes are becoming a potential production system to manufacture high quality engineering plastics.

As explained in previous chapters, during the PDP of the case company, the product concepts and further prototypes move throughout different design stages where functionalities and features are included in order to increase the maturity level of the product concept. During the manufacturing of technical prototypes in pre-production series, it is necessary to produce small and medium batches of plastic parts to use them in the assembly of Alpha-Prototypes.

The cost associated to the manufacturing of plastic parts for the assembly of Alpha-prototyping stage has a significant impact over the whole PDP cost. As explained in previous chapter 2.3 Conventional manufacturing methods, temporary tooling and injection molding is the standard system to produce plastic parts in the assembly of initial pre-production series. The volumes at this stage of the PDP change from product program to another product program but in general they vary from 10 to 2000 units.

The structural plastic parts used in pre-production series, are usually formed by thermoplastic polymeric materials such as Polycarbonates (PC), Acrylonitrile Butadiene Styrene (ABS) or PC-ABS blends among others. These types of plastics have optimal mechanical properties and they are widely used in injection molding for parts in medium and high volume production.

Injection molding processes have very high initial investment in comparison with AM methods. The cost pert part using injection molding is decreased as a function of the manufacturing batch size. Whereas, the production cost per part of AM does not decrease depending upon the produced batch size, the cost per part remains almost constant independently of the production volume, it is well understood by the industry that AM is economically competitive when the production volumes are small. [40]

This research design aims to study the technical feasibility of AM direct manufacturing of parts for the assembly of pre-production series and evaluate this technology as an alternative to current prototyping processes that rely mostly on temporary tooling and injection molding. At the same time, the economic feasibility of the process will be evaluated in order to understand the strengths and limitations of AM as a production system.

4.1.1. Geometry of the case study

The geometry used for this experiment is a typical inner structural plastic part similar to many other plastic parts found in mass produced consumer devices, it was supplied by the case company as a benchmark to perform the feasibility study. The overall design and features of this part fulfills certain functions of a particular product and it belonged to a real product program which was launched by the case company.

As a purely functional inner structural plastic part, there are no aesthetic requirements to satisfy. The entire list of requirements is dimensional and mechanical. The dimensional stability of the produced part needs to be assured in order to assess the feasibility of AM technology as a potential production technique. Simultaneously, the mechanical properties of the produced part need to be evaluated.

The final produced sample requires very tight geometrical and dimension tolerances as well as good surface quality in order to be feasible for the mechanic and electronic assembly of the product.

This geometry was selected for the experiment due to its complexity. It has several assembly points, undercuts and geometrical features that require pins and inserts to be manufactured. The tooling design for the injection molding as well as the manufacturing process has some complexity. Furthermore, the parts have small features that can make AM challenging, wall thickness in certain areas are lower than 1 mm and some geometrical features of the part can go under 0.5 mm.

As mentioned earlier, the conventional approach to manufacture this kind of parts would use Injection molding processes using temporary or soft tooling. At the ramp up stage of the product, hard tooling and automated injection molding is used to run the high volume manufacturing or mass production. The manufacturing techniques used depending upon the production volume has been already introduced in a previous chapter and this was depicted in Table 1.

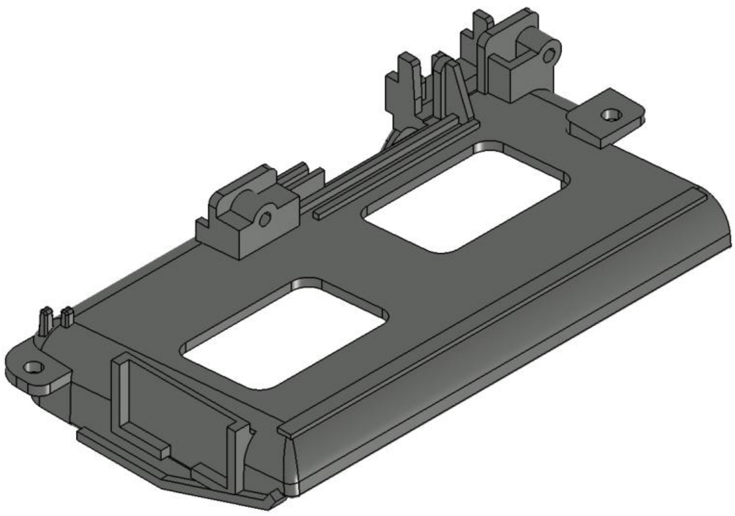


Figure 8 - Geometry of the case study

Figure 8 shows the perspective CAD view of the geometry. The general size of the part is defined by 68.125mm X 37.241mm X 14.854mm and its theoretical volume is about 3308 mm^3.

4.2. Research questions

The following research questions have been selected to evaluate the feasibility of AM technology. The first question focusses on the economic implications of producing plastic parts with AM technology. The answer to the second question will summarize the technical side of AM produced parts. The third question wants to evaluate the compromises needed to take during AM process and the last question focusses on studying the suitability of different AM process categories to manufacture inner structural plastics part for the assembly of pre-production series.

- Is it economically feasible to use AM methods to manufacture structural plastic parts for the assembly of pre-production series?
- Is it technically feasible to use AM methods to manufacture structural plastic parts for the assembly of pre-production series?
- What are the tradeoffs between the design variables versus the performance variables in the manufacturing of AM parts?
- Which are potentially the most suitable AM systems?

4.3. Data used in the Design of Experiment

The qualitative information about the manufacturing processes of the case company has been obtained by semi-structured interviews in which the topic of the interview was already predefined. Two to three interviews and several presentations were prepared with stakeholders of the case company in order to obtain data and share the topic of the Master´s Thesis.

At the same time during the research, qualitative information has been obtained from ten to twenty non-structured interviews with employees of various departments of the case company. In general, interviews were conducted during the whole research project and the feedback received has contributed to shape and validate the conclusions documented in this Master's Thesis.

The case company people interviewed during this research, had responsibilities for areas, such as industrial design, model making departments, prototyping labs, mechanical design, marketing, sales, supply chain as well as manufacturing and quality engineering. The interviews during the Master´s thesis wanted to include the tacit knowledge of the organization, especially regarding rapid prototyping and AM technologies.

The quantitative data, related to the research partner, presented in this research has been obtained by analyzing textual data in the form of internal reports and presentations collected during the research project. In addition, quantitative as well as qualitative information has been collected by analyzing current scientific journals and industrially oriented publications, in the form of scientific papers, industry reports, AM suppliers marketing material as well as magazines, books and media observations.

Several service suppliers have been interviewed to obtain qualitative as well as quantitative information regarding state of the arts of AM processes and their economic and technical implications. In total more than 20 service bureaus located globally have been contacted, and this work includes empirical data obtained from 12 of them. This data has been use to obtain cost estimations for the different manufacturing techniques used in prototyping and manufacturing. Rapid prototyping suppliers have been contacted to position the status of the technology in the industry and study the engineering problem from a real world perspective.

The experimental part of the research has been planned and executed taking into account the repeatability of the process. The randomization of the experimental sample has been achieved by using orthogonal arrays explained in Taguchi methods. A total of 27 samples were manufactured and measured twice to calculate mean values and standard deviations of the measured variables.

The obtained quantitative data has been used mostly during the experimental part of the research, research questions have been answered by quantitative analysis of the technical and economic variables used in the experiment. At the same time, qualitative and quantitative information has been used to study the big picture of AM technologies and to put the obtained experimental results in context.

4.4. Methodology used in the Design of Experiment

4.4.1. Methodology for the economic feasibility study

The methodology used in order to research the economic feasibility of AM produced part for the assembly of products in the pre-production stage, has been focused on surveying current service bureaus specialized in rapid prototyping services and AM solutions. As mentioned earlier, the data collected from 12 service supplier has been used in this research.

The survey was structured in the form a tender which was delivered randomly by email to more than 20 service suppliers. The planned outcome of this survey was to obtain cost estimations and production capacity of the different rapid prototyping services depending upon the investment cost, manufacturing volume and the delivery time of the different manufacturing options.

The data was obtained in the form of quotations, in which the service bureaus presented their most suitable manufacturing options, cost and delivery time for producing the case geometry. After collecting this data for a period of one month, the data has been structured and presented graphically in order to show the average manufacturing cost and delivery time to produce the geometry of the case study by using temporary tooling injection molding, silicon casting and most common AM techniques used in industry.

4.4.2. Methodology for the technical feasibility study

In technical sciences, engineers and scientist try to understand complex systems by empirical experimentation. During the experiment, the relevant variables of the system are changed in order to evaluate how they affect to the output variables. One approach is to change the values of the variable as one-factor-at-a-time and evaluate the results each time. This is known as a “trial and error” method. To be successful using this method a mixture of experience, intuition and luck is required to obtain valuable data. [41]

Another approach used in academia and industry is known as Design of Experiment (DOE) [41], this methodology is an alternative to obtain data in a more structured manner. When planning a DOE, several selected design variables or input factors can be varied simultaneously in a controlled manner in order to obtain reliable, repeatable and structured data. The data can be used to model the behavior of the input factors over the performance variables or output factors of the system; this is known as the objective function of the system. [42]

A widely used approach is to make a full factorial DOE, this approach requires to test all possible combinations of variables. The disadvantage of this method is that the amount of experiments required trying out all possibilities that grow with an exponential relationship. By approaching the problem in a factorial fashion, L^V experiments are needed to test all the possible combinations, where “V” refers to the number of design variables and “L” to the control levels of the same variable.

In complex systems, where the amount of design variables and control levels are high, a factorial DOE can become very complex and time consuming to carry out and end up being unmanageable. Nevertheless, a very popular method used by experiment practitioners to simplify complex experimental setups, is to use DOE process based on Taguchi methods and orthogonal arrays [43]. The DOE performed in this Master’s Thesis has been structured and planned by using the Taguchi method and orthogonal arrays.

This DOE has used 4 design variables with 3 levels each. If a factorial DOE would have been selected, this would require 81 experimental trials in order to test every possible combination. The Taguchi method has been demonstrated to be a very powerful method to simplify and randomize the amount of experiment needed to understand complex systems. At the same time, it can solve optimization problems in mechanical engineering for machine tool processes such as milling and lathing processes [44] [45]. In the context of layer by layer manufacturing, Taguchi methods are also widely used to optimize and research AM processes, RP techniques and RT techniques such as silicone casting applications. [46] [47] [48]

4.4.2.1 Design Variables and control levels

Ongoing research focused on studying layer manufacturing methods has described the possible sources of inaccuracies and the noise factors affecting the AM process [49]. The variables used in this experiment have been selected bearing in mind that they can potentially affect to the performance of all AM systems, independently of the type of AM processes category.

The sources of inaccuracies during the AM process are machine, geometry and process dependent. Therefore, the first design variable of this DOE, takes into consideration the machine factor of the manufacturing process. In this case, a selection of commercially available machines and their best suitable material choice was selected in this experiment.

Table 3 - Design Variables of the DOE and control levels

Design Variables		Level 1	Level 2	Level 3
P1	Machine and Material	M1	M2	M3
P2	Part Orientation	Horizontal	Vertical	Diagonal
P3	Part Location	Top Left	Center	Bottom Right
P4	Digital Quality	High	Medium	Low

The other three design variables of the DOE, take into account the geometry and process dependency of the AM systems. The second and the third variable are related with the part orientation and part location over the build platform. The fourth and last variable focuses on the effect of the quality of the digital data used in the AM process. The Table 3 makes an overview of the design variables and the control levels used during this experiment.

To define the levels of the machine and material design variable (P1), three different ASTM process categories were selected: Vat Photopolimerization process, Material Jetting process and Powder Bed Fusion process. Consequently, three different commercially available machines were included in the experiment.

Table 4 shows the selected AM systems and the comparison of the technical specifications of the machine as well as the basic technology involved in the process. At the same time, a comparison of the materials' mechanical properties versus the average mechanical properties of an injection molded PC-ABS blend is displayed.

Table 4 – Design variable V1, Machines and materials technical specifications. Adapted from technical data sheets of the machine manufacturers

Machine Specifications	M1	M2	M3
Machine supplier	3D Systems	Stratasys	EOS
Machine Type	Viper SI2	Objet 500	Formiga P110
Industrial Process Category	SLA	Polyjet	SLS
ASTM Process Category	Vat Photopolimerization	Material Jetting	Powder Bed fusion
Net Build size	250x250x250	490x390x201	200x250x330
Typical Accuracy	Vertical resolution 0.0025 mm	L<50mm (20-85 µm)	N/A
	Position repeatability 0.0076 mm	L>50mm (up to 200 µm)	
Layer Thickness (Z-Axis)	N /A	30 µm	100 µm

Material Properties			Supplier Material Code		
	Test Method	**Injection molded PC - ABS**	**Accura 25 Plastic**	**ABS Like**	**PA 2200**
Tensile Strength	ASTM D638	43.3-65.6 MPa	38 MPa	55-60 MPa	N/A
	ISO 527	44.7-66.4 MPa	N/A	N/A	45 MPa
Tensile Modulus	ASTM D638	1920-2960 MPa	2690-3100 MPa	2600-3000 MPa	N/A
	ISO 527	2000-2810 MPa	N/A	N/A	1700 MPa
Elongation at Break	ASTM D638	1.5-7.4%	13-20 %	25-40%	N/A
	ISO 527	3-5.8%	N/A	N/A	20%
Flexural Strength	ASTM D790	71.4-105 MPa	55-58 MPa	65-75 MPa	N/A
	ISO 178	74.1-101 MPa	N/A	N/A	
Flexural Modulus	ASTM D790	1880-2750 MPa	1380-1660 MPa	1700-2200 MPa	N/A
	ISO 178	1990-2770 MPa	N/A	N/A	1240 MPa
Izod - Notched Impact Strength	ASTM 256	68-700 J/m	19-24 J/m	65-80 J/m	N/A
	ISO 180	9.8-67 KJ/m^2	N/A	N/A	4'4 KJ/m^2
Shore D - Hardness	ASTM D785	110-121	80	85-87	N/A
	DIN	90-124	N/A	N/A	75

The building orientation of the part over the build platform was selected as the second design variable (P2). The part was printed in three different orientations, horizontal build, vertical build and a diagonal building at an angle of 45^{o}.

Research has demonstrated that the building orientation has a significant impact over the final topology and properties of the manufactured part [10] [50]. Just by looking at the commercially available machine data sheets, it is possible to note that the suppliers report different accuracies depending upon the manufacturing axis, thus the building orientation on the build platform has an influence on the accuracy of the manufactured parts. Table 4, also displays the accuracy parameters of the machines used in this experiment.

The third design variable chosen for the DOE was the part location over the building platform of the AM machines (P3). The printing platform size between machines is different from machine to machine, thus the parts were located on the tray by using the top left corner, the center and the bottom right corner of the build platform of each machine. The location of the part over the building platform has an effect in the topology of the final produced part. The dimensional and geometrical tolerances of the AM parts produced are affected by this variable, especially in certain AM process categories where the effect of temperature gradients in the building chamber can be sources of inaccuracies. [51]

The last input variable included in this experimental approach aims to research the effect of the digital quality of the data in the AM process. The communication between the CAD and AM systems is built by using a file format called STL (Standard Tessellation Language), AM systems preprocessors have their own slicing algorithms which use STL data. This file format is the de facto standard used by CAD software to create triangular facets to approximate the topology of the digital model. The tessellated CAD model represents an approximated polygon mesh which tries to define the original geometry. This approximation is defined by the cordal error or deviation of the tessellation process. [52] [53]

Most common commercially available CAD software includes the possibility to create an STL file of the original model. In some common CAD packages this process is performed automatically without using any special tools, on the contrary more developed CAD solutions allow you to select parameters such as the deviation, error factors or the amount of triangular facets of the polygon mesh among others.

During this DOE, the quality of the digital data was evaluated by selecting three different deviations. The deviation of the STL file is defined as the maximum possible distance from the theoretical surface of CAD model to the created polygon mesh. The deviations were scaled as low, medium and high digital quality and their values were 0.1mm, 0.01mm and 0.001mm respectively.

The set of design variables chosen for this DOE aim to simulate a real manufacturing situation in which the company needs to define the most suitable combination of parameters in order to produce a part by using AM systems. Figure 9 shows a representation of a typical parameter selection process from the perspective of the manufacturing engineer.

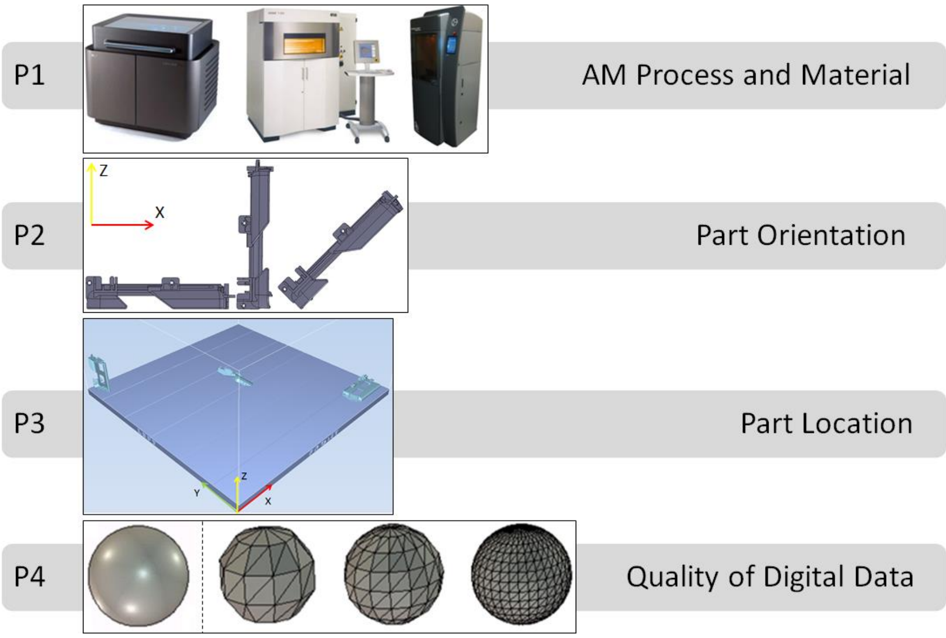


Figure 9 - The design variables for the DOE and the overview of the process steps of a typical AM process

The process can be considered as a sequential process in which the manufacturing engineer first needs to decide the most suitable AM process and the material for producing the part, second the building orientation also needs to be defined to enhance the desired final properties of the part. After this selection, the positioning of the part over the build platform is decided and finally the digital data is transferred from the machine pre-processor in order to manufacture the part.

4.4.2.2 Performance Variables and requirements

The performance variables selected in this study aimed to evaluate what are the most common trade-offs in the manufacturing of part using AM systems. The selected design variables have an overall impact over the performance variables. At the same time, the technical feasibility of AM was measured using these performance variables. Two types of performance variables were included in this DOE.

The first type of variable was related with the dimensional stability of the manufactured part, in that sense the flatness of the produced part was an influential variable to consider. At the same time, some specific distance between assembly holes of the geometry was a fundamental parameter to consider and research the technical feasibility of the AM produced parts. These two dimensional features, flatness (V1) and distance from hole to hole (V2), required being in a specific tolerance range to be suitable for the assembly of the product.

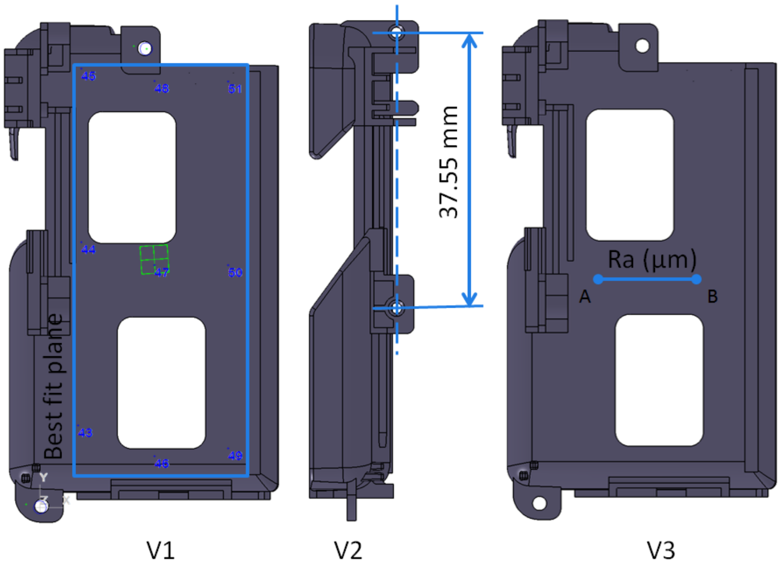


Figure 10 - The schematic view of the DOE performance variables

The third key variable selected for the experiment was the surface quality (V3) of the AM produced parts. Literature in the field has already explained that surface quality is a weak parameter in AM parts compared to conventionally manufactured parts [2]. In this DOE a specific part of the geometry surface was selected and measured in order to evaluate under which circumstances this parameter was inside tolerances. The Figure 10 shows the schematic view of the performance variables used in the DOE.

Table 5 - Performance variables and their requirements used in the DOE

	Performance Variables	Requirements	Description	Value
V1	Flatness (mm)	R1	Dimensional tolerance	0.3 mm (max)
V2	Hole to hole distance (mm)	R2	Dimensional tolerance	+/- 0.17 mm
V3	Surface roughness Ra (µm)	R3	ISO standard	N5 - 0.8 µm (max)

Table 5 makes a summary of the performance variables selected for the DOE. In addition, it shows the requirement list of the performance variables. The performance variables and their requirements were narrowed down together with the case company quality engineering department. The flatness (V1) required having a dimensional tolerance lower or equal to 0.3mm (R1), hole to hole distance (V2) required having a dimensional tolerance within the range of +/- 0.17 mm of the nominal value (R2), and finally the surface quality (V3) required to be lower or equal to Ra = 0.8 µm (R3) which is equivalent to N5 quality in the ISO standard [54]. The same requirements are commonly applied to parts which have been manufactured by silicon casting of injection molding methods.

4.4.2.3 Definition of the Taguchi Orthogonal Array

The behavior of the systems described in this DOE has been considered to be nonlinear, thus three control levels were selected per each design variable, control levels have been introduced previously in Table 3.

The interaction between the designs variables have been omitted in this DOE, this compromise was taken because of the resource implications of having a bigger sample or bigger Taguchi orthogonal array. For instance, a L18 orthogonal would have been more appropriate for the experiment but this would have implied practical difficulties in terms of managing the experimental part and having access during more time to AM systems.

The form of the finally chose general model of the DOE and the objective function of the performance variables is represented by:

$$Y_i = General\ mean + P1\ (L1, L2, L3) + P2\ (L1, L2, L3) + \ P3\ (L1, L2, L3) + P4\ (L1, L2, L3)$$

Equation 1 - The general model and objective function of the performance variables for the DOE

Where, Y_i represents the objective function per performance variable, the general mean of the performance variables is calculated by computing the total arithmetic mean of the empirical results obtained during the experiment. P1, P2, P3 and P4 refer to the design variables of the DOE and the each partial arithmetic mean values per level of the design variable is represented inside the parenthesis by L1, L2 and L3.

Each of the performance variables used in the experiment is defined by an objective function. Three performance variables were selected in the experiment, which were summarized previously in Table 5. The objective functions per performance variable are defined by Y1, objective function of the performance variable V1 Flatness, Y2 objective function of the performance variable V2 Hole to hole distance and finally, Y3 objective function of the performance variable V3. This will be explained in the following chapter by Table 7.

$$DOF(Design\ Variables) = 1 + \sum_i (\#L_i - 1) =$$
$$= \ 1 + (\#L_1 - 1) + (\#L_2 - 1) + (\#L_3 - 1) + (\#L_4 - 1)$$

Equation 2 - Degrees of freedom of the design variables and selection method of the Taguchi orthogonal array

Based on Equation 2, the Degree Of Freedom (DOF) of the design variables was calculated in order to choose a suitable Taguchi orthogonal array. Where, #L1, #L2, #L3 and #L4 refer to the number of levels of the design variables P1, P2, P3 and P4 respectively.

In this DOE, all design variables were considered symmetric and had 3 control levels each. Hence, the result after computing the Equation 2 showed that a L9 orthogonal array was suitable for structuring the experiment.

Table 6, shows the Taguchi L9 orthogonal array after substituting the levels for the real value of the design variables. The columns represent the design variables and the rows correspond to the amount of experiments needed to carry out the experiment. In the rightmost column, the part coding has been also defined for the traceability of all the printed parts.

Table 6 - Taguchi L9 Orthogonal array for the DOE

Exp.	P1 - Machine	P2 - Orientation	P3 - Part Location	P4 - Digital Quality	Part Coding
1	M1	Horizontal	Top Left	High	1HLH
2	M1	Vertical	Center	Medium	1VCM
3	M1	Diagonal (45deg)	Bottom Right	Low	1DRL
4	M2	Horizontal	Center	Low	2HCL
5	M2	Vertical	Bottom Right	High	2VRH
6	M2	Diagonal (45deg)	Top Left	Medium	2DLM
7	M3	Horizontal	Bottom Right	Medium	3HRM
8	M3	Vertical	Top Left	Low	3VLL
9	M3	Diagonal (45deg)	Center	High	3DCH

After the data acquisition, the Equation 3 is used to compute arithmetic mean values per level and performance variable, the same equation is used to illustrate and example to calculate the value P2(L2) of the objective function, this is described by the mathematical expression:

$$P2(L2) = \frac{1}{n}\sum_{i}^{n} P2\ in\ L2\ = \frac{1VCM + 2VRH + 3VLL}{3}$$

Equation 3 - Formula to calculate the partial mean values per level and performance variable

In this example, the value P2(L2) of the of the Equation 1 is calculated by making the arithmetic mean of the experimental values in which the performance variable P2, part orientation, is in level L2, vertical position. The rest of the values are calculated following the same procedure.

4.4.2.4 Performance variables measurement and the experimental setup

In order to assure the repeatability of the measurement process and consequently the DOE, each experiment was repeated three times. Thus, each part or experiment was manufactured three times in three different manufacturing processes for each machine. The result was that after completing the manufacturing of all the experimental combination described in the Taguchi Table 6, a total of three identical copies per each experiment were manufactured. In total 27 samples were produced and 54 measurements were taken, 6 measurements per each part or experiment.

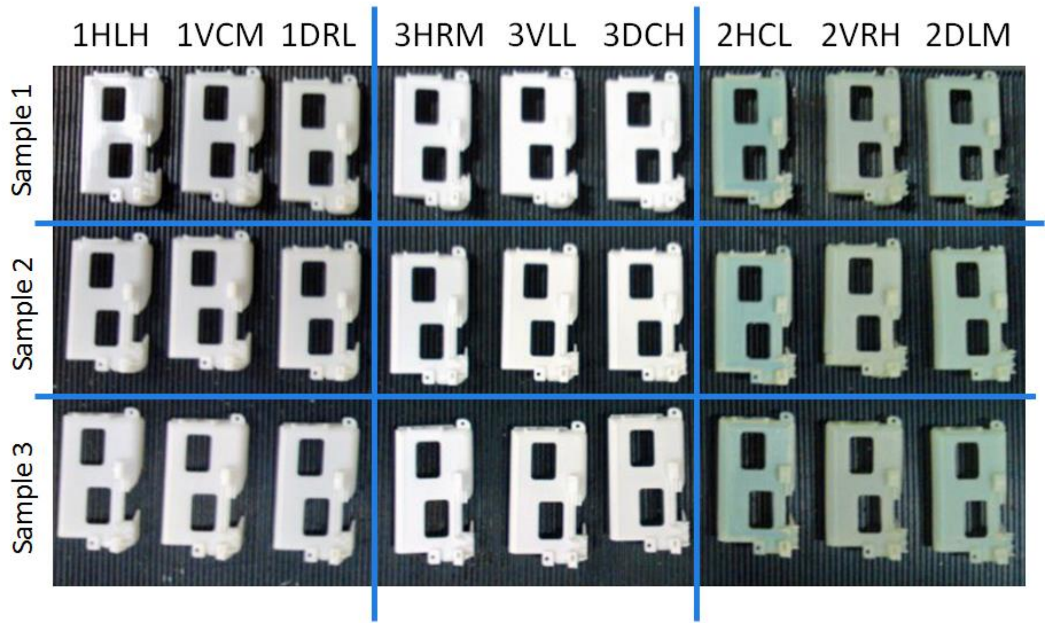


Figure 11 - Picture of the parts after the measuring process

Figure 11 shows the picture of all the manufactured parts. Moreover, in the top side of the picture the part code is shown, the rows correspond to the three different manufactured samples. Each of the produced part had embossed digitally the part code in order to assure the traceability of the part during the whole experiment.

The measurement of the performance variables V1 and V2 was performed by using an image based 3D laser coordinate measurement system. At the same time, the measurement of the performance variable V3 was obtain by using a profilometer or a roughness measuring instrument. Both measuring processes were planned and executed systematically taking into account the repeatability of the process. Regarding the environmental conditions, temperature was constant at 22°C and relative humidity at 35% and they were stable during the whole measuring process. For the performance variables V1 and V2, the same operator did all measurements using the same fixtures and guides. In the case of variable V3, a different instrument was used although the measurement process followed the same protocol.

As an example of the AM manufacturing process, the Figure 12 displays the screen caption of the part orientation and part location before the manufacturing process using M2 machine. The top left part has been oriented diagonally 45^{o} over the Y axis, the part in the center has been oriented horizontally and finally the part in the bottom right has been oriented vertically tilted 90^{o} over the Y axis. These experiments were related to experiment number 6, 5 and 4 of the Taguchi L9 orthogonal array.

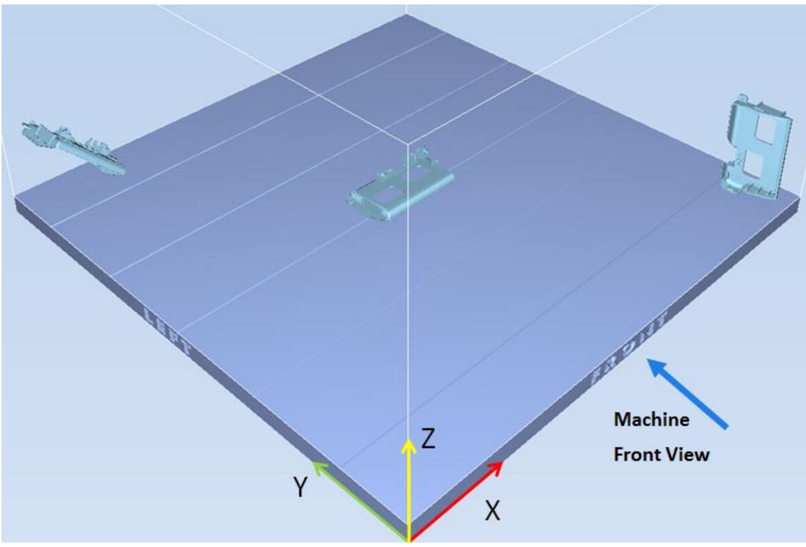


Figure 12 - Screen caption of the M2 machine user interface, it shows the part location and orientation on the build platform before the manufacturing process.

This process was identically repeated for the rest of the machines based on the organization obtained in the Taguchi L9 orthogonal array. For the manufacturing of the samples corresponding to M3, a service bureau was used. The samples related to M1 and M2 were manufactured by using internal resources of the company. During the manufacturing process random parts were also included around the build in order to simulate the noise of a real manufacturing process.

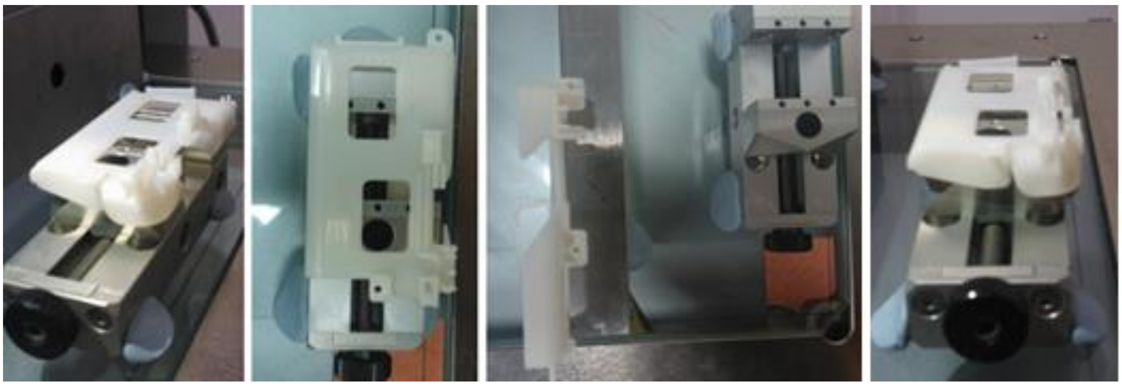


Figure 13 - Pictures of the measurement setup for the variables V1 and V2

The Figure 13 shows some pictures of the setup used during the measurement process of V1 and V2. The same set of fixtures and guides was used during the whole measurement process. One set of measurements was performed by the same operator during one day and the other set of measurement was taken by the same operator during the following day.

The Figure 14 shows the setup used to measure performance variable V3. This variable required a different equipment to be measured, in this case the same operator did all the measurement using the setup of fixtures and guides depicted in the pictures. One set of measurements was performed in one day and repeated the following day.

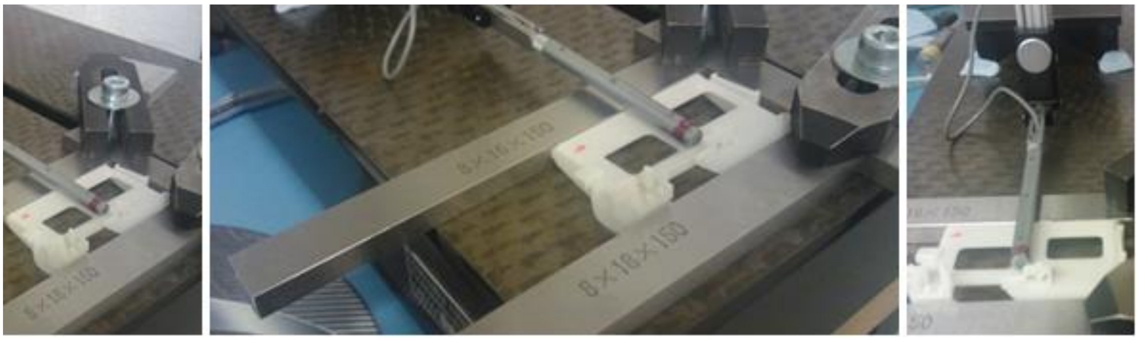


Figure 14 - Pictures of the measurement setup for the performance variables V3

For the calculation of flatness in performance variable V1, the ISO standard for geometrical product specifications was applied [55]. This standard defines the flatness tolerance as a zone that is delimited by two parallel planes with their radial distance equal to a certain distance. In other words, all the points of the manufactured plane need to be inside the perpendicular distance delimited by two different planes. The flatness requirement has been already introduced in Table 5 and during the experiment the calculation of the flatness value was automatically performed by the measurement equipment used in this study.

In the case of V2, hole to hole distance. These results were obtained by measuring directly the distance from the center of the hole to the center of the hole. As an assembly point, this value needed to fulfill the requirement specify by the case company. Based on image recognition algorithms, the measurement coordinate system determined automatically the approximate centers of the holes and the distance was determined based on this calculations.

Variable V3, surface roughness was obtained by calculating the value Ra of the chosen surface. The ISO standard [54], define Ra as the arithmetic average of the absolute values of the collected roughness data points. It is the most widely used parameter to define the dimensional roughness of produced parts. [9]

4.4.2.5 The decision analysis

During this DOE, a total of three performance variables were selected in order to measure the technical feasibility of AM to produce structural plastic parts in the assembly of pre-production series. This implied that the optimal solutions needed to fulfill more than one criterion at the same time. Hence, the optimal solution intrinsically implied trade-offs between conflicting objectives of the objective functions. This problem can be defined as multi-objective optimization. In practice this implies that while making any of the performance variables of the objective function better-off possibility will imply that the other performance variables will be worse-off. Therefore, a compromise solution must be taken in any case.

The methodology chosen to make the decision analysis systematically required computing all possible alternatives of the objective functions. Therefore, 81 possible objective functions were computed. After computing the objective functions using Equation 1, for each performance variable (Y1, Y2 and Y3), the results per performance variables was compared versus the requirement of the system by using a requirement filter.

The result of this filter was a finite set of design solutions able to fulfill all the requirements imposed to the performance variables. The requirements of the system have been defined previously in Table 5. The following step was to define the Pareto front or the set of choices that were Pareto efficient. Pareto efficiency is defined as a state of allocation of resources in which is not feasible to make any individual better-off without making at least one individual worse-off. [56]

To define the set of solution in the Pareto front, the dominancy between solutions was studied by evaluating the objectives of the performance variables described in Table 7. A pairwise comparison method was used to find the dominated and non-dominated solutions. At the same time, the weak or strong dominancy relationship between solutions was defined. Based on set-theory [56], all Pareto optimal solutions need to be non-dominated solutions.

Table 7 - Design optimization and objectives function of the performance variables

Objective Function	Design Optimization	Units
Y1	Minimize { V1 – Flatness}	mm
Y2	Minimize difference to nominal value { V2 – Hole to hole}	mm
Y3	Minimize { V3 – Surface roughness (Ra)}	µm

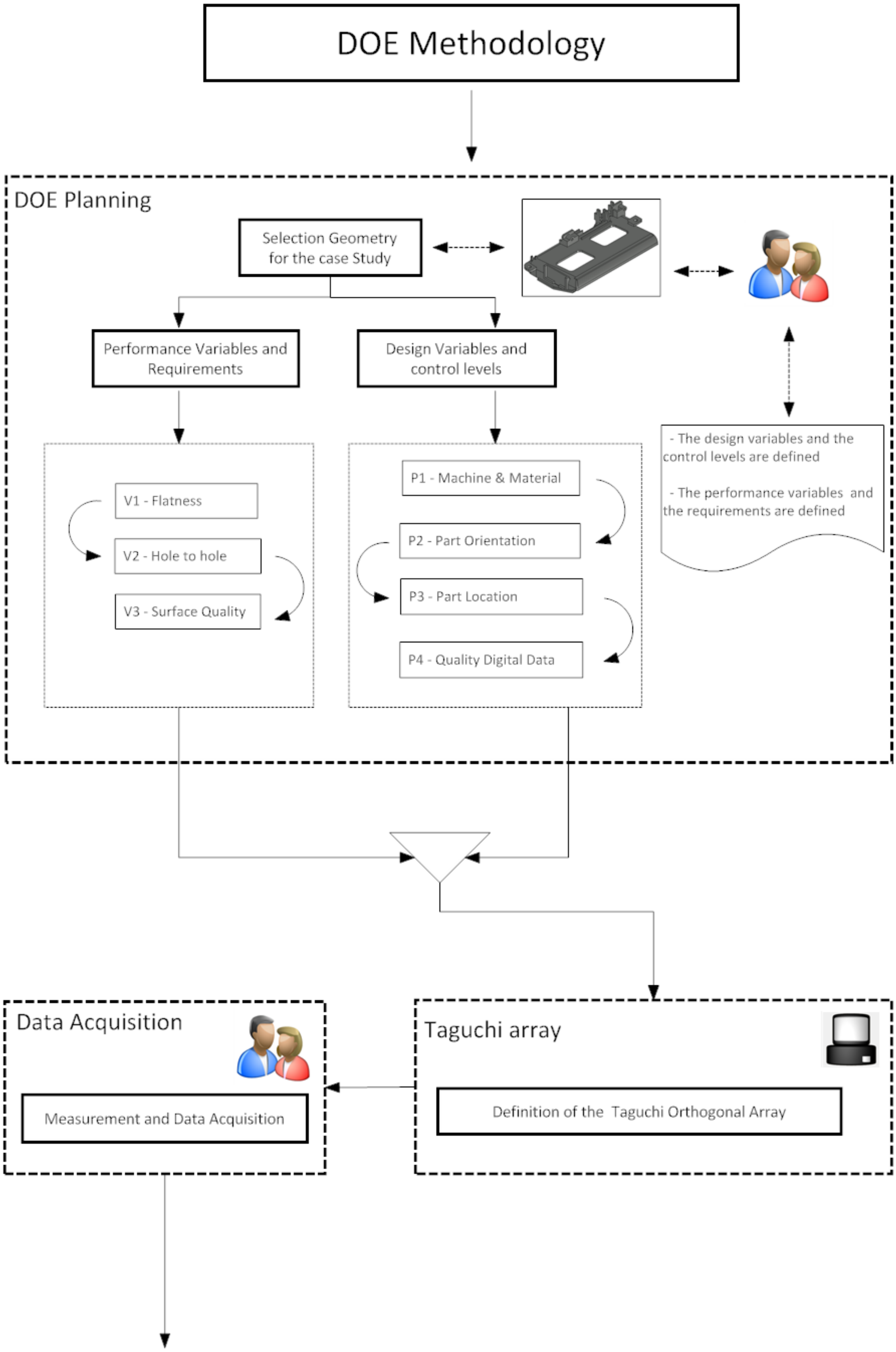
The following step, after defining the Pareto front, involved the client in the decision making. By doing so, the importance of the performance variable was scored by using the Analytic Hierarchy Process (AHP). AHP is a structured technique used in industry to organize and analyze complex decision in which multiple variables play a role in the decision making process [57].

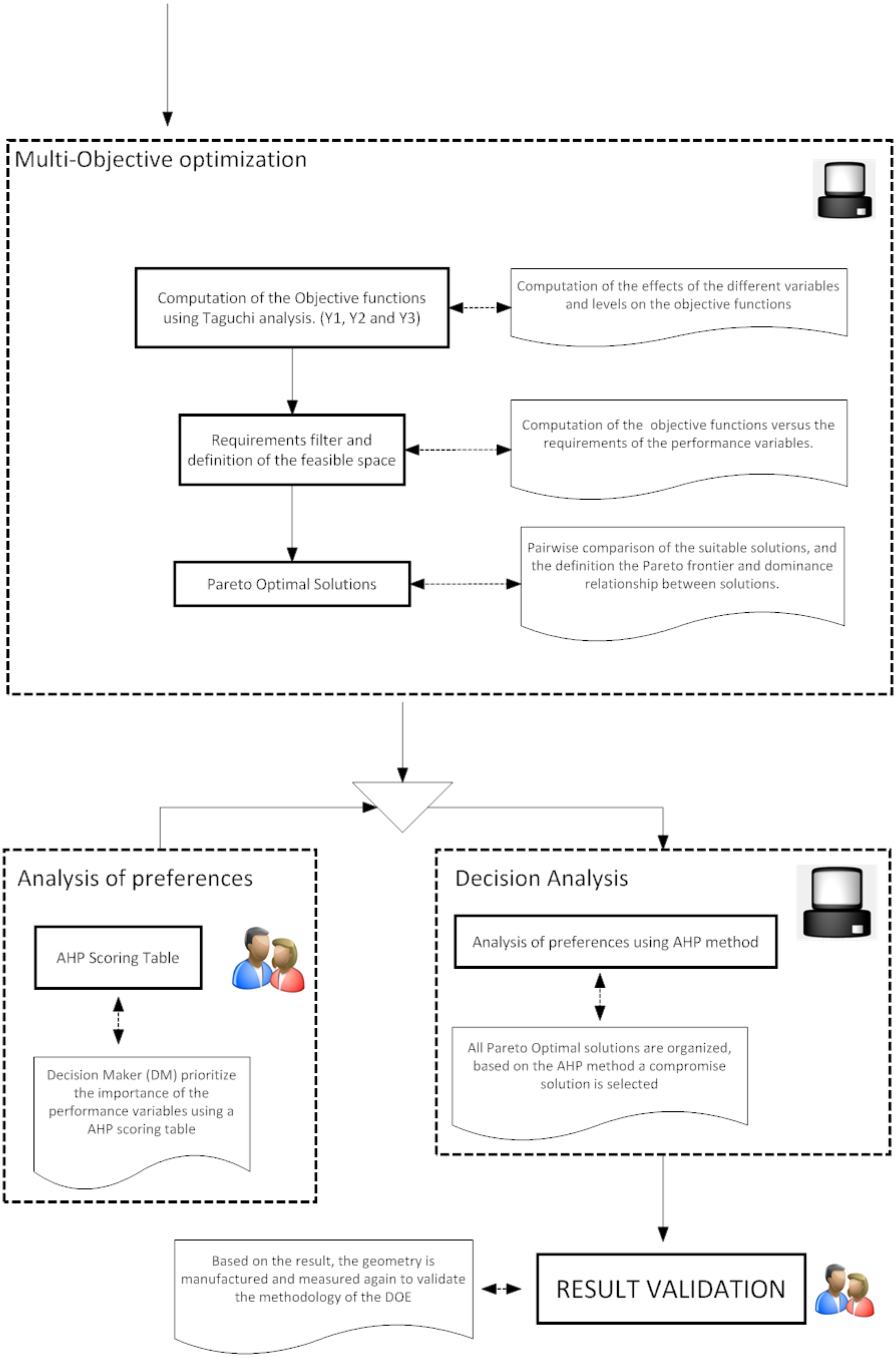
After obtaining the preferences of the client, the best suitable compromise was selected based on the result obtained by AHP method and the Pareto efficient solutions.

The following step was to manufacture the selected option in order to validate the methodology of the experiment. The manufactured part was measured again following a similar measuring procedure. The measuring process involved to repeat three times the measurements of the performance variables selected in this DOE, after the measuring process the arithmetic mean was calculated.

Finally, a 3D scanning of the manufactured part was included as a part of the result validation and a digital Part–CAD comparison was performed in order to calculate the real dimensional deviations from the AM part versus the theoretical model.

4.4.2.6 Process diagram of the methodology used during the DOE




Multi-Objective optimization
Computation of the Objective functions using Taguchi analysis. (Y1, Y2 and Y3)
Computation of the effects of the different variables and levels on the objective functions
Requirements filter and definition of the feasible space
Computation of the objective functions versus the requirements of the performance variables.
Pareto Optimal Solutions
Pairwise comparison of the suitable solutions, and the definition the Pareto frontier and dominance relationship between solutions.
Analysis of preferences
AHP Scoring Table
Decision Maker (DM) prioritize the importance of the performance variables using a AHP scoring table
Decision Analysis
Analysis of preferences using AHP method
All Pareto Optimal solutions are organized, based on the AHP method a compromise solution is selected
Based on the result, the geometry is manufactured and measured again to validate the methodology of the DOE
RESULT VALIDATION

5. Results

5.1. AM parts for pre-production series, economic feasibility study

As mentioned in previous chapter, the quantitative data obtained in order to evaluate the economic feasibility of AM technology has been obtained by surveying a total of 12 service suppliers and rapid prototyping manufacturers located globally. The economic feasibility of AM as a production system has been studied by calculating the unit cost of the produced part and delivery time as function of the produced volume.

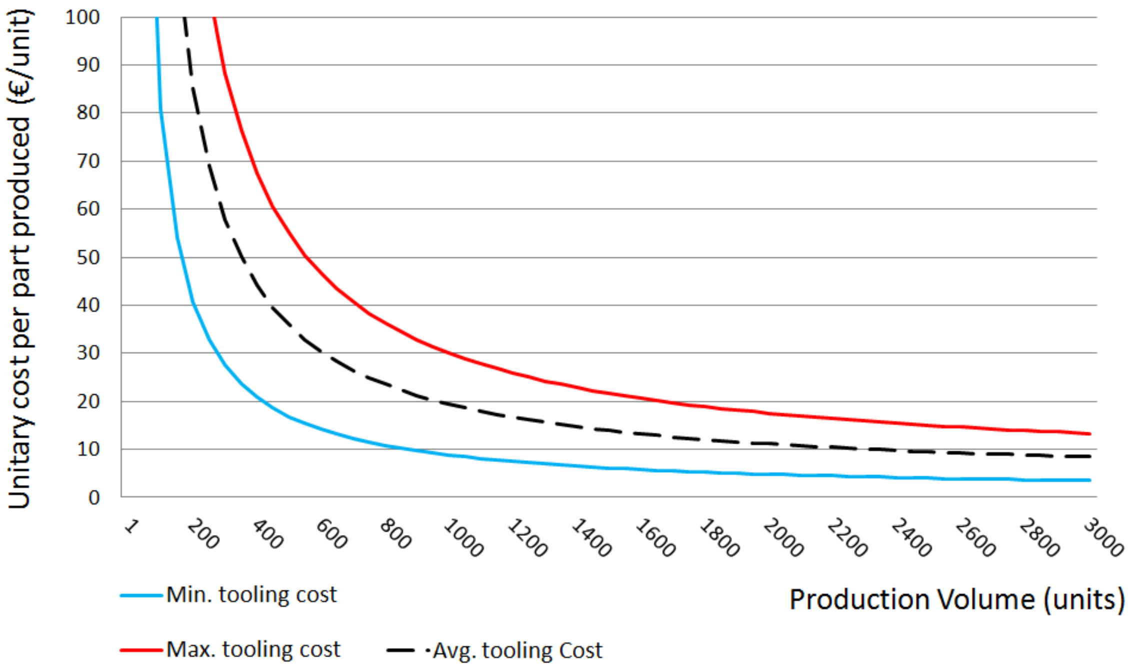


Figure 15 - Temporary tooling cost, adapted from the information given by the case company

Figure 15 shows the typical investment cost in temporary tooling to produce structural plastic parts by injection molding inside the case company. The cost represented in this figure displays current production cost during the PDP of the case company. Hence, the results shown in this figure are directly linked to the cost of producing plastic part for assembly Alpha-Prototypes in pre-production stage. The geometrical properties of the parts represented in this figure are within the dimension of 120mm X 100mm X 25mm.

The curve of figure 15 has been computed using the model described by the equation 4, and the points have been calculated by increments of 200 units in the horizontal axis. **Error! eference source not found.** shows the tooling investment cost and unit production cost of plastic parts according to the given geometry specifications. The table displays the minimum, maximum and mean cost values for these two parameters.

Table 8 - Typical investment cost to produce plastic parts using temporary tooling and injection molding, information adapted from the case company

Tool investment parameters	Minimum	Mean	Maximum
$T.P_{cost}$ - Tooling Investment Cost	8,000 €	16,500 €	25,000 €
$P.P_{cost}$ - Production cost per part	0.80 €/u	2.90 €/u	5.00 €/u

The calculation model of the tool investment cost is described by the Equation 4, where $P.U_{cost}$ represents the unitary cost per part produced , $T.P_{cost}$ is the tool production cost or the tool investment cost, $P.P_{cost}$ is the cost per part produced and finally P.V represents the production volume.

$$P.U_{cost} = [T.P_{cost} \times (P.P_{cost} \times P.V)] / P.V$$

Equation 4 - Calculation model of the unitary cost per part produced in injection molding

Based on empirical data gathered during the survey, the same model has been used to calculate the production cost of the geometry in this case study. Table 9 below shows the mean, maximum and minimum cost for producing the geometry of the case study. The tooling investment and the production cost per part parameters are also displayed in this same table.

Table 9 - Tool investment cost and production cost per part to produce the geometry of the case study by using temporary tooling and injection molding, information adapted from the industry survey

Tool investment parameters	Minimum	Mean	Maximum
$T.P_{cost}$ - Tooling Investment Cost	3,500 €	7,108.83 €	20,800 €
$P.P_{cost}$ - Production cost per part	0.56 €/u	1.15 €/u	4.00 €/u

Table 10 - Delivery time in days for producing the case study geometry depending upon the production technique, information adapted from the industry survey

Production technique	Production Volume		
	1 unit	**100 units**	**200 units**
	Delivery time in days (mean value)		
Injection Molding – Temporary tooling	26.4	27	27.5
Vacuum Casting	6	10.5	14.7
Selective Laser Sintering (SLS)	4.5	8	11
Stereolithography (SLA)	4.33	7.7	10.3

Table 10 shows the delivery time, in working days, depending upon the production volume and manufacturing technique used in the process. The delivery time for obtaining a single injection molded part, vacuum cast part, SLS part or SLA part is 26.4 days, 6 days, 4.50 days and 4.33 days respectively. The lead time in days for 100 units and 200 units can be also seen in this same table.

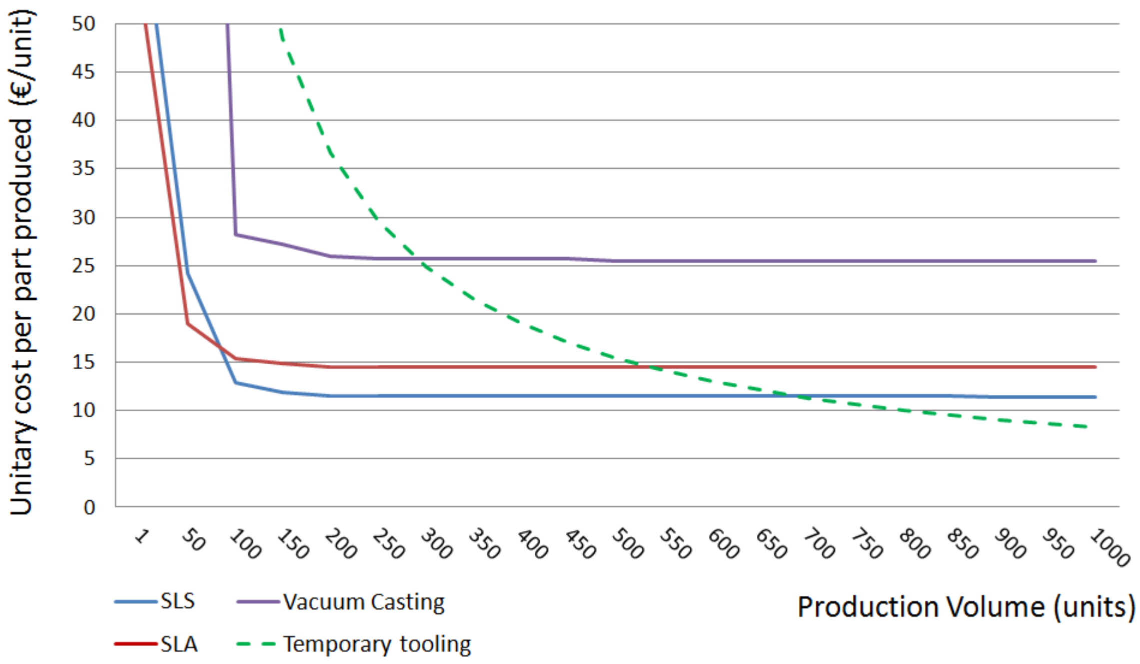


Figure 16 – Unit cost per part as a function of the produced volume, information adapted from the industry survey

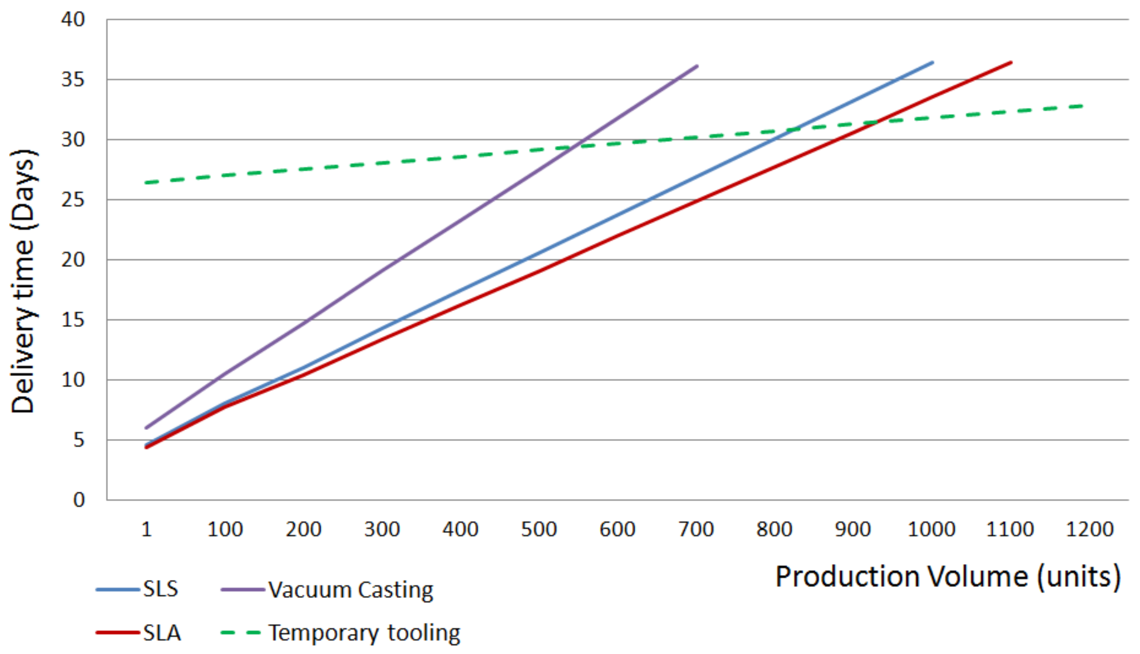


Figure 17 - Delivery time as a function of the produced volume, information adapted from the industry survey

The graphical representations of the results obtained during the industry survey are displayed in Figure 16 and Figure 17. The values represented show the unit production cost of plastic parts, vertical axis, as a function of the production volume, horizontal axis, and the delivery time in working days depending upon the production volume.

The production techniques displayed in Figure 16 and Figure 17 are injection molding using temporary tooling represented by the green dash line, vacuum casting represented by the purple line, Selective Laser Sintering (SLS) process represented by the blue line and finally

Stereolithography (SLA) process. SLA and SLS industrial process categories have been included in the DOE and they correspond to M1 and M3 machines respectively.

Figure 16 shows that the breakeven point for the production cost of vacuum cast parts, SLA parts and SLS parts versus injection molded parts are located at 300 units, 550 units and 700 units respectively. Figure 17 displays the breakeven point for the delivery time of vacuum cast parts, SLS parts and SLA parts versus injection molded parts, which is located at 550 units, 820 units and 930 units respectively.

Both graphics displayed in Figure 16 and 17 have been computed by using linear interpolations and extrapolations of the data obtained from the industry survey. The points of the graphic have been computed using increments of 200 units in the horizontal axis and increments of 5 units in the vertical axis.

Table 11 - Summary of production cost and delivery time cross even points versus injection molding manufacturing

Production technique	Production Cost (AM breakeven point versus Injection Molding)		Delivery time (AM breakeven point versus Injection Molding)	
	Units	€/unit	Units	Days
Vacuum Casting	300	26	550	29
Selective Laser Sintering (SLS)	550	12	820	31
Stereolithography (SLA)	700	14	930	32

A summary of the production cost breakeven point and delivery time breakeven point versus injection molding manufacturing is displayed in Table 11. This table shows the unit cost and the production volume depending upon the production technique. At the same time, it displays the lead time and production volume for the different production techniques.

5.2. AM parts for pre-production series, technical feasibility study

Table 12 displays the mean values per experiments and per performance variable after the measurement process of the performance variables. At the bottom of each column, the general mean per performance variable is also calculated. All the measurements of the experiment are displayed in Appendix A1. These tables include all the measurements of the 27 samples as well as the mean values per experiment.

Table 12 - Data acquisition and measurements results, total mean per performance variable and mean per experiment

Measurement results of the performance variables				
Exp.	**Coding**	**V1 - Flatness**	**V2 – Hole to hole**	**V2 – Surface Quality**
1	1HLH	0.138	37.620	3.338
2	1VCM	0.098	37.521	0.436
3	1DRL	0.115	37.618	1.267
4	2HCL	0.422	37.611	1.715
5	2VRH	0.553	37.391	3.387
6	2DLM	0.353	37.735	2.482
7	3HRM	0.185	37.698	6.757
8	3VLL	0.062	37.595	5.837
9	3DCH	0.101	37.699	6.340
General Mean		0.225	37.610	3.506

Table 13 – Computation of the objective function result using Taguchi analysis, the optimal solutions in green per performance variable without considering the requirements of the system

Computation of the objective functions					
		Y1	**Y2**	**Y3**	
		V1 (mm)	V2 (mm)	V3 (μm)	Optimal solution per Performance Variable
P1	L1 – M1 (SLA)	-0.108	-0.023	-1.826	L1(V3), L2(V2), L3(V1)
	L2 – M2 (Polyjet)	0.218	-0.031	-0.979	
	L3 – M3 (SLS)	-0.109	0.054	2.805	
P2	L1 – Horizontal	0.023	0.033	0.430	L2(V2-V3), L3(V1)
	L2 – Vertical	0.012	-0.107	-0.287	
	L3 – Diagonal	-0.036	0.074	-0.144	
P3	L1 – T. Left	-0.041	0.040	0.379	L1(V1-V2), L2(V3)
	L2 – Center	-0.018	0.001	-0.676	
	L3 – B. Right	0.059	-0.041	0.297	
P4	L1 – High	0.039	-0.040	0.849	L2 (V2), L3(V1-V3)
	L2 – Medium	-0.013	0.042	-0.282	
	L3 – Low	-0.026	-0.002	-0.567	
	Total Mean (DOE)	0.225	37.61	3.506	
	Optimal result (DOE)	0.014	37.554	0.150	

The Table 13 displayed the computation of all combinations of the objective functions using Taguchi analysis. The objective function was described previously in Equation 1 in which, Y1, Y2 and Y3 represent the computation of the objective function for the performance variable V1 Flatness, V2 Hole to hole distance and V3 Surface Roughness respectively.

In addition, P1, P2, P3 and P4 are the design variables chosen for the DOE, Machine and material, Part Orientation, Part location and Digital Quality respectively. The design variables have been already introduced during the previous chapters and summarized in the Table 3.

The bottom row of the Table 13 displays the optimal result per performance variable without taking into account the requirements of the system. At the same time the values for the optimal levels are marked in green. In the rightmost column the combination the optimal solution per performance variable is represented in which it is possible to see that there is no single solution that satisfies equally the objectives of performance variables.

Based on the result of the objective functions the mean values of the performance variable were computed depending upon the design variables and control levels. The following Figure 18, Figure 19 and Figure 20 compute these results per performance variable V1 Flatness, V2 Hole to hole distance and V3 Surface Roughness.

In addition, the mean values have been represented in green and the requirements of the system are displayed in each graphic. In the case of Y1, the objective is to minimize the value, for Y2 the objective is to minimize the difference between the nominal value of the CAD model and the manufactured part and finally the objective in Y3 is to minimize the surface roughness.

These graphical representations in Figure 18, 19 and 20 have been used to evaluate the trade-offs of the design variables versus the performance variables in the manufacturing of AM parts and research the effect of the machine and the process parameters of the experiment can be visualized.

Performance Variable V1 - Flatness

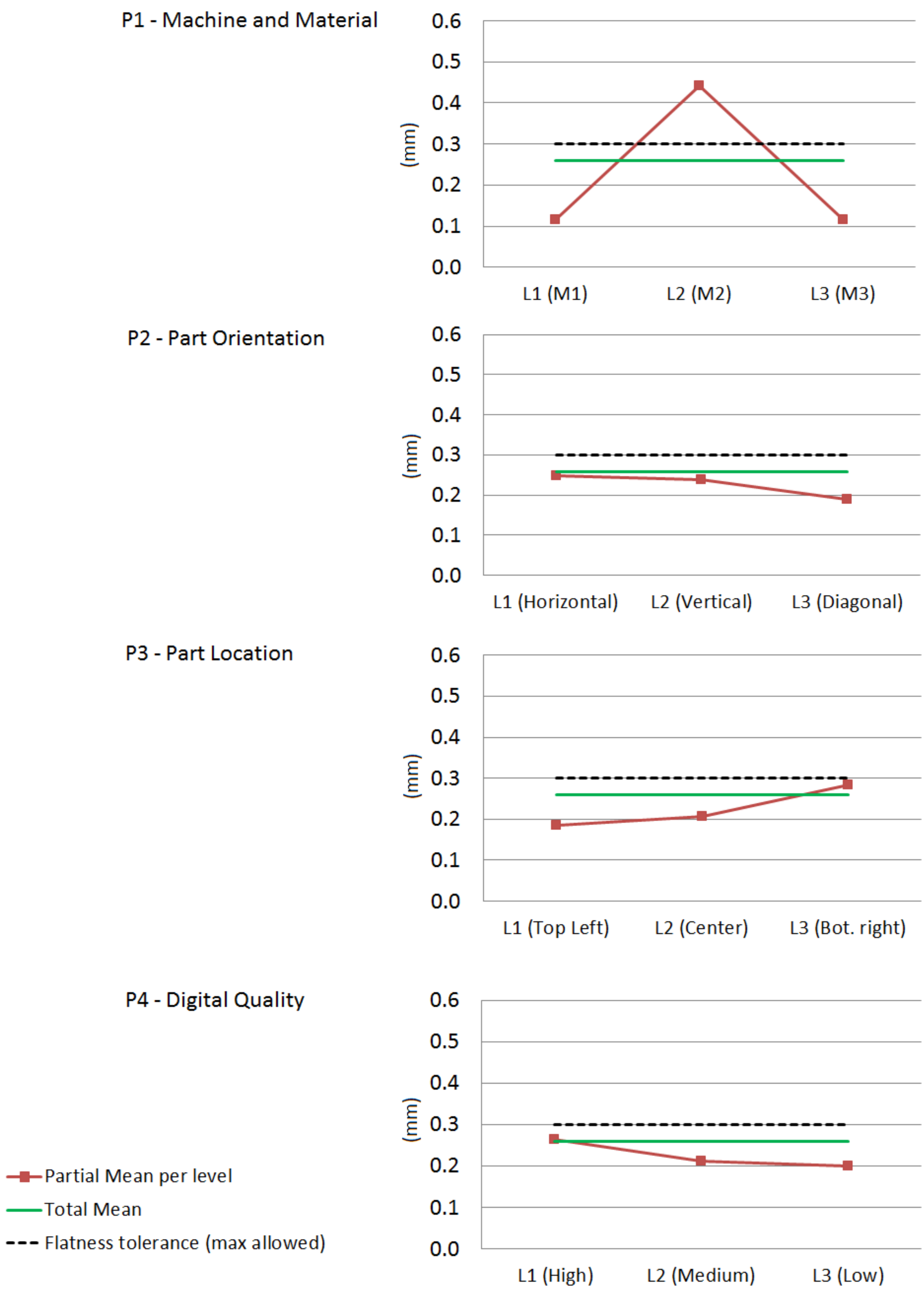


Figure 18 - Mean results of performance variable V1 - Flatness, depending upon the design variables and their control levels

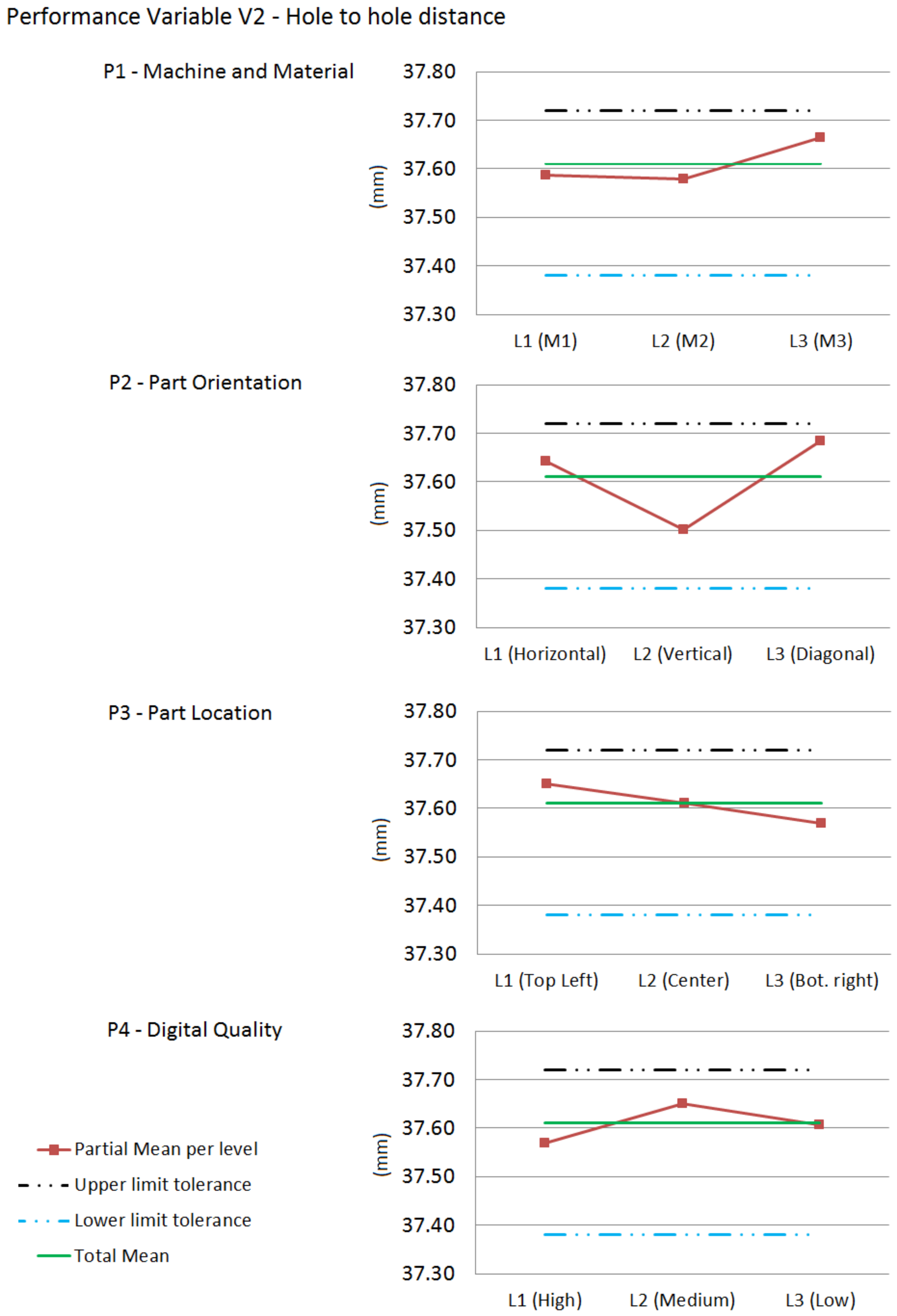


Figure 19 - Mean results of performance variable V2 - hole to hole distance, depending upon the design variables and their control levels

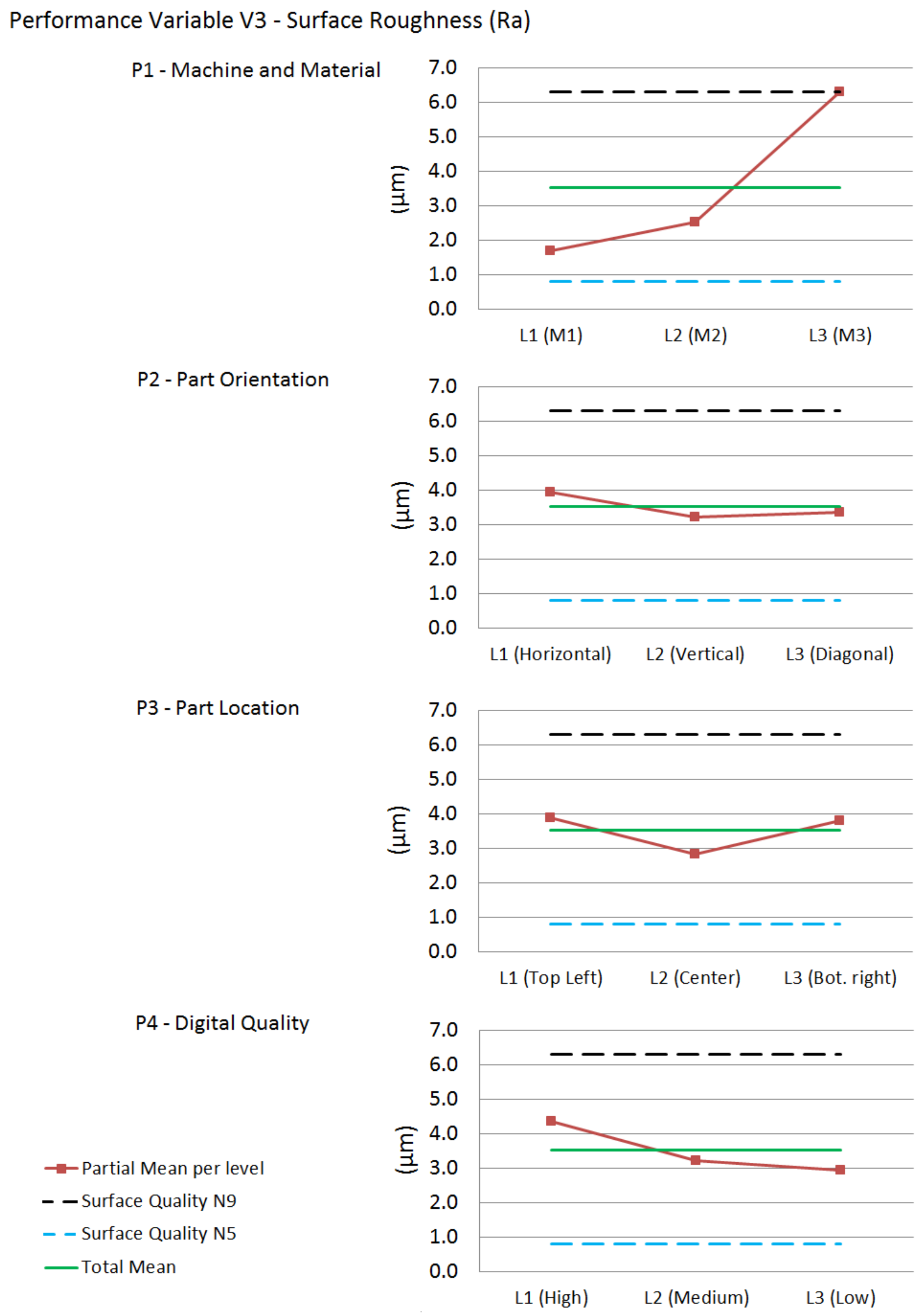


Figure 20 - Mean results of performance variable V3 - Surface roughness, depending upon the design variables and their control levels

After the computation of the objective functions in Table 13, the following Table 14 shows the feasible space of solutions. These four solutions have been obtained after applying the requirement filter described in Table 5. In addition, in the rightmost column the final model result per objective function is also computed.

Table 14 – Result after the requirement filter. Possible design variables solutions before the definition of the feasible space

Solution 1						
	P1	**P2**	**P3**	**P4**	**Total Mean (DOE)**	**Model Result (DOE)**
	L1	L2	L2	L2		
Y1	-0.108	0.012	-0.018	-0.013	0.225	0.098
Y2	-0.023	-0.107	0.001	0.042	37.610	37.522
Y3	-1.826	-0.287	-0.676	-0.282	3.506	0.436
Solution 2						
	P1	**P2**	**P3**	**P4**	**Total Mean (DOE)**	**Model Result (DOE)**
	L1	L2	L2	L3		
Y1	-0.108	0.012	-0.018	-0.026	0.225	0.085
Y2	-0.023	-0.107	0.001	-0.002	37.610	37.478
Y3	-1.826	-0.287	-0.676	-0.567	3.506	0.150
Solution 3						
	P1	**P2**	**P3**	**P4**	**Total Mean (DOE)**	**Model Result (DOE)**
	L1	L3	L2	L2		
Y1	-0.108	-0.036	-0.018	-0.013	0.225	0.050
Y2	-0.023	0.074	0.001	0.042	37.610	37.703
Y3	-1.826	-0.144	-0.676	-0.282	3.506	0.579
Solution 4						
	P1	**P2**	**P3**	**P4**	**Total Mean (DOE)**	**Model Result (DOE)**
	L1	L3	L2	L3		
Y1	-0.108	-0.036	-0.018	-0.026	0.225	0.037
Y2	-0.023	0.074	0.001	-0.002	37.610	37.660
Y3	-1.826	-0.144	-0.676	-0.567	3.506	0.294

All the solutions in the table above are feasible solutions to manufacture the geometry of the case study and fulfill the requirements imposed to the performance variables. However, this fact does not imply that all these solutions are Pareto optimal. To be a Pareto optimal solution, the solution must be a non-dominated solution [56]. Table 15 shows the matrix view of a pairwise comparison algorithm in order to describe the dominancy, non-dominancy and weak-dominances between solutions.

In order to perform the multi-objective optimization, the objectives of the performance variables were taken into account, the objectives of the systems were described previously in Table 7.

In practice, all the solutions of the feasible space are compared in which the numerical value per performance variable has to be also compared one against the other. The best solution per performance variable scores one based on the objective imposed, and finally the scores need to be accumulated to establish dominancy relationships.

Table 15 - Matrix view of the solution dominance relationship using a pairwise comparison between solutions

Solution Dominance Pairwise comparison					
Objective Function	**Solution 1**	**Logic**	**Solution 2**	**Score 1**	**Score 2**
Y1	0.098	>	0.085	0	1
Y2	37.522	<	37.478	1	0
Y3	0.436	>	0.150	0	1
			Total Score 1 vs. 2	1	2
Objective Function	**Solution 1**	**Logic**	**Solution 3**	**Score 1**	**Score 3**
Y1	0.098	>	0.050	0	1
Y2	37.522	<	37.703	1	0
Y3	0.436	<	0.579	1	0
			Total Score 1 vs. 3	2	1
Objective Function	**Solution 1**	**Logic**	**Solution 4**	**Score 1**	**Score 4**
Y1	0.098	>	0.037	0	1
Y2	37.522	<	37.660	1	0
Y3	0.436	>	0.294	0	1
			Total Score 1 vs. 4	1	2
Objective Function	**Solution 2**	**Logic**	**Solution 3**	**Score 2**	**Score 3**
Y1	0.085	>	0.050	0	1
Y2	37.478	<	37.703	1	0
Y3	0.150	<	0.579	1	0
			Total Score 2 vs. 3	2	1
Objective Function	**Solution 2**	**Logic**	**Solution 4**	**Score 2**	**Score 4**
Y1	0.085	>	0.037	0	1
Y2	37.478	<	37.660	1	0
Y3	0.150	<	0.294	1	0
			Total Score 2 vs. 4	2	1
Objective Function	**Solution 3**	**Logic**	**Solution 4**	**Score 3**	**Score 4**
Y1	0.050	>	0.037	0	1
Y2	37.703	>	37.660	0	1
Y3	0.579	>	0.294	0	1
			Total Score 3 vs. 4	0	3

The results in Table 15 demonstrate that the solutions of the Pareto front are defined by solutions 1, 2 and 4. Solution 3 is not a Pareto optimal because it is dominated by the solution 4. At the same time, there is a weak dominancy of solution 2 and 4, versus the solution 1. In addition, solution 2 weakly dominates solution 4. Nevertheless, each Pareto optimal solution represents a feasible compromise among the design objectives of the performance variables.

The Pareto front has been defined by Solution 1, Solution 2 and Solution 4. Solution 1 implies to manufacture the geometry of the case study by M1, part orientation is vertical, part location is central and digital quality is medium. Solution 2 implies to manufacture the part by M1, part orientation is vertical, part location is central and digital quality is low. Finally, Solution 4 implies to manufacture the part by M1, part orientation is vertical, part location is central and digital quality is low.

Table 16 - Total score matrix of the pairwise comparison between Pareto front solutions

Total Score matrix for the Pareto front solutions			
	Solution 1	**Solution 2**	**Solution 4**
V1	0	1	3
V2	3	2	1
V3	1	3	2
Sum	4	6	6
Design Objectives per solution	V2 – V3 – V1	V3 – V2 – V1	V1 – V3 – V2

Table 16 shows the total score of the Pareto front solutions after the pairwise comparison. Moreover, it is possible to see the prioritization of the design objectives depending upon which solution is chosen. This is represented in the bottom row of each solution column.

The following step involved the case company in the decision process, as mentioned the decision was based in the AHP scoring matrix in which the analysis of preferences of the client is evaluated in order to define the relevancy and importance of the performance variable in a pairwise manner. The used criteria for the AHP scoring table are shown in Appendix A2.

After computing the values obtained from AHP scoring methods with the case company, the analysis of preferences between performance variables was studied and the result is given in Figure 21.

The result after AHP concluded that V1 was the most important variable with 44% of the score, after that V3 is chosen with 39% of the score and finally the V2 with 17% has the lowest score. The analysis of the client preferences prioritized the selection of V1 – V3 – V2. Based on this result, solution 4 of the Pareto front has been selected as the most suitable option to manufacture the part among the studied solutions.

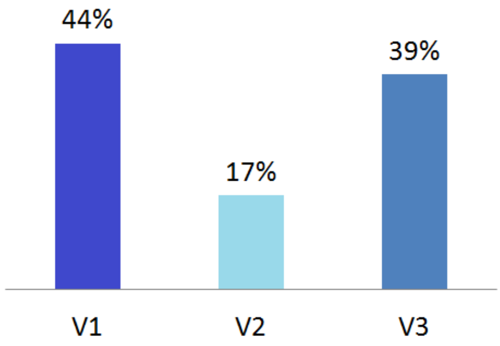


Figure 21 – Analysis of preferences of the performance variables based on client input

Validation of the result is presented in Table 17, the result obtained after measuring the part using solution 4 shows that the values of the performance variables are inside requirements, V1 flatness was 1.171 mm, V2 was 37.697mm and surface quality V3 was N5. All the set of measurement taken form the final manufactured part is depicted in Appendix A1.

Table 17 - Mean values of the final manufactured part, result validation using solution 4

Result Validation			
	V1	**V2**	**V3**
Solution 4	1.171 mm	37.697 mm	0.796 µm

The final step of the DOE included a CAD - Part comparison using the digitalized cloud point of the final manufactured part. The Figure 22, in the rightmost side shows the CAD model of the case geometry, the figure in the middle shows the tessellated point cloud data of the final manufactured part and, finally in the rightmost side of the figure, the positioning of the scanned geometry on the CAD model is performed.

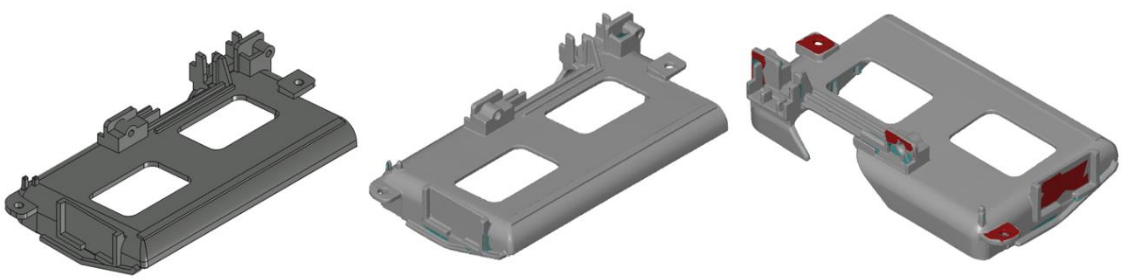


Figure 22 - CAD - Part comparison, digital scan and CAD positioning strategy

The planes in red are the most relevant interface points of the geometry on the main assembly of the product. These planes have been selected to position and constrain the scanned data on the CAD model. The deviations are calculated depending upon these geometrical assembly planes and comparing the scanned data of the manufactured part with the theoretical CAD model.

Figure 23 shows the deviation values in millimeters from the manufactured part versus the nominal CAD geometry. The values in negative indicate points of the manufactured part that are below the CAD model, the values in positive indicate points of the manufactured part that are above of the CAD model.

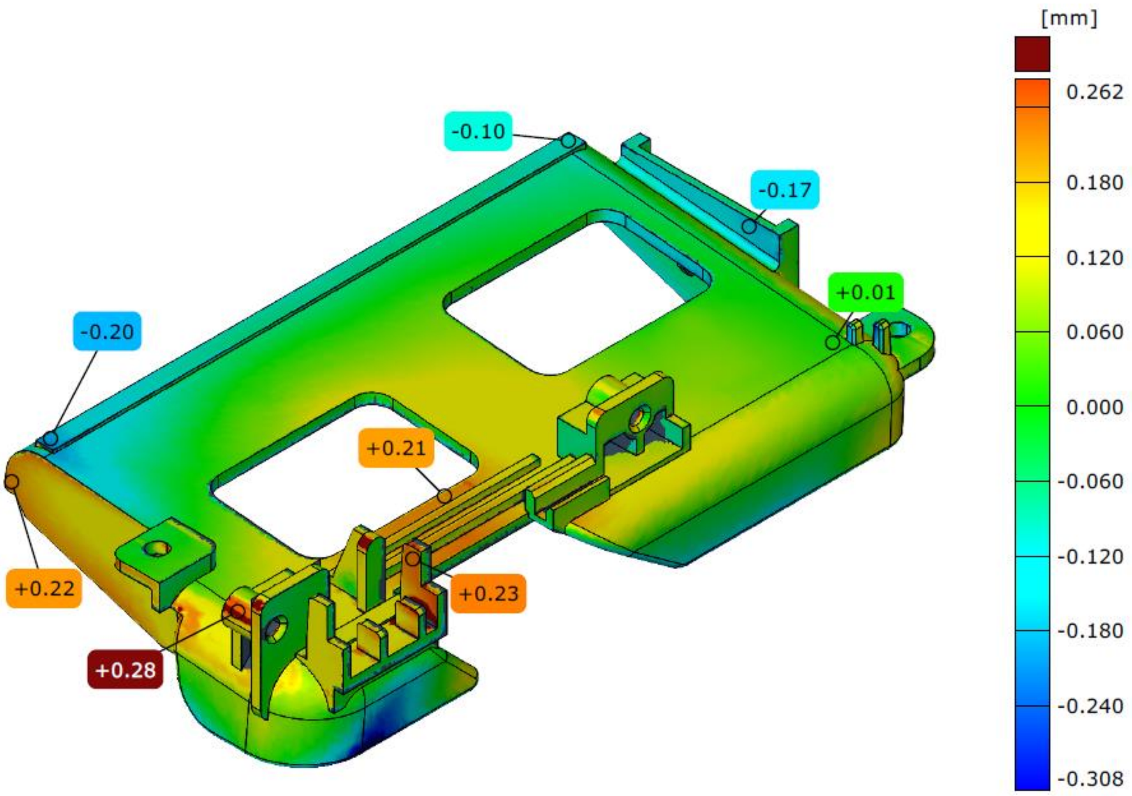


Figure 23 - CAD to manufactured part comparison

The final graphical representation displayed in Figure 24, the cross section of one hole of the geometry in the XZ plane. In the top rightmost of the figure, the cross section taken from the geometry is represented. The other figures display the deviation values in millimeters between the theoretical model and the manufactured part.

The results in Figure 23 and 24 indicate that the maximum and minimum deviations of the final manufactured part are in the range from 0.262 mm and -0.308 mm.

HOLE CROSS SECTION

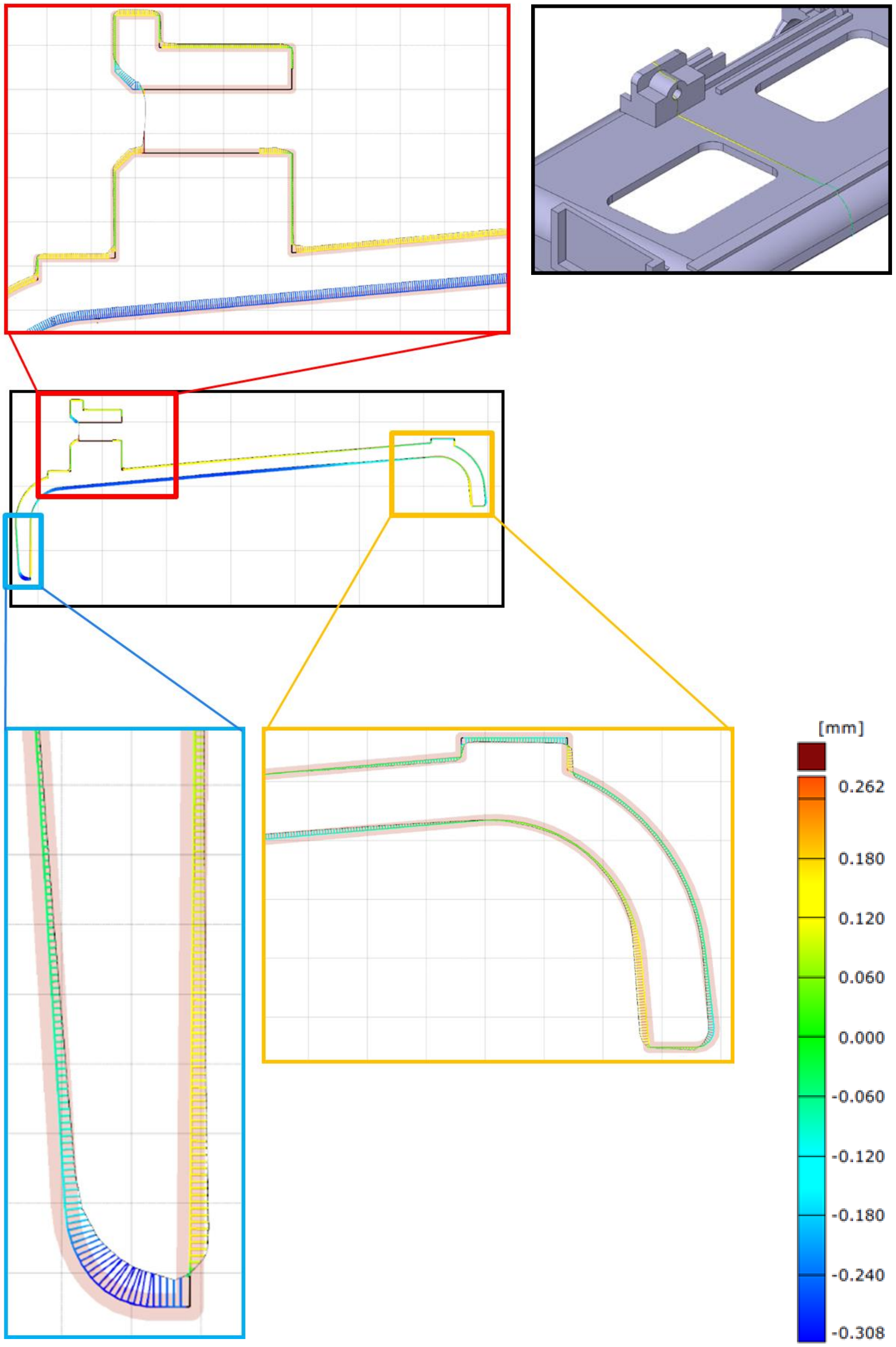


Figure 24 - CAD to manufactured part comparison, cross section

6. Discussion

6.1. Research questions

Is it economically feasible to use AM methods to manufacture structural plastic parts for the assembly of pre-production series?

Based on the results obtained in the industry survey, the layer by layer manufacturing of the geometry used in this study case is economically viable when the production volumes are approximately, equal or lower than 700 units and 550 units and production cost equal or lower than 12 €/unit and 14 €/unit, using SLA and SLS technology respectively. See Figure 16.

The geometrical features of the sample used are very similar to many to other plastic parts used in electronics consumer products, thus AM technology can be economically competitive versus injection molding or silicon casting techniques to produce inner structural plastic part for the assembly of technical prototypes.

In addition, the delivery time for AM produced parts are shorter compared to other methods, the cross even point versus injection molding using temporary tooling is located at 820 units and 31 days for SLS technology and 930 units and 32 days for SLA technology. See Figure 17.

However, in the case of higher production volumes, higher production cost or higher delivery times, injection molding using temporary tooling is more cost effective to produce the sample used in this study case.

The downside of AM part versus injection molded parts is that, after the visual evaluation of the small features, displayed in Appendix A3, such as assembly holes and assembly contact surfaces, is that AM produced part would need an additional cost in the form of post-processing and rework of assembly key features of the geometry.

The post-processing and rework of AM produced parts will impact directly on the unit cost per part and delivery time. Nevertheless, the cost for using high-speed milling or manual finishing techniques to finalize the AM part can be added to the process and based on cost estimations for the post-processing, AM produced parts will still in the acceptable range up to a certain production volume.

The post-processing techniques available can make AM parts more suitable for the intended function. However, this was not included in the scope of the Master's Thesis and it need to be studied in deep in further research.

Is it technically feasible to use AM methods to manufacture structural plastic parts for the assembly of pre-production series?

Based on the performance variables selected for the experiment, the results of the DOE demonstrates that AM systems are technically feasible to produce inner structural plastic parts for the assembly of technical prototypes in the manufacturing of Alpha-Prototypes during pre-production series.

Looking at the performance variable V1 Flatness, M1 and M3 are in the acceptable range. Regarding the performance variable V2 Hole to hole distance, all the machines are capable to produce parts within the acceptable dimensional tolerance. Finally, the analysis of the performance variable V3 surface roughness, demonstrates that by default AM produced parts have lower surface quality compared to parts manufactured used conventional methods.

The decision analysis and the applied methodology to select the best combination of design variables to enhance the result over the performance variables showed that, only M1 with parts printed vertically or diagonally, manufactured in the center of the machine and with low or high digital quality, were able to produce the geometry within the requirements.

Using the final results validation displayed in Table 17, AM produced parts can potentially fulfill the same dimensional requirements imposed to regular injection molded parts. In addition, after evaluating the data obtained from the CAD and AM part comparison, which shows that the deviations between the theoretical model and the manufactured part are in the range from 0.262 mm to -0.308 mm, is possible to conclude that AM produced part can be used in the assembly of technical prototypes.

However, the downside of parts manufactured with AM is that inevitably they will need to be post-processed and reworked in order to improve the quality on small features, such as assembly holes and important contact surfaces in the assembly of the product. The pictures displayed in the annexes 2, show that the quality of assembly holes need to be improved after the AM process.

Making an overview of the mechanical properties of the current AM resigns and powders. The values of AM produced parts regarding the tensile strength, tensile modulus, elongation at break and flexural modules are in the acceptable range.

However, AM produced parts are more brittle compared to conventionally manufactured plastics, impact strength values are lower compared to conventionally manufactured parts. Nevertheless, the current development of new materials has improved substantially this parameter making possible to obtain higher impact strength in AM produced parts.

What are the tradeoffs between the design variables versus the performance variables in the manufacturing of AM parts?

For the performance variable flatness (V1) and performance variable (V3) surface quality, the most influential design variable on this DOE is the type of machine used for producing the sample part (P1). For the performance variable hole to hole distance (V2), the most influential variable is the part orientation (P2).

In Figure 18, performance variable V1. The design variable, P1 Machine and material, shows that average results of M1 and M3 are inside requirements. In the case of M2 produced parts, flatness values are out of specifications. In the case of design variable P2 Part orientation, the best option to improve flatness values is to manufacture the part in diagonal orientation. The parts located and manufactured in the top left corner of the machines P3 have better flatness values. Regarding the digital quality, parts manufactured with a deviation of 0.1 mm have better results in flatness.

The results of the Figure 19, performance variable V2, show that in average all machines are inside requirements, independently of in which orientation the part was manufactured, located or the type of digital data used. Mention that, in average M2 and the parts printed vertically have been the most accurate and showed higher dimensional stability, as the measured distance from hole to hole was closer to the theoretical value.

The average surface finish ISO, displayed in the Figure 20, show that the manufactured part surface quality are N6, N8 and N9 for part manufactured by machines M1, M2 and M3 respectively. This machine ISO quality has been obtained by averaging the Ra values of the part printed on the three orientations. As mentioned before, parts printed in vertical and diagonal had better surface quality. The experiment has demonstrated that the quality of the surface is highly influenced mostly by the type of machine used for the manufacturing and also by the build orientation.

Some other sources of inaccuracies and tradeoff between of the design variables have been noticed when looking at geometrical features of the produced parts. For instance, inclined surfaces in the geometry caused what is called staircase effect. AM processes are fundamentally building the geometry by depositing material layer over layer. These layers have a certain thickness, the overlapping of the layers in inclined surfaces created staircase effect which is intrinsically linked to the process and only can be improved by minimizing the layer depth.

For instance some of the pictures displayed in the appendix A3, show small features such as assembly holes, in inclined surfaces staircase effect inaccuracies which have an impact on the surface quality. In addition, undercuts in the geometry, due to the orientation chosen in the build, will also add inaccuracies to the manufactured RP part. This is related to the effect of the need of external support structures to build the solid part. All this parameter need to be taken into account to maximize the expected performance of AM produced parts.

Which are potentially the most suitable AM systems?

After comparing three different process categories, the AM system used in this experiment based on Vat photo-polymerization technology, machine M1, is potentially the most suitable AM system to produce inner structural parts with requirements, such as high dimensional stability, good surface quality and suitable mechanical properties.

Results of the experiment demonstrate that, only the machine M1 was capable to produce parts within the requirements imposed to the system. During the experiment the performance variable V3 Surface roughness appeared to be the most critical and only M1 produced parts, in vertical and diagonal part orientation, were able to obtain an ISO surface quality under N5.

Nevertheless, alternative systems based on powder fusion technology M2 are also potentially suitable to produce inner structural plastic parts will lower quality requirement, especially in terms of surface finish. In addition, if a post-processing of the small features would be required, SLS technology can be also used to produce parts for the assembly of technical prototypes.

At the same time, M3 based on material jetting technology, has shown more drawbacks versus the other two machines. Parts produced with this machine, had two performance variables out of specifications, V1 Flatness and V3 Surface Quality. The application area of this technology is more focused on visual prototyping or functional prototyping

The data obtained in the industry survey shows that, the most common AM systems used by rapid prototyping suppliers and AM service bureaus are SLA and SLS systems. Other technologies, such as Polyjet or FDM are used to produce very small batches of visual and functional parts. From the obtained quotations, only two suppliers included a price for FDM produced part and only one supplier offered Polyjet services. For both of the technologies, the production volume never went higher than 10 units.

6.2. Limitation of the experimental setup

There are certain limitations related to this research, especially when analyzing the planning of the Design of Experiment (DOE), the results, the quantitative as well as the qualitative data obtained. For instance, due to lack of resources and time, some potentially interesting machine and material combinations were not included in the research scope. Nevertheless, in this experiment a representative sample of modern AM system has been tested. In further research, a different sample of machines and materials can be also researched to see the advantages and disadvantages between them.

At the same time, the results and data obtained from the industry survey can be improved by preparing a specific research study in which the principal focus of the research is to evaluate current technical possibilities of rapid prototyping suppliers and investigate in deep more variables such as production capacities of the service suppliers as well as production cost of parts and post processing techniques. In spite of that, the survey included in this research has shown some valuable industrial trends which might need to be confirmed in a more detailed research study.

Regarding the technical feasibility study, in this DOE no interaction between variables was assumed. However, a more robust design process must include some interactions between variables. For instance, the relationship between the part orientation and part location has objectively an interaction relationship.

In addition, the Taguchi L9 array might not be sufficient to gather a representative sample of experiments in order to create a more robust model of the phenomena. Not including interactions between variables and the small size of the selected Taguchi array certainly has had a downside effect over the results obtained in the experiment. Future research can include the interaction between the mentioned variables and the size of the Taguchi orthogonal array can be increased to improve the robustness of the experiment. For instance, a Taguchi L18 can be implemented to improve the experiment quality in further research.

During the experimental set up and the selection of the performance variables, a specific surface and measuring length was selected to record the surface roughness of the AM produced part. The AM produced part have different surface quality depending upon the measuring direction, to further research the surface quality in AM part a more developed measuring system would be necessary to implement and study deeper the differences between surface quality and build orientation.

Another weakness of the experimental set up is the effect of the design variable P4, digital quality on the selected performance variables. The effect of the digital quality is often visible in geometrical features, such as round surfaces. The selected performance variables did not measure quantitatively variables directly linked to the effect of the quality of the digital data on the manufactured parts. Moreover, the small sample size in this experiment would potentially be too noisy to distinguish the effect of this design variable.

One of the objectives in this Master's Thesis was to evaluate the differences between AM technologies or process categories. This has been performed by choosing three different machines and their materials as a design variable. In further research, it might be convenient to build an experiment including other AM process categories, such as extrusion systems or others in order to make a more detailed benchmark of current machine possibilities.

Nevertheless, a different research approach can be taken and focus the experiment in a single process category. To validate further the result obtained in this research, M1 has been demonstrated to be the most suitable solution for manufacturing the part of the study case. Thus, this process category can be studied as an entity.

In future research, the DOE can be focused on analyzing the design parameters of M1 in order to optimize the performance of the system to produce suitable samples for the assembly of technical prototypes. In this DOE, the selected design variables, such as part orientation, part location and digital data the experiment could include machine specific variables, such as different materials, building speeds, layer thickness and other parameters.

This research has showed that the part location has an impact in the dimensional stability of the produced part. However, when the production volumes are high, the real manufacturing process needs to be performed by using the whole tray capacity. In some cases also Z direction can be also included as variable, for instance in powder bed fusion systems. The impact of the part location needs to be researched further to evaluate the repeatability and reliability of M1 and other similar machines.

Due to limited time and scope of the project, mechanical properties of AM produced parts were not taken into account as variable to measure. It has been explained in previous research that AM produced part have anisotropic behavior, additionally the build orientation of AM produced part have an impact on the mechanical properties which is directly link with the anisotropic properties of the AM materials. [58] [59]

The part aging and the effect of environmental conditions in AM produced parts have not been included in this DOE quantitatively. These factors are especially relevant for AM subcategories in which the base material for producing the part is based on Photo-polymeric resins [60]. More other parameters to consider in further research are related with the radio transparency of AM produced parts. The effect of the material in the radio frequency signal might a variable to study in order to evaluate the feasibility of AM systems for producing technical prototypes.

The type of geometry selected in this experiment has been intentionally selected based on the capabilities of current AM machines. Current AM systems are not able to direct manufacture parts with high aesthetic requirements in one go. Necessarily, a part produced by AM needs to be post-processed, coated or treated to match the standards in terms of surface finish and colors required in aesthetic outer plastic part used in current products.

All these limitations need to be researched further in order to validate and standardize AM systems as production technique. The maturity level of the technology makes that academic research and applied research effort needs to focus on understanding AM systems and AM produced parts.

6.3. Future actions to implement AM systems in Pre-production series

Based on the results of the DOE, AM systems can be implemented during the assembly of technical prototypes. For that, it would be necessary to plan and execute a real product program in which the manufacturing of inner structural components is performed by AM systems during the Alpha-prototyping stage. The case company should take a similar approach taken in this Master´s Thesis, in which the AM process parameters, economics and technical variables were evaluated quantitatively.

During a potential certification process of the technology by the case company, a Rapid Prototyping service bureau should be included for further validation of AM systems to produce inner parts in Alpha-prototyping. Material, machine and process selection should be carefully defined with the aid of experts in the field. Current development of machines and resigns for

SLA process is very dynamic and more suitable options for producing the parts may appear rapidly.

After selecting the supplier and possible materials for the inner structural AM parts of the product, the implementation process needs to go through the same testing and refinement steps adopted in the case company. The packing and assembly of the product would determine the post-processing or re-work needed for the assembly of the product, this step would also define additional cost of the process as well as the additional manufacturing methods needed for the re-work of AM produced parts.

After assembling and packing the product, stress and performance testing need to be evaluated in the same way as conventionally manufactured Alpha-prototypes. The implementation of AM systems in this context should be perform by selecting an initial pilot case study and focusing more on the processes and change management implications rather than market driven forces.

Potentially, the adoption of AM can be incremental. Initially, the technology should be implemented using a pilot product programs. After evaluating the results and the lessons learned, further implementation can be adopted during the PDP of the case company. The manufacturing processes would be changed gradually adapting the conventional process to the new technology.

6.4. Design consideration for AM

The results displayed in Figure 18, 19 and 20 and the pictures displayed in Appendix 3 indicate some design rules to consider when planning the manufacturing of geometries using AM systems. However, AM systems and the geometrical features of the parts produced are very subordinate to machine, process and geometry parameters, such as part orientation, part location or part size. Therefore, the result obtained in this Master´s Thesis cannot be extrapolated to all types of geometries.

Nevertheless, the following basic design consideration or design rules have been extracted from the experiment to help in the planning of manufacturing for similar geometries in the future:

- Critical distances between assembly holes are optimized when the parts are manufactured in vertical position.
- The best surface quality is achieved in the planes of the geometry parallel to the vertical or Z axis of the manufacturing.
- A compromise between surface quality and critical distances can be achieved by manufacturing the part in diagonal position.
- To improve the quality of small features, such as assembly holes. The geometry needs to be orientated so the axis of the hole is aligned with the vertical axis or Z axis of the manufacturing.
- Thickness and features lower than 1 millimeter are problematic, and they need to be re-worked and prepared before assembly.

6.5. PDP scenarios of AM technology and injection molding tooling

AM systems are flexible manufacturing systems in which the production of tooling for the manufacturing is not required, the design changes are integrated to the CAD model and the part can be produced without major cost implications. Small design modifications do not affect substantially to AM systems and the cost per part remains basically constant when small changes are implemented to the original CAD design.

On the contrary, in the case of injection molding (IM), even minor design modifications to the initial geometry imply necessarily changes in tool geometry. Thus, the total cost of the IM process has to sum all the tool iterations needed during the PDP. In addition, companies that rely in temporary tooling and IM, used to develop multiple product variations of the same product idea. This implies that a tool per design option has to be manufactured, having also an impact in the final cost of the development of the product.

The use of injection molding for technical prototyping also has an impact in terms of time-to-market. The manufacturing of an IM tool takes from weeks to months to be ready. This study case has shown that, to obtain a single IM part of the case geometry, the average delivery time was at 26 working days. On the contrary, AM parts can be obtained in days or weeks.

During the tooling manufacturing process, very often design mistakes are made and the several times the tooling process needs to be iterated. Tools may go back and forth a few times from the producer to the tool builder until the final part is manufactured and the required quality is achieved, increasing costs to the PDP and product time-to-market. [29]

An ongoing scenario in the PDP, between product design and manufacturing departments is that, when the product idea is at very mature stage, any design modification has a big economic impact. In practice, in the case that the IM tooling has been manufactured, no more design changes can be included.

When looking at the marketing, industrial design as well as mechanical design necessities in PDP, the uncertainty of the business environment can cause that the product concept needs to be modified at any level of the PDP. The strongest advantage of AM versus conventional methods is the design flexibility. AM is toll-less manufacturing method with low initial investment, in addition delivery time for small manufacturing batches is demonstrated to be shorter.

Another common scenario in PDP of large consumer electronics companies is that the whole product program can canceled because of a late time-to-market or management decisions. AM is proven to shorten the time-to-market and it can be potentially be a cheaper option to produce parts for the assembly of technical prototypes without investing in IM tooling.

The testing and refinement of the mass production system, using IM tooling, can be exclusively implemented in beta-prototyping after the decision of the product features has been made by the company. This might have a positive economic impact in the PDP, decreasing product time-to-market and increasing design flexibility and adaptability of the company value chain.

6.6. AM machine suppliers, machine architecture and service suppliers

Many types of machines processes and type of materials are available for producing parts using AM systems. When an inexperienced company or individual wants to acquire or sub-contract rapid prototyping services, the amount of possibilities in the market and also machine dependent parameters, can make difficult to select the right combination of variables to enhance the desired performance from the additively manufactured part.

Moreover, machine suppliers have created unique machine and process names for their specific technology. Materials and machines are branded based on a marketing differentiation strategy. In most of the cases the process technology and material technology share the same principals from manufacturer to manufacturer, but the industrial brand is completely different.

All this has contributed to the generalized confusion around AM and 3D printing capabilities. Some of the new comers to the field feel disappointed after evaluating the quality of a part produced with a low-end FDM machine and because of their lack of knowledge, it is quite easy to make wrong decisions when their company decides for the first time to acquire machinery or sub-contract AM parts for their product development.

Many parameters needs to be considered in this decision, such as the intended use of the AM produced parts, the requirements of the produced parts, expected manufacturing volume, investment cost, infrastructure around the AM process and others.

Current business models of AM machines suppliers are not helping to promote the technology and gain momentum to increase the market share of AM industry. Generally, each AM equipment manufacturer uses its own machine architecture and often the materials are exclusive to the machine and supplied by the same equipment manufacturer.

Therefore, in practice the material compatibility between systems is non-existing within high-end machines that belong to the same process category. Manufacturers are increasingly locking customers in to their own materials supplies and this is slowing down the standardization and diffusion of AM technology.

Private companies that decide to invest on in-house AM capabilities for their PDP, find themselves in a weak situation after acquiring the machinery. Machine suppliers hold for themselves the whole business to avoid price competition so they are able to set the market price for the material supply, service and maintenance operations of the machinery. Once a company has invested in the machinery, they are hooked up with that AM supplier and there is a weak possibility to lower down operational cost of the AM services.

Nevertheless, the other option is to use service suppliers or service bureaus. Rapid prototyping service suppliers are acting as a bridge between AM machine manufactures and product development companies. Typically, service suppliers combine additive, subtractive and formative techniques to offer the complete prototyping possibilities to service contractors. In this process online prototyping quoting is an ongoing trend.

However, not all the online service suppliers have AM capabilities. Some of them only have a web based platform that offers AM and prototyping services without owning and operating AM equipment or prototyping facilities. In many cases, the autonomy of the suppliers is so high that the service contractor is not even aware of the type of process or material used to manufacture the outsourced prototype. Service suppliers are acting as a black-box for many AM service contractors.

6.7. Future trends in AM, lessons to learn by corporations

In the case of big product development corporations, based on current business models, the conception of AM as a production and rapid manufacturing technology is exclusively limited to the prototyping phases of the PDP.

The use of AM in this context, as a technology to produce visual and functional prototypes or to produce parts during the short-run manufacturing of technical prototypes in pre-production series, is proven to speed up the time-to-market in the development of new products and improve in overall economic and technical performance of the PDP, from idea to mass production.

However, the use of AM as final production technique will be always linked to variables, such as the complexity of the geometry, the intended use of the produced part and the manufacturing batches. Current, AM systems will not be competitive in a scenario in which the product has been conventionally designed to be conventionally manufactured and conventionally commercialized. Nevertheless, AM systems can transform some traditional production systems and drive a substantial change in the manufacturing industry as pointed out in this experiment but in any case will replace traditional mass production techniques as such.

The downside of AM systems is that is a slow process compared to IM due to the additive process itself. AM systems require to bond material layers on top of existing layers by means of combining energy and mechanisms in the process. Independently of the AM process category used in the process, an extruded filament using FDM process or a powder bed fusion using SLS process or a photo curable resin using SLA or Polyjet technology, the bonding reaction requires time to happen and it is highly subordinate to the machine architecture, part thickness, part size and manufacturing orientation.

Speed increase in AM systems is fundamentally limited by the material and the energy interactions of the additive process, current systems need time to build geometries layer by layer and it will be difficult to see AM systems competing directly against conventional manufacturing process such as IM in mass production context.

Nevertheless, when the production volume of the intended product is small or unknown, and the product adaptability is the fundamental variable to consider by the company. AM might become the key production technology of the near future. As an example of this, current small entrepreneurial initiatives and start-up companies using crowd-funding business models are fully embracing the potential of AM technology.

AM opens for them, new possibilities to low volume fabrication and manufacturing on demand of products. A single individual company has access today to high-end manufacturing capabilities using a cloud based digital manufacturing service. From an initial product idea a computer design CAD model is generated, after that a highly complex prototype can be manufactured using AM technology and combining open source electronics.

Products are developed in small innovation communities and modern entrepreneurs are learning and developing their business through a series of prototypes and market experiments. In this context, product series are short by nature. They are also local and originally designed for local users. This kind of PDP approach is creating the information of the product market feasibility by testing the product empirically. If the product is not successful, others versions will try to take the place, in some cases the steps to mass production are performed slowly in a Product Darwinist natural selection process.

It can be said that AM together with open source technologies are enabling the step toward mass personalization. However, today this is not strictly a giant technological revolution in terms of economies of scale, but there are positive signs that in the near future these technologies can potentially become a real business revolution.

What about large companies?

Current big corporations are forced to operate in a highly competitive and dynamic environment. In this context it is just necessary to accept the uncertainty of the business. However, the companies launch their new product and product campaign based in rigid planning, long and costly product development processes as well as complex manufacturing systems and supply chains.

Even though, the tools and resources allocated to define the product portfolio and development works are highly important to manage big corporation, the evidences demonstrate the difficulty to predict the market viability of the product beforehand. By looking at ongoing new business models of small entrepreneurs and start-up companies, big corporations should learn from the opportunities coming from this new business models.

The level of customization of the product is increasing and potentially the current business models can become obsolete, large corporation need to adapt to a new scenario in which a higher flexibility in product portfolio and PDP will be needed in order to be profitable in the long run.

Super Machines

Most of the criticisms of industry against AM systems underestimate the technology because the same metrics are used to evaluate conventional and additive manufacturing methods. Product designers and manufacturing industry experts argue that products cannot be manufactured exclusively by using AM systems and it is necessary in any case to use alternative methods in parallel.

Some industry and academia experts believe that the greatest future potential of AM comes from combining two or more purely additive processes, such as SLS or SLA together with DW technologies and combining them with subtractive processes during the same manufacturing process. This concept of manufacturing is already explored by current machine suppliers and used in some niche applications.

Academia is focused on basic and applied research to develop scalable hybrid methods to produce goods with integrated functional properties, such as electrical conductivity, semiconductor technology in a highly complex geometry in a single fully automated process.

The possibility of achieving the whole functionality of the product in one go will change how things are design and manufactured today. In addition, the desire of material and energy savings can potentially drive to adopt AM and hybrid technologies in which only the needed material is consumed during the manufacturing. Simultaneously, scanning technologies and digital inventories will change the way how corporations organize their stocks for spare part and product repair activities.

Potentially, future “Super Machines” will be multi-functional, fully automated production systems, they will be more efficient, they will waste less material and they will optimize the energy used in the process. Once the machines are fully capable to produce goods in a single automated process, the most demanded skills in industry would be digital design skills.

7. Summary and Conclusions

AM systems have improved their capabilities substantially over the past years. Material and system development has made AM systems suitable to manufacture engineering components. Quality, reliability and repeatability have improved and currently the applications area of layer by layer manufacturing equipment is growing very rapidly. Therefore, AM systems are no longer just a tool to produce rapid visual parts.

The State of the Arts presented on this Master's Thesis has shown some of the most promising and ongoing applications of AM systems in product development and manufacturing industry. Currently, additively produced plastic parts assist to create visual as well as functional engineering plastics. Based on the results of this work, it is feasible to manufacture on demand low and medium batches of AM engineering plastic without high initial tool investment.

In addition, for tolling and manufacturing applications, AM systems are commonly applied to produce master and patters for soft indirect tooling applications. At the same time, soft direct tooling applications are also possible using AM systems. Moreover, niche application related to high performance tooling, have created an scenario in which the free-form design and manufacturing of conformal cooling geometries in the tool and inserts for IM processes is possible. Assembly tooling can be produced directly by AM systems, mechanical properties of the produced plastics together with the design flexibility of AM systems help to reduce the waste in the form of energy and material associated to conventional methods.

Furthermore, with the development of advance technologies that combine several additive technologies and/or subtractive processes simultaneously, it is possible to produce conformal functional structures to manufacture components, such as antennas structure, 3D electronic components, connectors as well as conformal wiring solutions in a single process. In addition, current commercial hybrid systems combine metal powder bed systems and high speed milling processes to produce tooling with geometries and functionalities which were not achievable with conventional solutions.

AM systems are enabling to product developers and innovators to drive towards a new scenario in which manufacturing becomes accessible for a bigger audience. High initial investment related to conventional mass production methods is not applicable to AM systems. Thus, the development of new ideas and further commercial products can be more democratic, simpler and faster. Direct manufacturing using online services, open-source electronic hardware and crowd funding possibilities, opens up new possibilities in which small entrepreneurs can productize their ideas in a totally new way.

The initial aim of this work was to present a comprehensive framework of Additive Manufacturing process categories and their application area suitable for the activities developed by the case company. In addition, the technology and applications have been linked to a Product Development Framework in order to help non-expert professionals to understand current capabilities of AM systems. The framework has introduced the idea of using engineering plastics produced by AM to be used in the assembly of Alpha-Prototypes during the assembly pre-production series of the sponsoring company.

The research design, developed in this Master's Thesis, has demonstrated that AM systems are technically and economically feasible to manufacture plastic parts to be used in technical prototyping. IM and temporary tooling can be substituted by AM system to direct manufacture non-aesthetic structural plastic parts in Alpha-prototyping.

The trends in the industry and the experiment presented in this Master's Thesis indicate that AM systems might be a suitable option versus conventional IM and temporary tooling processes to gain flexibility in the PDP of big corporation. The investment in tooling determines substantially the compromises between the economics of the PDP, design considerations as well as the time-to-market of the intended new product. AM systems open up possibilities to reduce cost in the product development, give more design flexibility and reduce product time-to-market

The implementation of AM systems in the production of technical prototypes at Alpha-prototyping stage could provide the option to integrate design modifications at the very late of the PDP. Based on the study case exposed in this Master's Thesis, AM systems can be used to increase the design flexibility and provide more time to decision makers in order to select final product features, such as battery capacity, electronic package design or camera options until very late in the product development.

Adopting AM processes can lead to significant economic and technical benefits to modern product development organizations. The impact of AM applications on current manufacturing processes and business models can be profound in the future, a new scenario of toll-less manufacturing, non-inventory product distribution and low initial investment cost can drive to organization to manufacture their new products on-demand, and eventually the market can determine the suitability of the product as well as dictate how the product needs to evolve to adapt to consumer necessities.

However, current technology around AM systems is limited. AM by themselves are not fully capable to produce parts that fulfill some of the common technical and aesthetical requirements imposed to consumer electronics products. In addition, the lack of standardized processes and material characterization is an obstacle to overtake in the coming years. Current limitations in materials, together with the higher production cost of AM system make that at this development stage of the technology; early adopters of the technology are forced to study case by case the introduction of AM systems to produce parts in their PDP.

Nevertheless, during the past years the industry has taken strong momentum due to the visibility and publicly coming from the media. The expectation towards AM systems as a game changing technology is high. Private as well as public funded research and development initiatives are growing in an unprecedented manner and despite the technical obstacles related to AM technologies, the industry is expected to grow rapidly in the near future.

As AM material quality, process repeatability and reliability improves as well as more industrial standards are developed, the applications of Additive Manufacturing technologies will increase significantly in the near future.

References

[1] E. M. a. H. Lipson, *Fab@Home the personla desktop fabrication kit,* Mechanical and Aerospace Engineering, Cornell University, Ithaca, New York, USA: Rapid Prototyping Journal, 2007.

[2] D. W. R. B. S. I. Gibson, *Additive Manufacturing Technologies, Rapid Prototyping to Direct Digital Manufacturing,* Springer, 2010.

[3] W. Associates, *Wohlers Report, Additive Manufacturing and 3D Printing State of the Industry,* 2013.

[4] ASTM, *Standard Terminology for Additive Manufacturing Technologies,* ASTM F2792 – 12a, 2013.

[5] K. S. N. d. B. D. Dimitrov, *Advances in three dimensional printing – state of the art and future perspectives,* Rapid Prototyping Journal, 2006.

[6] L. S. Z. R. L. F. W. R. L. Q. X. Z. W. X. YAN Yongnian, *RP and Manufacturing Technology Principle, Representative Technics, Applications, and Development Trends,* Key Laboratory for Advanced Materials Processing Technology of Ministry of Education, Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China: TSINGHUA SCIENCE AND TECHNOLOGY, 2009.

[7] F. V. F. V. B. Vayrea, *Designing for Additive Manufacturing,* ELSEVIER, CIRP Conference on Manufacturing Systems, 2012.

[8] D. B. I. G. Ian Campbell, *Additive manufacturing: rapid prototyping comes of age,* Rapid Prototyping Journal, 2012.

[9] Y. W. J. F. H. L. M. Mahesh, *Benchmarking for comparative evaluation of RP systems and processes,* Department of Mechanical Engineering, Faculty of Engineering, National University of Singapore, Singapore: Rapid Prototyping Journal, 2004.

[10] S. A. Ratnadeep Paul, *Optimal part orientation in Rapid Manufacturing process for achieving geometric tolerances,* Computer-Aided Manufacturing Laboratory, School of Dynamic Systems, Mechanical Engineering Program, University of Cincinnati, Cincinnati, United States: Journal of Manufacturing Systems, 2011.

[11] B. V. J. B. I. D. Tomaz Brajlih, *Speed and accuracy evaluation of additive manufacturing machines,* Faculty of Medical Engineering, University of Maribor, Maribor, Slovenia: Rapid Prototyping Journal, 2010.

[12] W. v. W. K. S. N. d. B. D. Dimitrov, *Investigating the achievable accuracy of three dimensional printing,* Rapid Prototyping Journal, 2006.

[13] ASTM, *Standard Terminology for Additive Manufacturing—Coordinate Systems and Test Methodologies,* ASTM F2921 − 11, 2013

[14] L. H. D. Z. Stephen Mellor, *Additive Manufacturing: A Framework for Implementation,* College of Engineering, Mathematics and Physical Science, University of Exeter: International Journal of Production Economics, 2013.

[15] A. G. Anders Drejer, *Towards multiple product development,* Center for Industrial Produktion, Aalborg University, Fibigerstraede 16, DK-9220 Aalborg East, Denmark: Elsevier, 2002.

[16] S. D. E. Karl T. Ulrich, *Product Design and Development,* McGraw Hill, International Edition, 2012.

[17] K. Syrjala, *Development of Processes and Bussiness Models for the Design and Manufacture of Injection Molds,* Tampere: Tampere University of Technology, 2005.

[18] S. Ottosson, *Dynamic product development, DPD,* Linkoping University, S-60174 Norrkoping, Sweden: Elsevier, Technovation, 2002

[19] L. L. I. H. K.K.B. Hon, Direct writing technology, Advances and developments, CIRP Annals - Manufacturing Technology, 2008.

[20] M. C. C. S. A. U. F.-L. Krause, Enhanced Rapid Prototyping for Faster Product Development Processes, Fraunhofer Institute for Production Systems and Design Technology IPK, Berlin, Germany: Annals of the CIRP, 1997.

[21] T. Wohlers, *Wholers Report 2012, Additive Manuafcturing and 3D Printing State of the Industry,* 2012.

[22] R. L. J. James E. Folkestad, *Integrated rapid prototyping and rapid tooling (IRPRT),* Department of MAnufacturing Technology and Construction Management, Colorado State University, Fort Collins, Colorado, USA: Emerald - Integrated Manufacturing Systems, 2002.

[23] R. V. D. Anneke Vandevelde, *Managing the design-manufacturing Interface,* Vlerick Leuven Gent Management School, Associated with Ghent University and with the Katholieke Universiteit Leuven, Gent-Ledeberg, Belgium: Emerald - International Journal of Operations & Production Management, 2003.

[24] A. M. A. Rosochowskia, *Rapid tooling: the state of the art,* Elsevier - Journal of Materials Processing Technology, 2000.

[25] R. S. J. K. G. Levy, *Rapid Manufacturing and Rapid Tooling with Layer Manufacturing technologies, state of the arts and future perspectives,* Annals of CIRP - Manufacturing Technology, 2003.

[26] R. S. Munish Chhabra, Rapid casting solutions: a review, Rapid Prototyping Journal, 2011.

[27] http://www.stratasys.com/, 2013

[28] M. S. a. M. R.-S. Damir Godec, Influence of hybrid mould on moulded parts properties, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, Zagreb, Croatia: Rapid Prototyping Journal, 2008.

[29] S. A. M. C. E. W. H. G. Emanuel Sachs, Production of Injection Molding Tooling with Conformal Cooling Channels using The Three Dimensional Printing Process, Massachusetts Institute of Technology Cambridge, Massachusetts (USA), 2000.

[30] F. g. Branislav Duleba, Conformal Cooling for Plastic Injection Moulding, Faculty of Mechanical Engineering, Technical University of Kosice, Letná, 2009.

[31] K.-M. Y. C. C. W. Y. Z. Yu Wanga, Automatic design of conformal cooling circuits for rapid tooling, Elsevier, Computer-Aided Design, 2011.

[32] V. S. R. L. Y. J. Alban Agazzi, Optimal cooling design in injection moulding process, a new approach based on morphological surfaces, Elsevier, Applied Thermal Engineering, 2013.

[33] K. Y. W. C. K.M. Au, Visibility-based conformal cooling channel generation for rapid tooling, Elsevier, Computer-Aided Design, 2011.

[34] J. H. P. S. R. F. L. D. R. P. Letizia Mortara, Proposed classification scheme for direct writing technologies, Department of Engineering, Institute for Manufacturing, University of Cambridge, Cambridge, UK: Rapid Prototyping Journal, 2009.

[35] *http://www.VTT.fi/, 2013*

[36] E. M. R. B. W. Amit Joe Lopes, *Integrating stereolithography and direct print technologies for 3D structural electronics fabrication,* W.M. Keck Center for 3D Innovation, The University of Texas at El Paso, El Paso, Texas, USA: Rapid Prototyping Journal, 2012.

[37] S. J. Hu, *Evolving Paradigms of Manufacturing: From Mass Production to Mass Customization and Personalization,* Mechanical Engineering, University of Michigan, USA: Forty Sixth CIRP Conference on Manufacturing Systems, 2013.

[38] J. P. G.-Z. K. N. O. Jeffrey B. Dahmus, *Modular product architecture,* Center for Innovation in Product Development, Massachusetts Institute of Technology, Cambridge, MA 02139, USA: Elsevier Science, 2001.

[39] H. W. S. J. H. Christopher Berry, *Product architecting for personalization,* Department of Mechanical Engineering, University of Michigan, USA: Journal of Manufacturing Systems, 2013.

[40] B. Berman, 3-D printing: The new industrial revolution, Frank G. Zarb School of Business, Hofstra University, 222 Weller Hall, Hempstead, NY 11549, U.S.A.: Elsevier, 2012.

[41] T.-Y. C. S. G. Juju Antony, *Training for design of experiments,* Warwick Manufacturing Group, University of Warwick, Coventry, UK: Emerald, 2003.

[42] A. R. P. C. O. R. Nuno R.P. Costa, *Guidelines to help practitioners of design of experiments,* Emerald, The TQM Magazine, 2006.

[43] K. R. R. B. A. G. M. P. R. Konda, *Design of experiments to study and optimize process performance,* International Journal of Quality, 1998.

[44] I. C. H. H. J.A. Ghani, *Application of Taguchi method in the optimization of end milling parameters,* Department of Engineering Design and Manufacture, Faculty of Engineering, Universiti Malaya, 50603 Kuala Lumpur, Malaysia: Elsevier, Journal of Materials Processing Technology, 2003.

[45] H. G. G. S. M. Nalbant, *Application of Taguchi method in the optimization of cutting parameters for surface roughness in turning,* Department of Mechanical Education, Faculty of Technical Education, Gazi University, 06503 Teknikokullar, Ankara, Turkey: Elsevier, Materials and Design, 2006.

[46] Y. T. Albert W.L. Yao, *A robust process optimization for a powder type rapid prototyper,* Department of Mechanical and Automation Engineering, Taiwan: Emerald, Rapid Prototyping Journal, 2002

[47] J. A. E. B. S. Rahmati, *Dimensional accuracy analysis of wax patterns created by RTV silicone rubber molding using the Taguchi approach,* Emerald, Rapid Prototyping Journal, 2007.

[48] T.-W. L. S.-S. H. Che Chung Wang, *Optimizing the rapid prototyping process by integrating the Taguchi method with the Gray relational analysis,* Emerald, Rapid Prototyping Journal, 2007.

[49] A. M. D. D. Prashant Kulkarni, A review of process planning techniques in layered manufacturing, Department of Mechanical Engineering, The University of Michigan, Ann Arbor, USA: Rapid Prototyping Journal, 2000.

[50] H. L. Y. W. F. Xu, *Considerations and selection of optimal orientation for different rapid prototyping systems,* Department of Mechanical and Production Engineering, National University of Singapore, Singapore: Rapid Prototyping Journal, 1999.

[51] P. P. P. R. K. Senthilkumaran, Statistical modeling and minimization of form error in SLS prototyping, Emerald, Rapid Prototyping Journal, 2012.

[52] C. K. Georges M. Fadel, *Accuracy issues in CAD to RP translations,* Mechanical Engineering

Department, Clemson University,: Rapid Prototyping Journal, 1996.

[53] N. V. R. S. G. D. Pulak Mohan Pandey, *Slicing procedures in layered manufacturing: a review,* Rapid Prototyping Journal, 2003.

[54] ISO, *Geometrical Product Specifications (GPS). Indication of surface texture in technical product documentation,* ISO 1302:2002, 2002.

[55] ISO, *Geometrical Product Specifications (GPS). Geometrical tolerancing. Tolerancing of for, orientation, location and run-out,* ISO 1101:2004.

[56] K. Miettinen, *Nonlinear Multiobjective Optimization,* Boston, 1999.

[57] A. Armillotta, *Selection of layered manufacturing techniques by an adaptive AHP decision model,* Dipartimento di Meccanica, Politecnico di Milano, via La Masa 34, 20158 Milano, Italy: Elsevier, Robotics and Computer-Integrated Manufacturing, 2008.

[58] N. H. Candice Majewski, *Effect of section thickness and build orientation on tensile properties and material characteristics of laser sintered nylon-12 parts,* Additive Manufacturing Research Group, Loughborough University, Loughborough, UK: Rapid Prototyping Journal, 2011.

[59] T. J. G. J. S. U. Thomas L. Starr, *The effect of process conditions on mechanical properties of laser-sintered nylon,* Rapid Prototyping Journal, 2011.

[60] K. A. R. Q. R. B. W. Karina Puebla, *Effects of environmental conditions, aging, and build orientations on the mechanical properties of ASTM type I specimens manufactured via stereolithography,* Department of Mechanical Engineering, The University of Texas at El Paso, El Paso, Texas, USA: Rapid Prototyping Journal, 2012.

Appendix

A1 - Measurements obtained during the DOE

Performance Variable V1 – Flatness (mm)								
		First Measurement			Second Measurement			Mean per line
Coding	Exp.	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	
1HLH	1	0.130	0.120	0.180	0.126	0.116	0.153	0.138
1VCM	2	0.150	0.090	0.050	0.151	0.085	0.062	0.098
1DRL	3	0.180	0.080	0.090	0.134	0.086	0.119	0.115
2HCL	4	0.400	0.420	0.440	0.432	0.398	0.442	0.422
2VRH	5	0.620	0.520	0.540	0.605	0.509	0.523	0.553
2DLM	6	0.240	0.500	0.310	0.222	0.536	0.312	0.353
3HRM	7	0.210	0.190	0.150	0.147	0.195	0.219	0.185
3VLL	8	0.100	0.050	0.040	0.091	0.053	0.037	0.062
3DCH	9	0.160	0.070	0.100	0.136	0.066	0.073	0.101
						Total mean		**0.225**

Measurements of the performance variable V1 Flatness

Performance Variable V2 – Hole to hole distance (mm)								
		First Measurement			Second Measurement			Mean per line
Coding	Exp.	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	
1HLH	1	37.620	37.580	37.660	37.623	37.575	37.662	37.620
1VCM	2	37.510	37.570	37.510	37.484	37.597	37.457	37.521
1DRL	3	37.630	37.600	37.630	37.619	37.601	37.626	37.618
2HCL	4	37.610	37.610	37.600	37.614	37.615	37.616	37.611
2VRH	5	37.340	37.620	37.340	37.233	37.570	37.240	37.391
2DLM	6	37.720	37.720	37.770	37.720	37.707	37.771	37.735
3HRM	7	37.690	37.680	37.720	37.699	37.678	37.719	37.698
3VLL	8	37.690	37.750	37.300	37.666	37.809	37.356	37.595
3DCH	9	37.740	37.670	37.700	37.718	37.686	37.679	37.699
						Total mean		**37.610**

Measurements of the performance variable V2 Hole to hole distance

Performance Variable V3 – Surface Roughness Ra (µm)								
		First Measurement			Second Measurement			Mean per line
Coding	Exp.	Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3	
1HLH	1	3.080	3.420	3.150	3.500	3.350	3.530	3.338
1VCM	2	0.575	0.346	0.490	0.384	0.378	0.444	0.436
1DRL	3	1.370	0.964	1.710	0.929	1.020	1.610	1.267
2HCL	4	1.730	2.090	1.580	1.460	1.720	1.710	1.715
2VRH	5	4.280	2.270	2.950	4.410	2.750	3.660	3.387
2DLM	6	2.930	2.400	2.360	2.370	2.280	2.550	2.482
3HRM	7	7.910	6.640	7.020	6.050	5.560	7.360	6.757
3VLL	8	5.760	4.970	5.140	8.290	6.060	4.800	5.837
3DCH	9	6.690	7.350	6.190	5.680	5.070	7.060	6.340
						Total mean		**3.506**

Measurements of the performance variable V3 Surface Quality

Result Validation				
	Measurement			
Performance Variable	First	Second	Third	Total Mean
V1 – Flatness (mm)	0.168	0.206	0.138	0.171
V2 – Hole to hole (mm)	37.715	37.694	37.683	37.697
V3 – Surface Roughness (µm)	0.760	0.890	0.740	0.796

Measurements of the experiment validation

A2 – AHP Performance variable scoring matrixes

AHP Scoring Criteria	
Intensity Value	**Interpretation**
1	Requirement i and j are of equal value
3	Requirement i has a moderate higher value than j
5	Requirement i has a medium higher value than j
7	Requirement i has a strong higher value than j
9	Requirement i has an absolutely higher value than j
2,4,6,8	There are intermediate scales between two adjacent judgments
Reciprocals	If requirement i has lower value than j (1 / Intensity Value)

AHP scoring criteria used with the client

Client - AHP Scoring Matrix			
	V1	V2	V3
V1	1	3.00	1.00
V2	0.33	1	0.50
V3	1	2.00	1
Sum	2.33	6.00	2.50

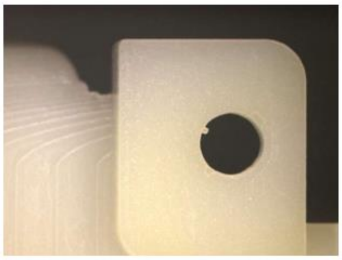
AHP scoring matrix results after client input

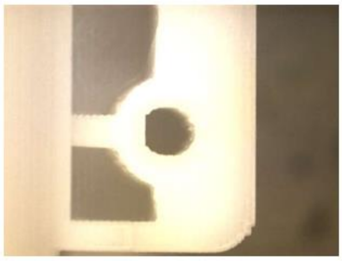
AHP Scoring Matrix					
	V1	V2	V3		**Percentage**
V1	0.43	0.50	0.40	1.33	44%
V2	0.14	0.17	0.20	0.51	17%
V3	0.43	0.33	0.40	1.16	39%

AHP method results

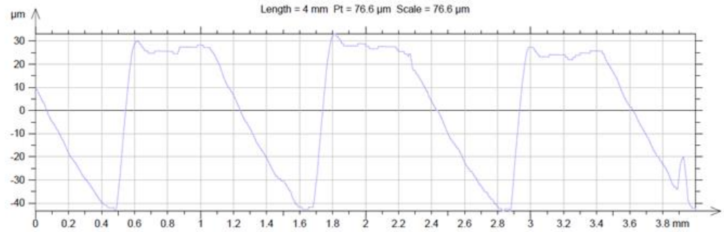
A3 – Pictures obtained during the DOE, small features

Experiment 1 - 1HLH
Sample 1
Measurement 1

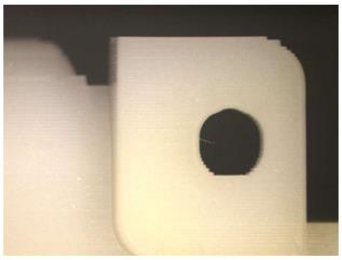


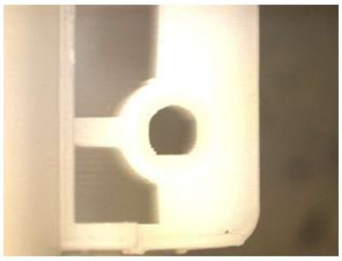


Roughness profile
(Ra = 3.08 µm)
Performance Variable V3

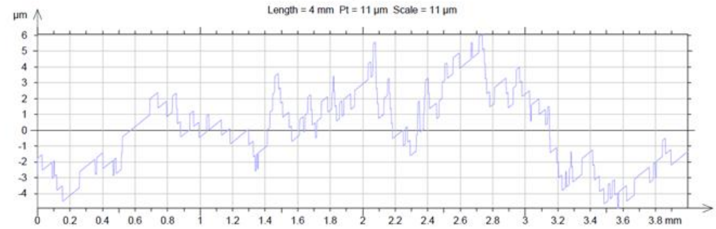


Experiment 2 - 1VCM
Sample 1
Measurement 1

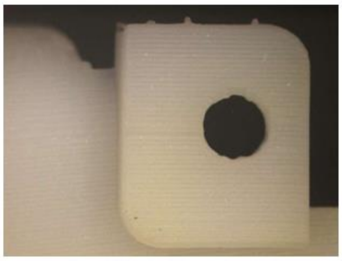


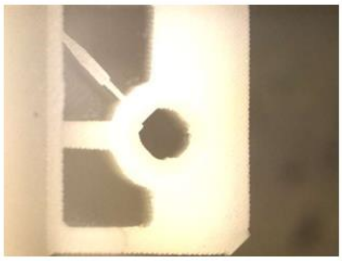


Roughness profile
(Ra = 0.574 µm)
Performance Variable V3



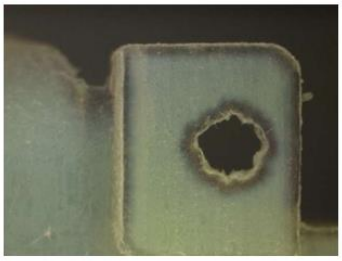
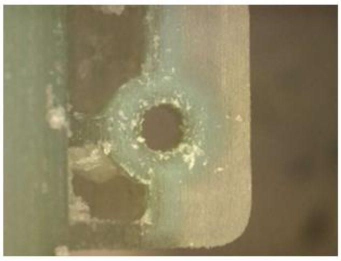
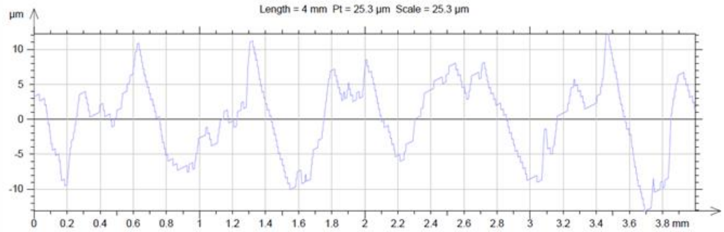
Experiment 3 - 1DRL
Sample 1
Measurement 1

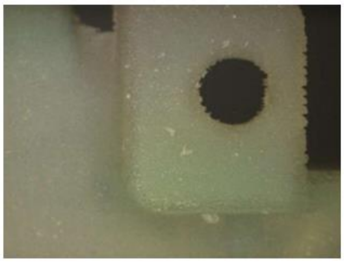
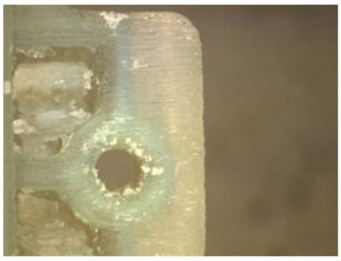
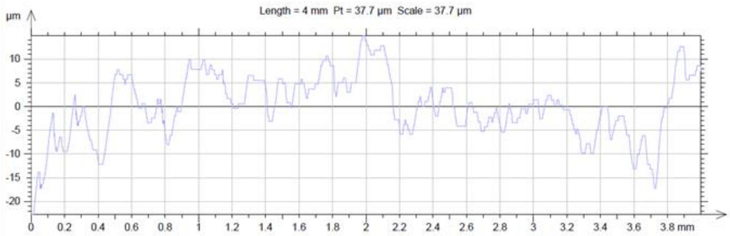


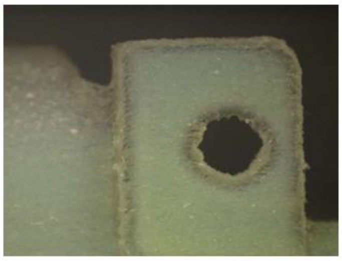
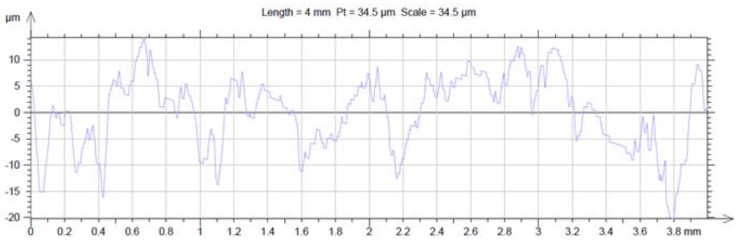


Roughness profile
(Ra = 0.964 µm)
Performance Variable V3

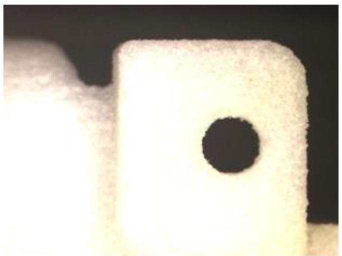
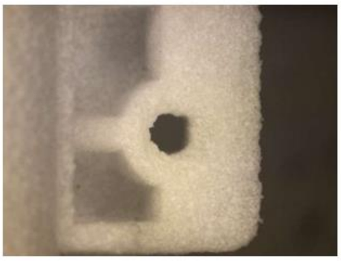
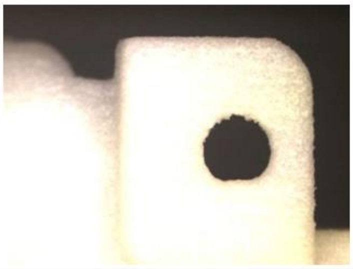
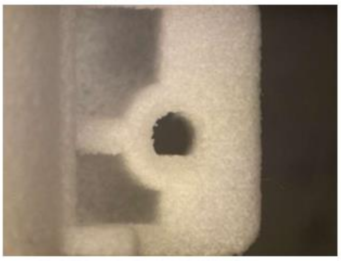
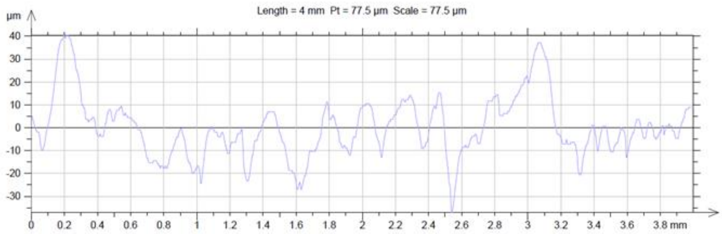
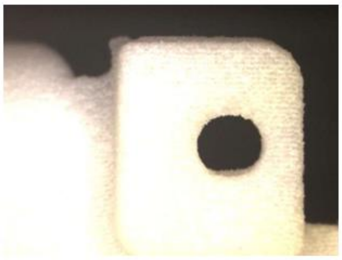
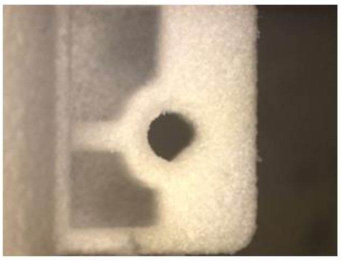
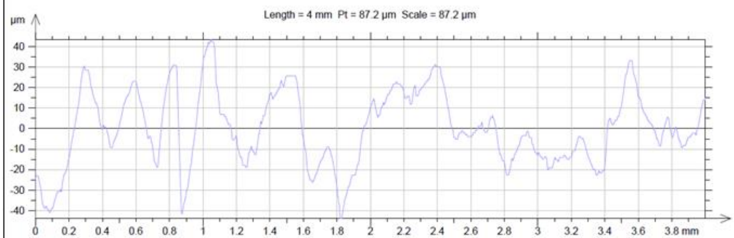
Pictures of small features in M1 produced parts and the example of roughness profile for experiments 1, 2 and 3

<table>
<tr><td>Experiment 4 – 2HCL
Sample 1
Measurement 1</td><td></td><td></td></tr>
<tr><td>Roughness profile
(Ra = 1.46 µm)
Performance Variable V3</td><td colspan="2">
</td></tr>
</table>

<table>
<tr><td>Experiment 5 – 2VRH
Sample 1
Measurement 1</td><td></td><td></td></tr>
<tr><td>Roughness profile
(Ra = 2.27 µm)
Performance Variable V3</td><td colspan="2">
</td></tr>
</table>

<table>
<tr><td>Experiment 6 – 2DLM
Sample 1
Measurement 1</td><td></td><td></td></tr>
<tr><td>Roughness profile
(Ra = 2.28 µm)
Performance Variable V3</td><td colspan="2">
</td></tr>
</table>

Pictures of small features in M2 produced parts and the example of roughness profile for experiments 4, 5 and 6

Experiment 7 – 3HRM **Sample 1** **Measurement 1**		
Roughness profile (Ra = 5.56 µm) Performance Variable V3		
Experiment 8 – 3VLL **Sample 1** **Measurement 1**		
Roughness profile (Ra = 4.97 µm) Performance Variable V3		
Experiment 9 – 3DCH **Sample 1** **Measurement 1**		
Roughness profile (Ra = 6.69 µm) Performance Variable V3		

Pictures of small features in M3 produced parts and the example of roughness profile for experiments 7, 8 and 9

Aalto University
School of Engineering
Degree Programme in Mechanical Engineering

Sergei Chekurov

Additive Manufacturing Needs and Practices in the Finnish Industry

Master's Thesis

Espoo, May 26, 2014

Supervisor: Professor Jouni Partanen

Thesis advisor: Jukka Tuomi, Lic. Sc. (Tech.)

Abstract

Author: Sergei Chekurov Title: Additive Manufacturing Needs and Practices in the Finnish Industry Date: 26.5.2014	Number of pages: 96
School: School of Engineering Department: Department of Engineering Design and Production Professorship: Kon-15 Production Engineering	
Supervisor: Professor Jouni Partanen	
Instructor: Jukka Tuomi, Lic. Sc. (Tech.)	

The purpose of this thesis is to present the current needs and practices of additive manufacturing in the Finnish industry. To obtain the necessary information, a survey of eight companies was carried out. An introduction to additive manufacturing and its applications is given to give the reader a better understanding of the survey.

A survey was designed and the process explained. The main tool, the questionnaire, was chosen to be the best option to conduct the survey and was designed to consist of a combination of open questions and scale questions. The questionnaire was presented to eight companies of varying size in the research and development industry. Fifteen people from these companies were chosen for the survey.

All of the qualitative answers were analytically quantified and expanded upon. The findings of the survey were compared to the findings of other worldwide reports.

The results obtained through this study include data regarding familiarity of AM technologies, ownership of machinery, outsourcing practices, and general perception of AM in Finnish companies.

It was found that while the Finnish industry is somewhat lagging behind on some fronts of AM usage, the trend is showing that AM is becoming more widely understood and its usage in more advanced applications is on the rise.

Keywords: Additive Manufacturing, Rapid Prototyping, Rapid Tooling, Rapid Manufacturing, Industry Survey

Tiivistelmä

Tekijä: Sergei Chekurov Nimi: Materiaalia lisäävän valmistuksen tarpeet ja käytännöt Suomen teollisuudessa Pvm: 26.5.2014	Sivuja: 96
Korkeakoulu: Insinööritieteiden korkeakoulu Laitos: Koneenrakennustekniikan laitos Professuuri: Kon-15 Tuotantotekniikka	
Valvoja: Professori Jouni Partanen	
Ohjaaja: Tekniikan lisensiaatti Jukka Tuomi	
Tämän työn tarkoituksena on esittää Suomen teollisuuden nykytarpeet ja käytännöt materiaalia lisäävään valmistukseen liittyen. Työssä suoritettiin haastattelututkimus kahdeksassa yrityksessä vaaditun tiedon saamista varten. Työssä annetaan lyhyt johdatus materiaalia lisäävään valmistukseen tutkimuksen parempaa ymmärtämistä varten. Haastattelututkimus kehitettiin ja prosessi selitettiin. Pääasiallinen työkalu tutkimuksessa, kyselykaavake, valittiin parhaaksi tavaksi suorittaa tutkimus. Kyselykaavakkeeseen sisällytettiin avoimia kysymyksiä ja skaalakysymyksiä. Kysely suoritettiin kahdeksassa erikokoisessa tuotekehitysyrityksessä. Viisitoista ihmistä valittiin haastateltaviksi. Kaikki kvalitatiiviset vastaukset kvantifioitiin analyyttisesti. Tutkimuksen tuloksia verrattiin muihin maailmalla suoritettuihin tutkimuksiin. Tutkimuksen tulokset sisältävät tietoa suomalaisen teollisuuden AM-tekniikoiden tuntemuksesta, koneiden omistamisesta, ulkoistamiskäytännöistä, sekä yleisistä käsityksistä liittyen AM-tekniikoihin. Tutkimuksesta ilmeni, että Suomi on jonkin verran muuta maailmaa jäljessä AM-tekniikoiden omaksumisessa, mutta trendi osoittaa, että adoptio on käynnissä ja kehittyneempien sovellutusten käyttö on nousussa.	
Avainsanat: Materiaalia lisäävä valmistus, Rapid Prototyping, Rapid Tooling, Rapid Manufacturing, teollisuuskysely	

Acknowledgements

The work presented in this thesis is a part of the research conducted as a part of the SuperMachines project initiated as collaboration between Aalto University and a consortium of companies involved in the additive manufacturing business.

I would like to thank the companies involved in the SuperMachines project, the companies that participated in the survey, and especially Risto Ojala of Multiprint Oy.

In addition, my gratitude goes to the instructor of the thesis Jukka Tuomi, the supervisor of the thesis professor Jouni Partanen, and everyone else in the 3D manufacturing research group.

A very special thank you to doctor Mika Salmi for sharing his experience and making sure that the thesis gets written.

in Espoo 26.5.2014

Sergei Chekurov

Contents

Glossary and abbreviations

3DP	Three-Dimensional Printing
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
.AMF	Additive Manufacturing File Format (file format)
EBM	Electron Beam Melting
DLP	Digital Light Processing
DM	Direct Manufacturing
DPP	Direct Part Production
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
HDPE	High-density polyethylene
LENS	Laser-Engineered Net Shaping
MJM	Multijet Modeling
PC	Polycarbonate
PCL	Polycaprolactone
PEEK	Polyether Ether Ketone
PLA	Polylactic Acid
R&D	Research and development
RM	Rapid manufacturing

RP	Rapid prototyping
RT	Rapid tooling
RTV Silicone	Room Temperature Vulcanizing Silicone
SHS	Selective Heat Sintering
SL	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
.*STL*	STereoLithography (file format)
UAM	Ultrasonic Additive manufacturing

1 Introduction

Additive manufacturing (AM) is a group of technologies that create physical objects using digital files containing a three-dimensional representation of parts without the use of traditional molding techniques. All AM technologies produce parts by constructing them layer by layer, but they can be divided into seven categories of processes, each using different materials and a unique way of producing the layers. [1]

The invention of the first viable AM process, stereolithography, is credited to Charles W. Hull in 1986. Using that as a reference point AM technology is 27 years old at the time of writing, making it a relatively young technology. During the past decades AM has improved significantly from the state it was in at the beginning of its lifespan. In the past, using AM was only possible with polymer based materials, whereas now producing parts out of metallic and ceramic materials is possible. [2]

Until the developments in the last decade, AM was considered a technology used exclusively for rapid prototyping (RP), causing it to be named after the application. Nowadays AM is not limited to producing prototypes but can also be employed in tooling purposes (rapid tooling, RT) and in direct part manufacturing (rapid manufacturing, RM). This development is important because it allows for a far wider range of applications for AM, and it is important that companies recognize these advancements. [1]

The biggest technical challenges of AM are limited speed, accuracy, nonlinearity, build volume and cost. Due to these reasons, conventional manufacturing is more efficient in high volume production. In low level parts with high geometrical complexity, nevertheless, AM is rapidly gaining prominence as companies such as NASA, Boeing and Renault are starting to use it on a large scale [2]. Apart from speed, reasons to use AM are generally divided into four categories, which are user-fit requirement, improved functionality, parts consolidation, and aesthetics [3]. To use the full potential of AM, the parts that are created using AM technology should be designed according to a new set of restrictions and possibilities. One such possibility is the geometrical optimization of parts from the perspective of stress distribution [4]. An example of AM usage is a re-engineered latch that allows for tighter installation and optimized geometries, shown in Figure 1.

Figure 1: Traditionally manufactured latch on top. Latch re-engineered for AM at bottom. [5]

The goal of this thesis is to map out the extensity of the use of additive manufacturing (AM) in different sectors of the Finnish industry and compare them to that of other countries. Additionally, this thesis will evaluate the progress of the spreading of AM and provide guidelines to further speed up its creep. Global state of the art reviews are done on a yearly basis by several research centers [6]. However, the country specific information they provide is not extensive and commonly focuses on AM technology development companies and research centers. In order to review the actual use of AM, a survey consisting of a series of interviews was conducted. Eight Finnish companies were interviewed and the results were consolidated in order to preserve the non-disclosure agreements.

A variety of factors were investigated in order to get a clear view of the current usage of AM. The ownership of machinery was looked into and reasons for owning and operating certain machinery in a certain way was examined. Reasons and criteria for outsourcing AM services were looked into.

2 Overview of Additive Manufacturing technologies

Additive manufacturing is a term used to describe the technologies, process and use that makes possible the rapid production of parts from digital data. Using AM eliminates or radically diminishes the importance of pre-production planning and depending on the application reduces R&D cycle time or improves performance of the final product [1].

While all AM technologies follow the same concept of delivering parts without the need of tooling, they differ from each other and are classified according to an ASTM standard. All of the technologies also have different characteristics that limit their use to different applications. The applications in the industry can be divided into three rough categories: rapid prototyping, rapid tooling, and rapid manufacturing, each divisible into subcategories. The need to divide the technologies into classes and the applications into categories is not solely academic. Companies rely on these denominations when considering adopting AM technology and when looking to produce a certain part. [7] The distribution of AM usage by industrial sectors is provided in Figure 2.

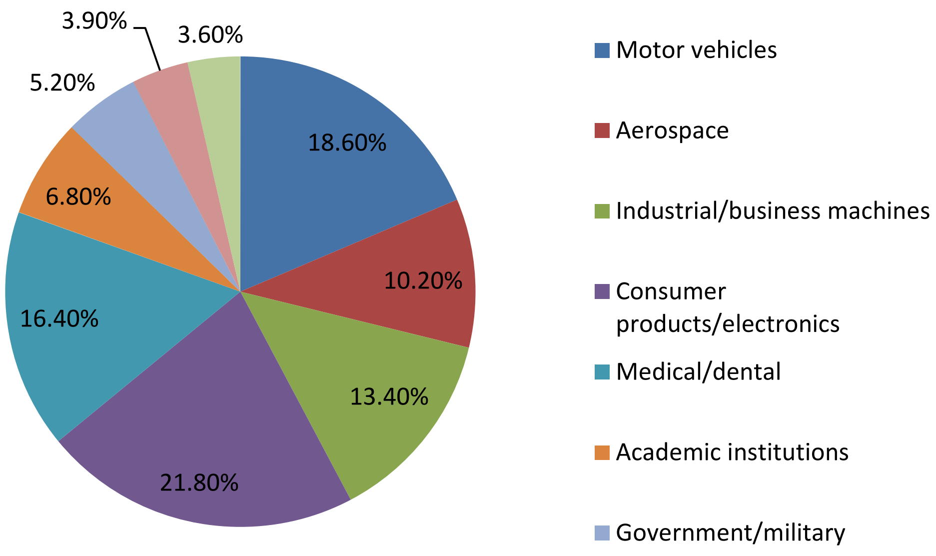


Figure 2: AM usage by industrial sector [6]

Motor vehicles, aerospace, industrial/business machines, and consumer products/electronics amount to a total of 64% of all AM usage. This thesis will primarily focus on investigating the needs and practices of the industrial/business machines and consumer products/electronics sectors which together cover 35.2% of AM usage.

3 Classifications of AM

Even though all of the current AM technologies produce parts by constructing one cross-section at a time, their work principle varies. The range of the way of producing layers on top of each other varies from using lasers to melt plastic powder to cutting and gluing sheets of paper. This has an effect on the main attributes of parts manufactured with additive manufacturing: size, cost, accuracy, and material. The technologies can be divided into classes according to their technical processes or according to their applications. [8]

3.1 Classification of technologies

The technical terminology of AM technologies has been standardized by dividing them into seven different categories. These categories are binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, sheet lamination, and vat photopolymerization [9].

A short description of the seven categories is given in this chapter and the most common technologies associated with the categories are presented in table 1.

Table 1: Classification of AM technologies

Technology	**Category**
Three Dimensional Printing (3DP)	Binder jetting
Laser-Engineered Net Shaping (LENS)	Direct energy deposition
Fused Deposition Modeling (FDM)	Material extrusion
Polyjet	Material jetting
Selective Laser Sintering (SLS)	Powder bed fusion
Selective Laser Melting (SLM)	Powder bed fusion
Electron Beam Melting (EBM)	Powder bed fusion
Selective Heat Sintering (SHS)	Powder bed fusion
Laminated Object Manufacturing (LOM)	Sheet Lamination
Stereolithography (SL)	Vat photopolymerization
Digital Light Processing (DLP)	Vat photopolymerization

The most common technology used by service providers worldwide is stereolithography (SL), the second most common is Fused Deposition Modeling (FDM) and third most common is Selective Laser Sintering (SLS) [6]. In order to better introduce the general idea of how AM technologies work and how severely they differ from each other, a description of each process is given, advantages and disadvantages are discussed and material choices presented.

3.1.1 Binder jetting

Binder jetting is a powder based process in which a liquid bonding agent is deposited according to the cross-section of an object [9]. Although most commonly used with gypsum, sand and metallic materials are also used. In the case of plastics a layer of colored ink can be deposited on top of the each powder to give the part a colored outer shell. When using binder jetting technologies that allow the use of metallic materials, the final part needs to be sintered and infiltrated with another metal for the part to be durable. The commercial name for binder jetting is 3D Printing (3DP). [1]

3.1.2 Direct energy deposition

Direct energy deposition is a metallic process closely associated with welding. A stream of metallic powder or metallic wire is projected onto a pre-existing object and a heat source is used to melt the powder on top of it [9]. The most notable commercial brands using this approach include direct metal deposition (DMD), laser consolidation (LC), and laser-engineered net shaping (LENS) [1].

3.1.3 Material extrusion

Material extrusion is an approach that melts solid material and extrudes it selectively onto an x-y plane [9]. As this type of technology has the largest installed base of AM machines, its working principle is explained in detail through commercial brands.

Fused deposition modeling (FDM), or fused filament fabrication (FFF), is a material extrusion technology which uses filaments of plastics to extrude layers in order to create parts. An FDM or FFF process set-up consists of a movable build platform, extrusion nozzles, and a build material spool.

Filament material is fed from the build material spool to the heated extrusion nozzles which proceed to melt the material on extrude it onto the build platform in the form of a 2D cross-section of a part. If the machine is equipped with multiple nozzles, the secondary nozzle can extrude support material on the same layer. Once the layer is done, the build platform is lowered by the thickness of one layer, and the extrusion nozzles continue building the second layer.

Once all layers of the part are done, the part is removed from the machine. Post processing in FDM or FFF only requires the user to submerge the part in an ultrasonic bath to remove the water soluble support material. A variety of optional post processing methods exist for the technology, such as using acetone vapor to smooth the part from the outside [2]. A schematic of the set-up of and FDM or FFF machine is presented in Figure 3.

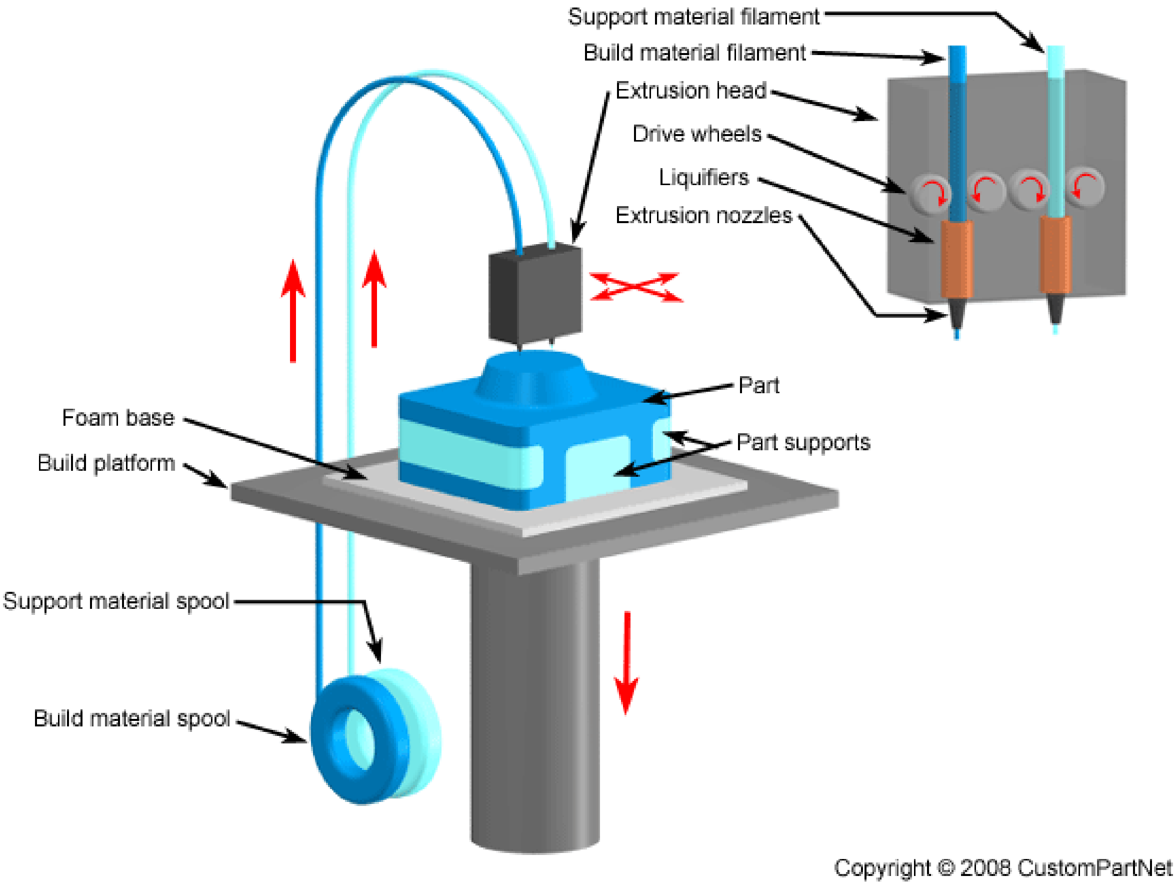


Figure 3: A schematic of an FDM or FFF set-up [10]

FDM or FFF technology ranges from very low end machines to high end machines. The technology operates in an open air environment which requires it to use supports in order to build parts with overhang structures. The ease of the post processing is one of its advantages as it is completely hands-off. The materials for FDM or FFF include plastics such as ABS, PLA, PC, Nylon, HDPE, and PCL. [2]

3.1.4 Material jetting

Material jetting is based on selectively depositing droplets of ultraviolet-curable materials on a plane and subsequently curing them with ultraviolet light [9]. The materials compatible with the technology are photopolymers and wax-like materials. The commercial brands that use this approach are PolyJet and multi-jet modeling (MJM) [1].

3.1.5 Powder bed fusion

Powder bed fusion works on the principle of selectively focusing energy on a cross-section of powder to bind it together [9]. Powder bed fusion technologies represent some of the most widely spread technologies and is explained in detail through the commercial brand selective laser sintering (SLS).

Selective laser sintering (SLS) is a powder bed fusion process in which plastic powder is sintered by a laser and bound to the layers of material below it. An SLS process consists of two or three chambers, one of which is the build chamber and one or two are powder supply chambers, pistons to raise or lower the powder in the chamber, a leveling roller or blade, lenses, and a scanning mirror. [2]

At the beginning of the process the build chamber is empty and the powder feed supplies are full. The process starts by moving one of the feed pistons up by a distance that is equivalent to the desired thickness of one layer in the final part and lowering the build piston an equal distance. A leveling roller or a blade moves from behind the elevated powder supply chamber, spreads the powder evenly on the build chamber and positions itself either behind the second powder supply or returns to the original position depending on the machine. A laser then activates and projects a beam into the lens system, which focuses the beam and sends it to the mirror which in its part projects the beam onto the build chamber surface and traces a cross-section of a part. Once the process reaches this stage the laser de-activates, the pistons move in their intended directions and the work starts on a new layer. This process is continued until all layers of the part are produced. Once the part is ready it is removed from the machine and all excess powder removed. [1]

SLS is capable of using nylon 11 and nylon 12 powders and PEEK. Composites of nylon materials are created for the process by mixing the nylon with other powders such as glass, carbon, or aluminum. One of the most notable advantages of SLS is the fact that due to the part being surrounded by powder it does not need support structures. This allows for a greater degree of freedom in designing objects [11]. SLS is also the best technology to be used in order to produce parts with moving features, including joints [12]. The set-up of an SLS machine is presented in Figure 4.

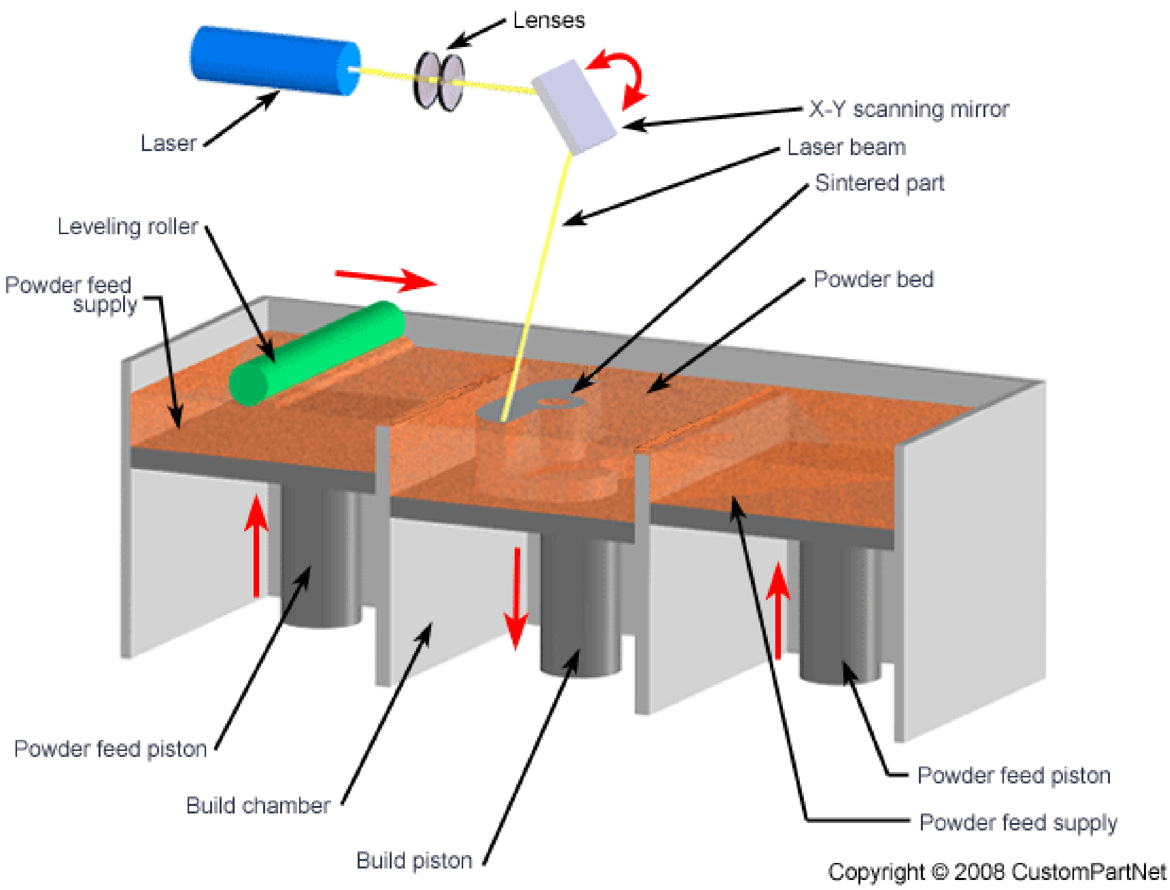


Figure 4: A schematic of an SLS set-up [13]

Other commercial brands based on powder bed fusion include selective laser melting (SLM), direct metal laser sintering (DMLS), electron beam melting (EBM) and selective heat sintering (SHS). SLM and DMLS work in the general same way as SLS but replace the carbon dioxide laser with an ytterbium fiber laser and work in an inert gas-filled environment which allows it to melt metallic powders. EBM follows the same concept but replaces the laser with an electron beam and the gas environment with a vacuum. SHS is very similar to SLS but replaces the laser with a heat thermal print head in order to lower the cost of the process. Parts produced with a powder bed fusion method require extensive post processing in the form of machining and placing the part in a furnace. [6]

3.1.6 Sheet lamination

Sheet lamination is a method of AM in which sheets of material are placed on top of each other and bonded together [9]. This can be achieved by preparing the cross-sections beforehand and stacking them or by stacking layers of material first and cutting a contour of a cross-section of the part on each layer. Notable commercial brands using this method are laminated object manufacturing (LOM) using paper, and ultrasonic additive manufacturing (UAM) using metal tapes and foils. [6]

3.1.7 Vat photopolymerization

Vat photopolymerization is a process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization [9]. Stereolithography (SL) is a vat photopolymerization process in which a laser is used to cure photopolymer resin to for solid parts. The process set-up consists of a vat, a build platform, an elevator, a sweeper, a laser, lenses, and a scanning mirror. In some variations of the process, the elevator is replaced with a piston underneath the build platform.

The build platform is lowered into the vat and the sweeper deposits photopolymer resin across the platform in the thickness of one layer of the final part. A laser then activates and sends a beam to be focused by the lenses and from there to a mirror that scans a 2D cross-section of the part.

Once the layer is done, the laser de-activates, the build platform is lowered by the thickness of one layer, and the process starts again by adding more photopolymer resin. After all layers have been finished the build platform is raised and the part taken out of the machine. Stereolithography requires post processing in which the part is first submerged into a chemical bath to remove excess resin and then placed in an ultraviolet oven to cure it further. [1]

The schematic of the process of stereolithography is presented in Figure 5:

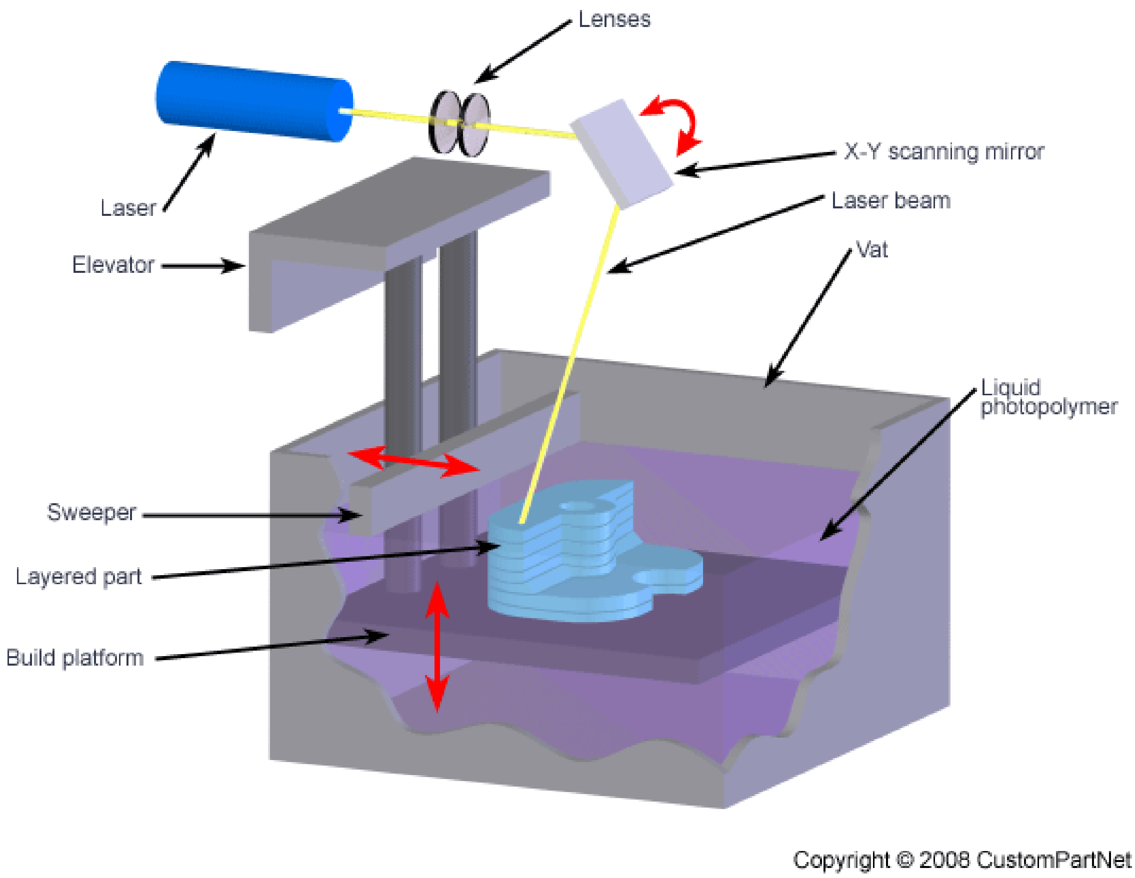


Figure 5: Sterelithography process schematic [14]

Stereolithography is one of the most accurate technologies available and it allows layer thicknesses as low as 0.05 mm. As the resin cannot physically support solidified parts of the build, support structures are needed for overhanging features. Stereolithography is one of the faster technologies but is also one of the more expensive ones. Materials used for stereolithography are proprietary resins manufactured exclusively for the process and varying in attributes from strength to flexibility. [15]

3.2 Classification of applications of AM in the industry

Industrial applications of AM are generally divided into three categories: rapid prototyping (RP), rapid tooling (RT) and rapid manufacturing (RM). It should be noted that the classification of applications in this chapter only applies in industrial use and that it does not fit the applications in the medical field. [16]

3.2.1 Rapid prototyping

Prototyping is the action of producing an approximation of a product. A prototype can be analytical, digital, or physical. The scale of a prototype can be defined by its dimensions of interest which are singular features that are in the need to be examined and iterated before finalizing the product. In the field of product development and R&D it is common to create two separate prototypes, one which looks like the final product and one that works like the final product. [17]

Rapid prototyping is producing a physical representation of an object in a manner that is rapid compared to conventional manufacturing. RP is mostly used in R&D where it serves to increase the iteration speed and produce tangible prototypes for verification of feel and proportion. [18]

RP can be divided into visual prototyping and functional prototyping. Visual prototyping entails using AM to produce parts solely for visual and limited tangible examination to physically present the design attributes such as dimensions. In functional prototyping a part is created to showcase its functionality. Assembly tests can be performed on both prototyping categories although functional prototypes tend to be more accurate. Visual prototypes typically do not contain moving parts whereas functional prototypes do. [6]

3.2.2 Rapid tooling

Rapid tooling (RT) can be divided into indirect tooling and direct tooling. In indirect tooling a mold is manufactured using a master created using AM. An example of indirect tooling is investment casting. In direct tooling a tool is created directly using AM. An example of direct tooling is conformal cooling used widely in plastic injection molds to improve the geometry of cooling channels. [16]

Conformal cooling is a method of creating cooling channels in a way that is challenging or impossible with traditional machining. Commonly, the cooling channels take the form of a spiral or, as the name suggests, conform to the shape of the object itself [19]. Traditionally cooling channels have to be created by drilling or boring, which means that the channels have to all be straight and in some designs the excess holes have to be plugged as shown in Figure 6.

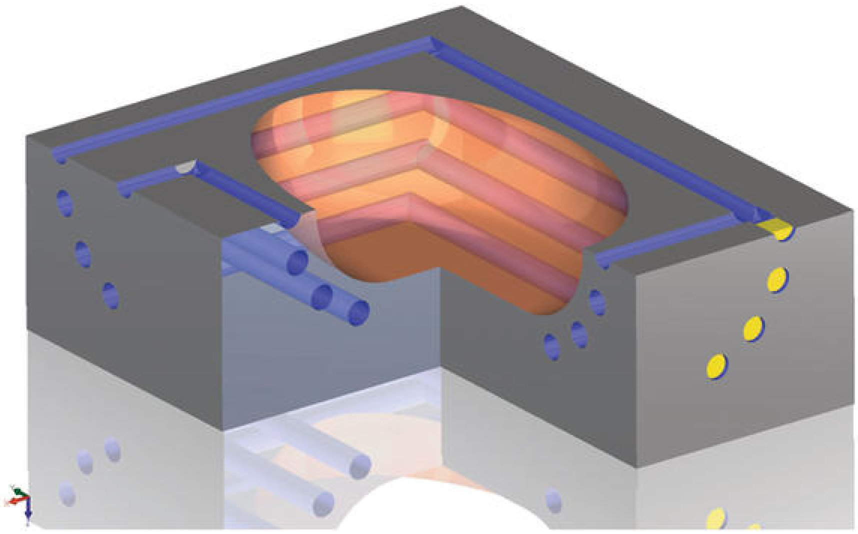


Figure 6: Traditional cooling channels in an injection mold. [20]

Conformal cooling can be used either in parts themselves, as shown in the example in Figure 7, or it can be used in production molds, as shown in Figure 8.

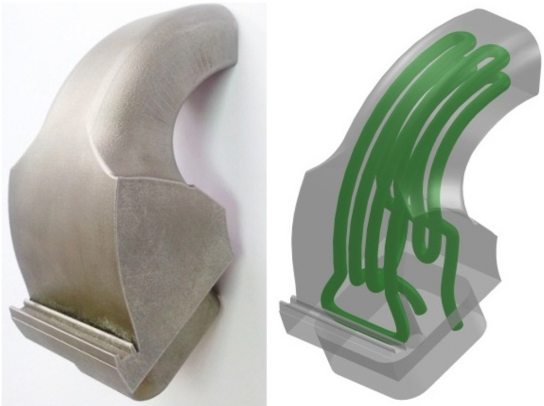


Figure 7: Conformal cooling in a part. [21]

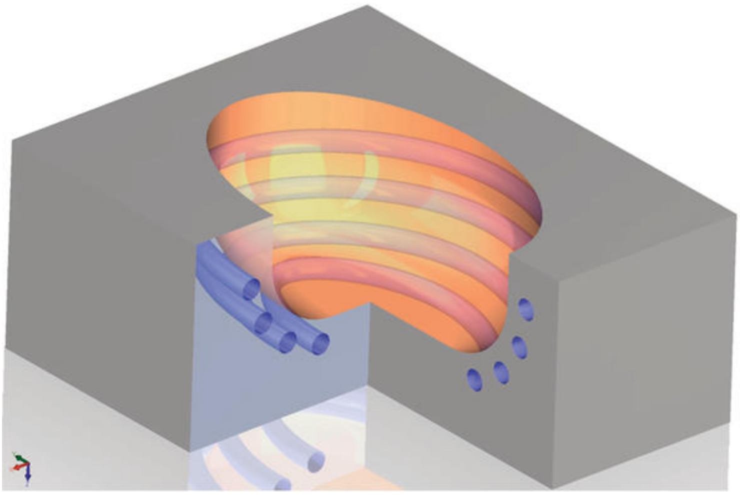


Figure 8: Conformal cooling in an injection molding mold. [20]

Silicone molding is an indirect method for producing low volume batches of silicone parts using AM. In silicone molding a master model is created using vat photopolymerization, which is post processed to achieve the required surface finish.

Liquid room temperature vulcanizing silicone (RTV silicone) is then poured on top of the master model and left to cure. Once cured, the silicone mold is split in half and is then ready to be used as a low volume injection mold. [22]

The process of direct mold tooling includes creating a two-part negative mold directly with a sufficiently accurate technology, such as vat photopolymerization, post processing to achieve the desired surface properties, pouring liquid silicone inside the mold and closing it for curing. This process creates silicone parts. Using processes capable of producing metallic parts, metallic injection molds can be manufactured directly using AM. [23] Sand molds are possible to manufacture using binder jetting AM technologies [24]. Figure 9 demonstrates direct mold tooling.

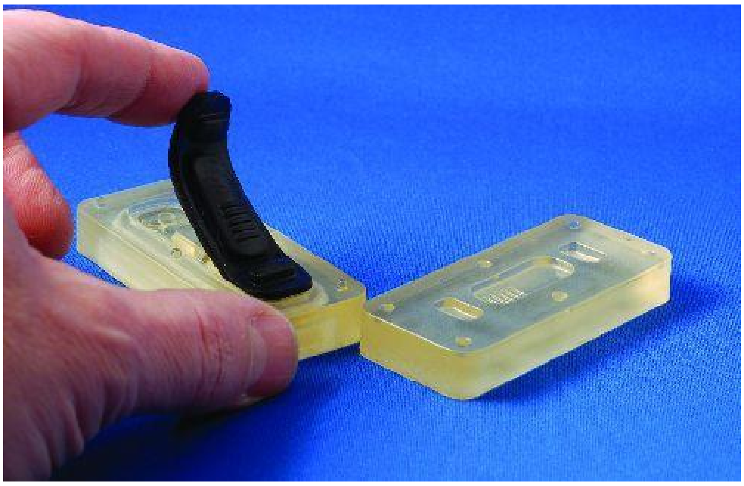


Figure 9: Direct mold tooling. [25]

Investment casting is used in conjunction with AM to create metal parts with minimal molding. The process includes using a master created with AM using materials of low ash content such as wax and certain plastics. [26] The master is coated with ceramic slurry, gas exhaust channels added, and after a period of drying the master is burned out leaving a hollow ceramic shell to cast liquid metal into. After the casting, the shell is cracked and excess material removed from the part by machining. [24] Figure 10 demonstrates the process of investment casting.

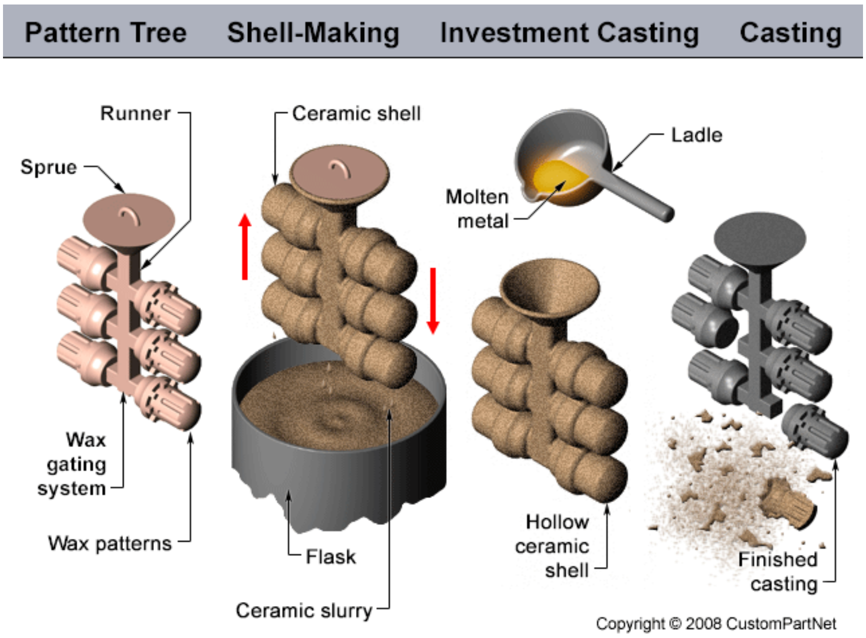


Figure 10: Investment casting. [27]

3.2.3 Rapid manufacturing

Rapid manufacturing (RM), also referred to as direct part production (DPP) and direct manufacturing (DM), is creating the part directly for end use using AM. Depending on the needs of the user, plastics or metals are used. In order to achieve the quality of a finished product, extensive post processing is usually required. In 2012 the share of direct part production was 28.3% which is a considerable percentage compared to 3.9% it was in 2003. While in the medical industry producing parts with AM is commonplace, it has only niche applications in the industry. [6] [28]

3.3 Previous surveys on AM

In order to accurately assess the needs and practices of the Finnish industry it was essential to take a look at past research done in the field. The most relevant reports to this thesis were Wohlers report 2013 [6], Selvitys 3D-tulostuksen tilanteesta Suomessa [29], and Thinking ahead the Future of Additive Manufacturing [30].

3.3.1 “Wohlers report 2013”, 2013

Wohlers 2013 conducted a survey on 74 service providers from 19 different countries, the closest one to Finland being Sweden. Additionally, Wohlers report 2013 contains state of the art reports from 23 countries written by AM experts from each country. Such information would prove useful for this thesis but it is unfortunately provided on a very large scale without going into details. The report contains information on the distribution of AM usage. This information is presented in Figure 11.

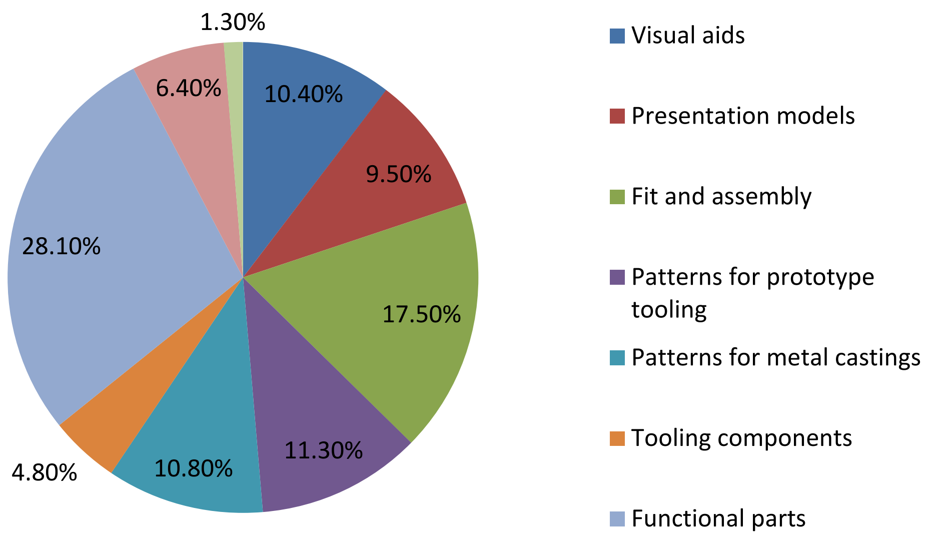


Figure 11: distribution of AM usage. [6]

As can be seen from Figure 11 functional part production is at 28.1%, tooling components at 4.8%, patterns for prototype tooling at 11.3%, patterns for metal castings 10.8%, fit and assembly 17.5%, presentation models 9.5%, visual aids 10.4%, education and research at 6.4%, and other uses at 1.3%.

In order for this information to be relevant to the thesis, it needed to be formatted to correspond with the RP/RT/RM model presented earlier. Presentation models and fit and assembly can be seen to be rapid prototyping. Patterns for prototype tooling and metal castings and tooling components are rapid tooling and functional part production translates well into direct manufacturing. Taking this into consideration and leaving out educational and other use, the distribution of RP/RT/RM of AM according to Wohlers is shown in Figure 12.

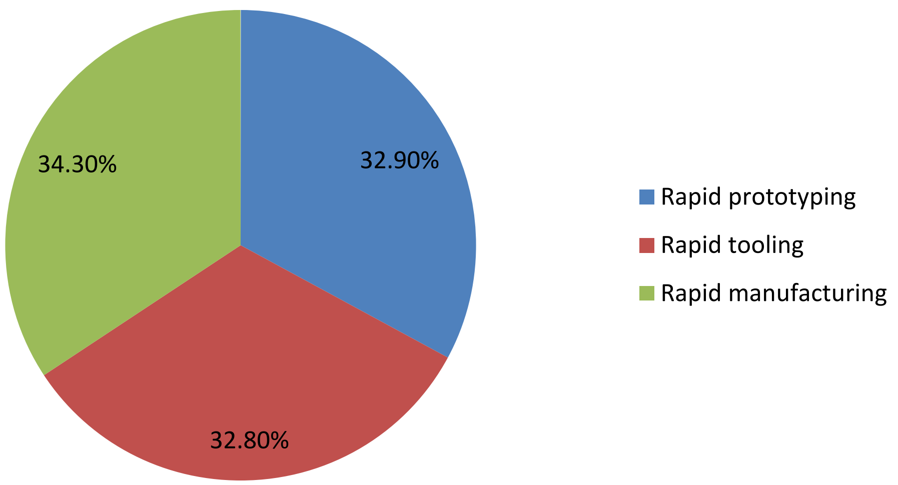


Figure 12: Distribution of applications of AM formatted in RP/RT/RM.

Transformed into the RP/RT/RM format the distribution of applications according to Wohlers is very closely divided into equal categories with RP having 32.9%, RT 32.8% and RM 34.3%.

The data in the Wohlers report regarding the distribution of technologies employed by service providers is presented in Figure 13.

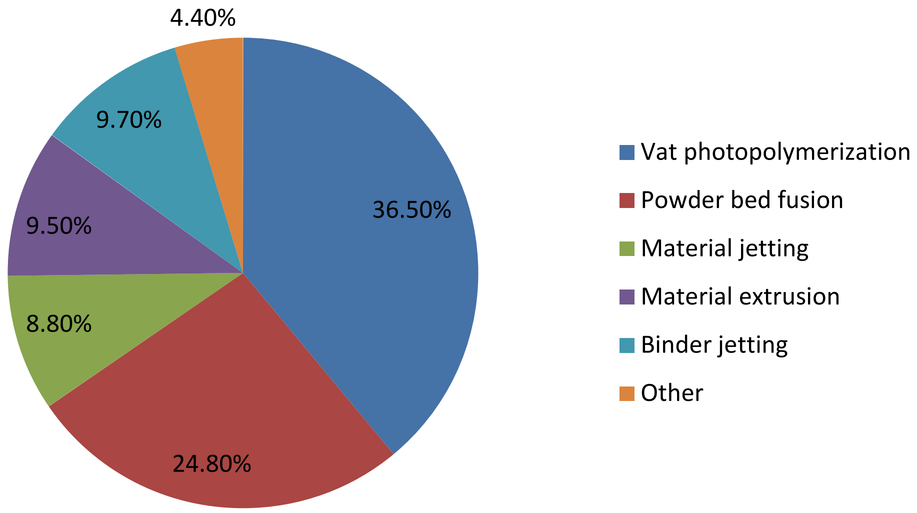


Figure 13: Share of technologies used by service providers worldwide [6]

Vat photopolymerization and powder bed fusion form a 61.3% share of all AM technologies used by AM companies. Using powder bed fusion processes such as SLS has many advantages for service providers that include high process stability, high accuracy, relatively low cost of material, and easy post processing. The large share of vat photopolymerization can be partially explained by the accuracy of the process and a large material library available for stereolithography but it should be noted that while stereolithography has currently the largest install base, it is in a steady decline. [6]

3.3.2 “An investigation of the state of the industry of 3D printing in Finland”, 2011

In 2011 Oulu University of Applied Sciences released the thesis work of Jarkko Lohilahti with the topic of “Selvitys 3D-tulostamisen tilanteesta Suomessa” which translates to “An investigation of the state of the industry of 3D printing in Finland”. The goal of the thesis was to map out the AM service providers of the Oulu region and compare them to the service of Oulu PMC. Another goal of the thesis was to find a preparative way to monetize 3D printing and to create a draft of marketing material. The thesis compared five service providers including Oulu PMC. Financial information of the service providers was provided. A grading system was created to include evaluation of the web pages, marketing, machinery, utilization time and turnover of the service providers. No surveys were conducted that included the personnel of the service providers or industrial companies. [29]

3.3.3 “Thinking ahead the Future of Additive Manufacturing”, 2013

The Direct Manufacturing Research Center (DMRC) of the University of Paderborn released a study concerning the future prospects of AM. Two surveys were conducted for the study. The first survey was conducted on 325 experts in the field. The survey was completed by 56 of the experts amounting to a 17% response rate. The survey consisted of four parts; the first one addressing the professional background of the experts, the second asking the experts to assess multiple general requirements for AM, the third asking more specific questions concerning AM technologies, and the fourth outlining final statements of the experts.

According to the results, 41% of the respondents were users but no distinction was made between service providers and industrial companies. It is indicated in the report that 77.3% of the users used AM for direct manufacturing, 72.7% for rapid prototyping, 54.5% for rapid tooling, and 4.5% for other purposes. Direct manufacturing is another term for rapid manufacturing. These figures are different compared to the ones in Wohlers report which can be explained by the fact that multiple choices were allowed in this questionnaire. These results are presented in Figure 14.

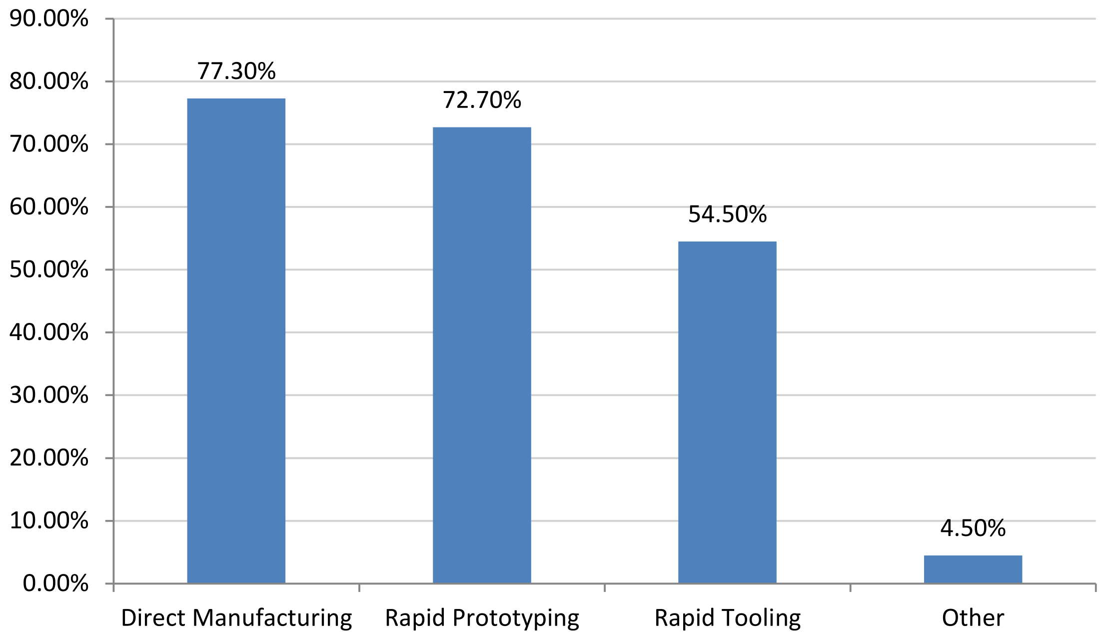


Figure 14: Percentage of users using certain applications [30]

According to the study, the experts valued high process stability, databases containing material properties, quality control processes, continuous certification, design rules, recyclability of materials, possibility to use carbon-fiber-reinforced polymers, fire resistance of AM materials, larger build chamber volumes, faster build speeds, better surface quality, higher dimensional accuracy, and lower maintenance costs. A large portion of the study focused on expert opinions on the future development of powder bed fusion processes.

The second survey was conducted on 395 experts out of which 75 answered which gave a 19% answer rate. In this study 50% of the respondents identified as users. This time 78.6% of the users reported to be using direct manufacturing, 64.3% rapid prototyping, 31.4% rapid tooling and 15.7% reported to be using AM for other purposes. While the amount of participants using direct manufacturing and rapid prototyping stayed roughly the same, the amount of participants using rapid tooling had declined by 23.1% and the amount of users using AM for other purposes rose by 18.6%. [30]

3.3.4 "AM in South Africa: building on the foundations", 2011

In 2011 Ian Campbell, Deon de Beer and Eujin Pei from the Vaal University of Technology, Vanderbijlpark, South Africa, released an article in rapid prototyping journal concerning the state of the industry of AM in South Africa.

The report states that South Africa had an install base of 138 AM machines at the time of writing of the report. Out of the 138 machines, 120 were low end FDM machines and 18 unspecified high end AM machines. The report also states that 91% of the machines in the industry were low end FDM machines and 82% of the machines in universities and research centers were high end machines. [31]

4 Assessing the needs and practices of AM in the industry

In order to understand the needs and practices of AM in the Finnish industry, an investigation into the steps required to run a survey was conducted. Appropriate works of literature were chosen as guides.

The five stages in the development and completion of a survey according to Ronald Czaja [32] are the following:

1. Survey design and preliminary planning
2. Pretesting
3. Final survey design and planning
4. Data collection
5. Data coding, data-file construction, analysis, and final report

These first part of the process, designing the survey and planning its execution, includes going through the goals and methods of the survey, determining who and how many companies and people were to be surveyed, looking into available resources, designing the questionnaire, and preparing guidelines to analyze the data.

4.1 Goals

The goal of the assessment was to find out how and how much the Finnish industry was using AM and what lead them to specific choices. The points of interest outlined for this goal are the following.

- Mapping out how well different AM technologies are known and how they are being utilized

- Understanding how companies procure machinery, what machines they have, and how they use them
- Understanding company practices in outsourcing, how much of their AM activity is outsourced, and what are the reasons behind this
- Acquiring a hypothetical link between ownership of machinery and outsourcing of AM activity through the means of finding general information concerning both.

4.2 Determining sampling decisions

As it was not viable to investigate every single company in Finland to determine how they are using AM or if they are using AM at all, a decision had to be made to narrow down the list of companies to those that potentially use AM. The first criterion for being accepted to the list of potentially surveyed companies was that they should be in one of the fields cited as users of AM in Wohlers report 2013 which meant that companies in the following fields qualified:

- Motor vehicles
- Aerospace
- Industrial/business machines
- Consumer products/electronics
- Medical/dental
- Academic institutions
- Government/military
- Architectural

Because the goal of the survey is to find out how AM is used for industrial purposes in Finland, a second criterion was put into place demanding that the companies must be industrial, leaving the following fields as acceptable categories for companies to survey:

- Motor vehicles
- Aerospace
- Industrial/business machines
- Consumer products/electronics

Keeping the two criteria in mind, AM experts were consulted on which companies would fit the profile. The list of potential companies consisted initially of 28 companies, of which eight agreed to be interviewed, which gives a reply rate of 29% which is slightly higher than the 19% response rate cited in University of Paderborn's survey. [6] [30]

The hesitant approach of the companies is explained through a variety of reasons. Most of the companies did not agree to be interviewed because of their lack usage of AM. Some companies refused to participate on the grounds that their practices in usage of AM are sensitive. Others declined citing lack of time.

The remaining eight consisted of both small and medium-large companies. The majority of the companies were in the field of consumer products and electronics and the rest were in the field of industrial and business machines. No companies from the motor vehicles and aerospace fields chose to participate.

4.3 Choice of interviewees

The interviewees within the companies were chosen on the grounds of being close to the usage of AM or being decision makers regarding the technologies in use. Fifteen employees spread as evenly as possible between the companies were chosen to be interviewed. Among occupations of the interviewees were machine operators, production managers, project managers, industrial designers, CAD specialists, and CEOs.

4.4 Determining available resources

In order to properly plan the scope of the survey an evaluation of available resources was necessary. The resources needed to conduct the survey were the amount of people working on the survey, the cost of conducting the survey, and the duration of time until the survey had to be done. The staff of the survey consisted of a master's thesis worker whose salary was covered by the budget of the survey, and the duration of time until delivering final results was five months.

4.5 Questionnaire

One of the most important decisions to make when constructing a questionnaire is to decide whether to make the questions open-ended or closed-ended, which roughly correspond with qualitative and quantitative methods. The United States department of energy uses the comparison chart shown in Table 2 to determine how their surveys should be structured.

Table 2: Qualitative/quantitative comparison chart [33]

Qualitative Methods	**Quantitative Methods**
Methods include focus groups, in-depth interviews, and reviews	Surveys
Primarily inductive process used to formulate theory	Primarily deductive process used to test pre-specified concepts, constructs, and hypotheses that make up a theory
More subjective: describes a problem or condition from the point of view of those experiencing it	More objective: provides observed effects (interpreted by researchers) of a program on a problem or condition
Text-based	Number-based
More in-depth information on a few cases	Less in-depth but more breadth of information across a large number of cases
Unstructured or semi-structured response options	Fixed response options
No statistical tests	Statistical tests are used for analysis
Can be valid and reliable: largely depends on skill and rigor of the researcher	Can be valid and reliable: largely depends on the measurement device or instrument used
Time expenditure lighter on the planning end and heavier during the analysis phase	Time expenditure heavier on the planning phase and lighter on the analysis phase
Less generalizable	More generalizable

While quantitative methods are more objective, cover a large number of cases, and are more generalizable, qualitative methods provide more in-depth information.

In order to produce results that are easily comparable to each other and scientifically valid, the method of data acquisition had to be of a quantitative nature. However, many of the goals were too ambiguous to be answered with a closed-ended question.

As a result of evaluation between different types of assessment methods, a multi-part questionnaire consisting of both qualitative and quantitative questions was devised in order to gather data. The qualitative answers would then be converted into quantitative data. Because of the fact that the resulting questionnaire contained open-ended questions, the best approach was seen to be a personal interview with each interviewee. This approach consumes more time in the data gathering and analysis stages but as there were enough resources it was deemed acceptable.

Questionnaires are typically organized into sections that follow the logic of the pursuit of the survey's goal. [32] The questionnaire was made to consist of five parts. The first and fifth parts were completely quantitative and second, third, and fourth part contained multiple qualitative questions. Each interview lasted between an hour and two hours.

The introductory first part consisted of assessing how familiar the interviewee was with certain technology brands. This was deemed to be a good way to introduce the interviewee to the goals of the survey and to make them more inclined to give more straightforward answers in the content heavier parts of the interview. The familiarity of technology brands was graded in binary. The technology brands examined were:

- Three dimensional printing
- Laser cladding
- Fused deposition modeling
- PolyJet
- Selective laser sintering
- Selective laser melting
- Electron beam melting
- Selective heat sintering
- Laminated object manufacturing
- Stereolithography
- Digital light processing

The second part focused on the ownership of machinery inside the company and consisted of the following questions:

1. Do you own AM machinery?
    a. Which technologies/machines do you own?
    b. On what grounds were they chosen?
2. Who operates the machinery?
3. What are the practices of maintenance of the machines and are the machines upgraded?
4. How high is the utilization rate of the machines?

The third part focused on the outsourcing of AM parts and consisted of the following questions:

1. Do you outsource manufacturing of AM parts?
2. Could a part of the manipulation of CAD parts be outsourced?
3. How secret are the CAD files?
4. How is it decided what to outsource?
5. Is secrecy a deciding factor in outsourcing?
6. Is quality assurance carried out on the outsourced parts?
7. Are the costs of outsourced parts monitored?
8. Are there technologies that the company would like to use but the investment costs are too high?
9. Is there a need to use a certain technology but they are not available?

The fourth part focused on information relevant to both outsourcing and producing parts in-house and contained the following questions:

1. How fast do you receive parts from the moment you have a finished CAD file and intend to print it or outsource it?
    a. Less than a day
    b. Approximately a day
    c. Multiple days

   d. Approximately a week
2. Is there a need to shorten this time or is a slower time acceptable?
3. In which distribution do you use RP/RT/RM?

The fifth part examined the perceived importance of different factors related to AM, which were:

1. Receiving the part quickly
2. Accuracy of the part
3. Suitability of the material
4. Security of CAD files
5. Optimality of processes
6. General knowledge in the field of AM

The questionnaire was tested on AM experts to verify that the questions were valid and the potential data extracted using them was useful.

4.6 Collecting data

Once the companies were selected and contacted to participate in the survey, the data collection process was straightforward. A time slot of two hours was reserved with each employee and a place for the interview was set. The location of the interview varied from interview to interview using Business Innovation Technology’s meeting rooms or available spaces in companies’ premises. If convenient, multiple employees from the same company were interviewed in one session. The data collection period lasted three months.

4.7 Analyzing data and writing a report

It is important to decide what questions are being sought answers for before the actual implementation stage [32]. As was listed in the goals and methods of this chapter, analyzing the data should be from the perspective of technologies, machinery ownership, outsourcing, and general information. These sub-goals were further broken down into topics of interest and data analyzed from their perspective. Quantitative information was to be sorted into tables and charts and qualitative information was to be presented as is and quantified wherever possible.

Mapping out the knowledge and usage of AM technologies was to be divided into a section describing the familiarity of technologies and ranking them according to how many interviewees were familiar with a technology, and a section where each technology was examined and all information given by interviewees explained. A further analysis of the ratio of usage of AM applications was also to be written. The list of viewpoints used to analyze the data was the following:

- Familiarity of technologies
- Individual view of each technology
- Distribution of applications

Analyzing ownership of machinery was to be done by listing how many machines companies owned in average, what their practices were in procuring machinery, who they employed to operate the machines, what was the utilization rate of the machines, how they maintained the machines, what was the average build time, and how they monitored the costs of using the machinery. The list produced to analyze the ownership was the following:

- Practices in procuring AM machinery
- Operating AM machinery
- Utilization rate

- Maintenance of machinery
- Build time
- Monitoring costs

Outsourcing of AM parts was to be analyzed through the viewpoints of how much of their AM activity was outsourced by percentage and its cost, how their quality assurance works when outsourcing, how they monitor costs inflicted by outsourcing, how important the security of their intellectual property is, what is their average lead time, and what is their maximum benefit threshold. The viewpoints used for analyzing this data were:

- Quality assurance
- Information security of CAD files
- Order lead time
- Maximum benefit threshold
- Monitoring costs

The general factors to connect ownership of machinery and outsourcing were to be presented as a table and expanded upon. A report of the analyzed data was written in Finnish and is appended to the thesis as appendix 1. This report was sent to the participating companies immediately after completion.

5 Results

Fifteen people from eight companies were interviewed and each gave a separate answer to the questions in the questionnaire. The interviews were stored separately and later combined into single file consisting of the questionnaire and each individual answer under every question. The quantitative answers were analyzed through statistical means by listing the answers and calculating the percentage of interviewees to give a certain answer and calculating the average and percentiles where applicable. Qualitative answers were quantified where possible and given the same statistical analysis as quantitative answers. In the case of qualitative answers that could not be quantified, they were arranged together and an impartial interpretation conducted.

5.1 Familiarity of technologies

In the first part of the survey, the familiarity of the chosen technologies was investigated. The results of this part of the questionnaire are listed in Table 3. The results are given as the amount of interviewees familiar with the technology divided by the total amount of interviewees. A technology by technology breakdown in the familiarity is given in subsequent subchapters.

Table 3: Familiarity of technologies

Place	**Commercial name**	**Familiarity (%)**
1.	FDM	88.9
-	SLS	88.9
-	SL	88.9
4.	SLM	77.8
-	LOM	77.8
6.	Polyjet	55.6
7.	3DP	22.2
-	DLP	22.2
9.	EBM	11.1
-	SHS	11.1
11.	LENS	0

88.9% of the interviewees were familiar with FDM, SLS, and SLA. 77.8% were familiar with SLM and LOM. 55.6% were familiar with Polyjet. 22.2% were familiar with 3DP and DLP. 11.1% were familiar with EBM and SHS. None of the interviewees were familiar with LENS. Generally, only FDM, SLS and SLA were widely known and the rest of the technologies were more obscure. It can be expected that the familiarity of technology would directly relate to the distribution of usage of technologies.

5.1.1 Fused Deposition Modeling

In order to produce clarity, Fused Deposition Modeling (FDM) technology is divided into consumer devices and industrial devices. Devices manufactured by Stratasys can be seen as industrial devices and the ones based on the RepRap project can be seen as consumer devices. Approximately 15% of the companies owned several consumer FDM devices. These have been acquired to try out accelerating R&D in-house. Generally these devices have been considered very inaccurate and unreliable among the interviewed companies.

25% of the companies owned an industrial FDM device and utilized them approximately 19 hours per week. Approximately 8% of the companies outsourced the creation of FDM parts but the amount of outsourced FDM parts compared to the total amount of outsourced parts is minimal. The selection of materials, which is adequately strong and durable according to the users, was noted to be a positive factor in FDM. The ease of post processing was also seen as a positive aspect.

High end devices of 100,000 euros and up were not well known. The improved accuracy and an expanded material library of the high end machines were received as news.

5.1.2 Selective Laser Sintering

None of the participating companies owned a Selective Laser Sintering (SLS) machine. However, companies outsource SLS models heavily. The durability of the material was seen as positive and the accuracy divided opinions. Out of the companies that outsource SLS models, half have been satisfied with the accuracy of SLS and the other half only employ SLS when the accuracy does not need to be high. The rough surface quality was universally seen as a problem.

As it is faster and more cost efficient to produce more than singular parts at once with SLS, companies with less usage tend to avoid buying an SLS machine and outsourcing the part instead. SLS also requires special facilities for usage because the plastic powder it uses to produce parts has a tendency to spread around and disturb a work space. A post processing station is needed and material handling planned for an SLS process. These are also contributing factors to why SLS machines are not acquired by companies looking for an office friendly solution for AM.

5.1.2 Stereolithography

12.5% of the companies owned a stereolithography (SL) machine. 50% of the companies outsource SLA models with the main suppliers being a well-known German service provider with a subsidiary in Finland, and several foreign suppliers from China.

Stereolithography continues being the one technology associated with outsourced quality parts. While it is partially true that stereolithography is one of the most accurate AM technologies, its popularity can also be attributed to the fact that it was widely spread at an early stage of AM development in the 1990s. Several more affordable technologies have surfaced since and have been proven to be as effective as SL in select applications. According to Wohlers report 2013 SL is the most profitable technology for service providers yet it is not anymore the most acquired machine type in the industry. [6] This supports the hypothesis that the use of SL will diminish in the coming years and gradually lose its share to other technologies.

5.1.3 Selective Laser Melting

None of the companies owned Selective Laser Melting (SLM) machines or actively outsource SLM models. The technology has been attempted in some projects with differing levels of success. The major problems were seen to be the cost, quality, and slowness of the technology. Smaller problems were the removal of supports and the accuracy of the technology. 75% of the companies showed interest in using SLM in the future.

A restricting factor in acquiring SLM machines is the abundant need for post processing. In order to produce parts of desired quality, the part needs to be heat treated in an industrial oven and machined afterwards. This not only discourages companies from acquiring this type of machines but also service providers are vary, because it would mean a large investment and either training or hiring of staff in order to be able to carry out the post processing tasks. This limits the availablility of the technology and drives up the cost. However, as there is considerable interest in producing metallic parts through the use of AM, it can be seen as a gap in the market for service providers.

5.1.4 Laminated Object Manufacturing

None of the companies owned a Laminated Object Manufacturing (LOM) machine or outsourced LOM models. The high familiarity of the technology is caused by its wide use in the 1990s. When working with paper, the biggest restriction of LOM is the limitation of the mechanical properties of paper. If the machine used can handle plastics, the loss of material in the form of excess in each sheet is an issue. However, the material in the newest iteration of LOM is commonly available A4 paper, which makes it a tempting option for companies that produce a lot of visual prototypes. These companies are commonly architectural or planning offices which were not included in the survey and thus do not show up in the results.

5.1.5 PolyJet

37.5% of the companies owned a Polyjet or a comparable Multijet Modeling (MJM) machine. The machinery has been perceived as very sensitive and as needing a lot of continuous preventive maintenance.

The users have noted that the need for a consistently high utilization rate to prevent degradation of the build quality is a problem. With Polyjet, the manually intensive post processing process is another problem. With MJM the warping of the parts during post processing is a problem. The shrinkage effect inherent to the technology is also seen as problematic. Positive factors included the accuracy of the parts and the excellent flatness was cited. The materials have been generally adequate for their intended use. PolyJet machines are well adopted by industrial companies due to its ability to produce high quality parts quickly and the simplicity of post processing.

5.1.6 Three-Dimensional Printing

None of the companies owned a Three-Dimensional Printing (3DP) machine or outsourced 3DP models. The biggest problem was seen to be the fragility of the parts. Producing colored parts was not seen as a value adding factor. As with LOM, 3DP is generally used for visual prototypes in the fields of planning and architecture which are not represented in this survey.

5.1.7 Digital Light Processing

None of the companies owned a Digital Light Processing (DLP) machine or outsourced DLP models. The familiarity of the technology is low. Major factors preventing the penetration of DLP are the relatively small build volume and the fragility of the parts. As it is a very accurate technology, DLP is well applied in the fields of jewelry and dentistry which were not present in this survey.

5.1.8 Electron Beam Melting

None of the companies owned an Electron Beam Melting (EBM) machine or outsourced EBM models. The familiarity of the technology is low. EBM is generally used for the production of implants and as there were no medical companies involved in this survey, the technology is not well known.

5.1.9 Selective Heat Sintering

While the only machine using Selective Heat Sintering (SHS) is already on the market and has a Finnish importer [34], it is not yet widespread. None of the companies owned an SHS machine or outsourced SHS models. The recognizability of the technology is low. After becoming familiar with the technology, a few companies showed interest in using the technology in R&D once the details of the technology are made available. The major attraction of SHS is its low price but it comes at the cost of reduced quality and mechanical properties which concerns companies.

5.1.10 Laser-Engineered Net Shaping

None of the companies owned a Laser-Engineered Net Shaping (LENS) machine or outsourced LENS models. None of the interviewees were familiar with the technology. LENS is largely used in the aerospace and automotive industries in niche applications and repairs which give reason for it not to be popular among the participants of this survey.

5.2 Distribution of applications

The applications of AM are divided into rapid prototyping (RP), rapid tooling (RT), and rapid manufacturing (RM). When outsourcing the application is determined by the end product ordered by and delivered to the outsourcing company. If the product is a prototype producer through silicon molding, the application is seen as RP. If the product delivered is the silicon mold itself, the application is seen as RT. 37.5% of the companies use silicon molds but most of these molds do not leave the service provider. The obtained data on the distribution of applications of AM in the companies is presented in Table 5.

Table 5: Distribution of applications

Application	Average	25th percentile	50th percentile	75th percentile
RP	84%	80%	90%	90%
RT	6%	0%	0%	5%
RM	10%	1%	10%	20%

RP is overwhelmingly the largest application of AM in the companies. 90% of the companies do almost exclusively RP. Compared to the rest of the world, RT is used to a very small extent in Finland. Silicon molding is common but usually the company only sees the end product. Investment casting has been experimented with but abandoned due to high expenses. The demand for RM would be large but its high price and insufficient quality have thus far been restricting factors. In companies with production facilities fixtures are being made for facilitating production. For some companies AM is the only type of production they have in Finland with everything else being outsourced to other countries. Compared to the data provided by Wohlers Report 2013, the distribution of applications in Finnish companies is highly skewed towards RP. A visual representation of the comparison of the distributions is given in Figure 15.

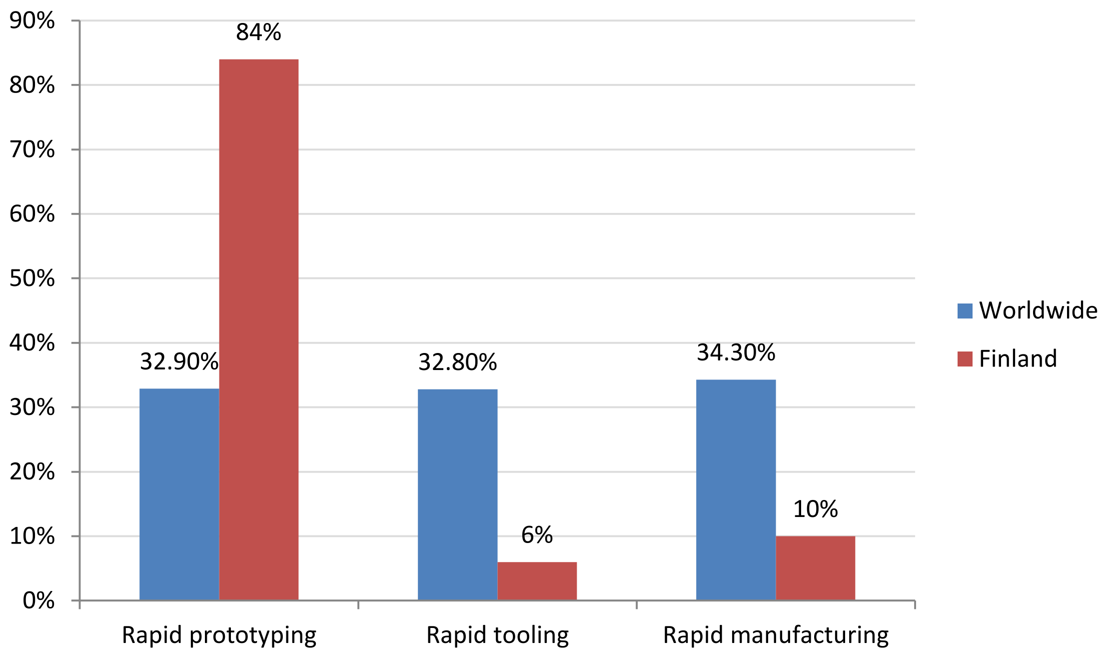


Figure 15: Distribution of AM applications in Wohlers Report 2013 and this survey

There are several points to consider as to why the distribution of applications in Finland is so drastically different from the worldwide one. The major reason is that the companies surveyed for Wohlers Report 2013 were service providers, whereas in this survey they were the companies that needed AM parts. The rising awareness of AM and the reduction of the cost of machinery has driven many industrial companies to procure their own AM machines which they use for prototyping, hence diminishing the amount of prototypes manufactured by service providers. The second reason is that the companies surveyed for this thesis were mostly in the field of consumer electronics which is heavily slanted towards RP. In addition, there is not as much automotive and aerospace engineering in Finland, which are big users of RM.

Even when taking all of the above reasons into consideration, the difference in the distributions is too large to fit into the margin of error. While RP is well understood and used in Finland, RT and RM are novel applications and the industry has not yet adapted to their usage.

5.4 Ownership and usage of AM machinery

The share of companies owning an AM machine is shown in Table 6. The amount of companies owning a machine is equal to the amount of companies with no machine. 25% of the companies own several machines. The quantity of machines by percentage of companies is given in Figure 16.

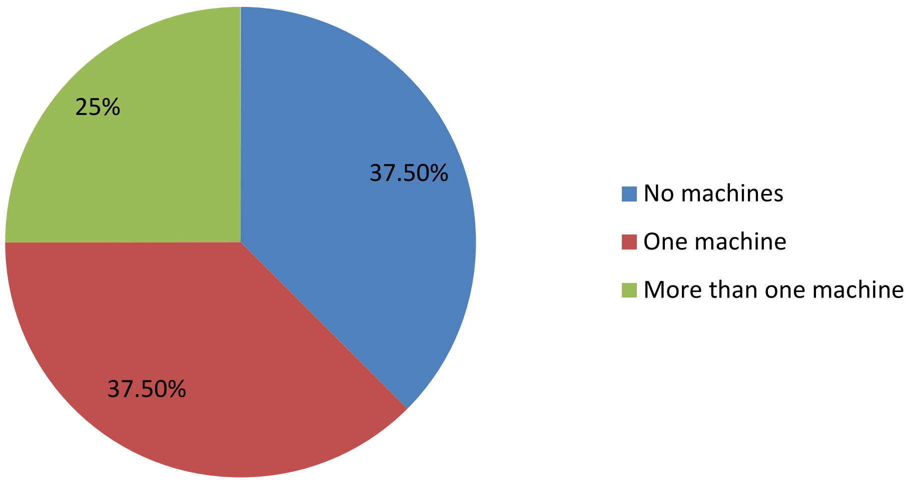


Figure 16: Quantity of machines in companies by percentage

Figure 16 shows the distribution of companies that own machinery. While this is important information from the point of view of companies showing interest toward AM and having a high probability of investing in it later, a representation of the distribution of industrial machine gives a better picture of how many companies are able to produce AM parts in-house. This information is given In Figure 17.

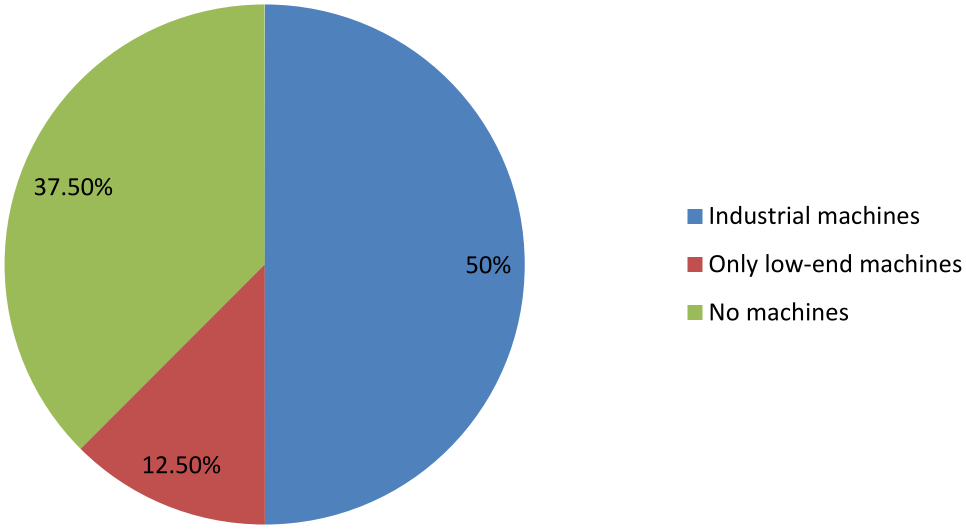


Figure 17: Distribution of companies by machine type

A company that owns an industrial machine is less likely to outsource the manufacture of AM parts. The ownership also improves their speed of obtaining a part and offers better protection of the secrecy of their CAD files. According to Figure 17, 62.5% of the companies own a machine and 37.5% do not and instead rely solely on outsourcing.

5.4.1 Practices in procuring AM machinery

The procurement of an in-house machine has typically been preceded by heavy outsourcing of AM parts. Companies have wanted to get an in-house machine in order to remove delivery times, speed up R&D iterations and to incentivize the use of AM machines for the R&D personnel. Another reason for procuring an in-house machine has been cost efficiency because producing parts with an in-house machine is cheaper than outsourcing and there are no hidden costs. The technologies of owned machines are shown in Figure 18

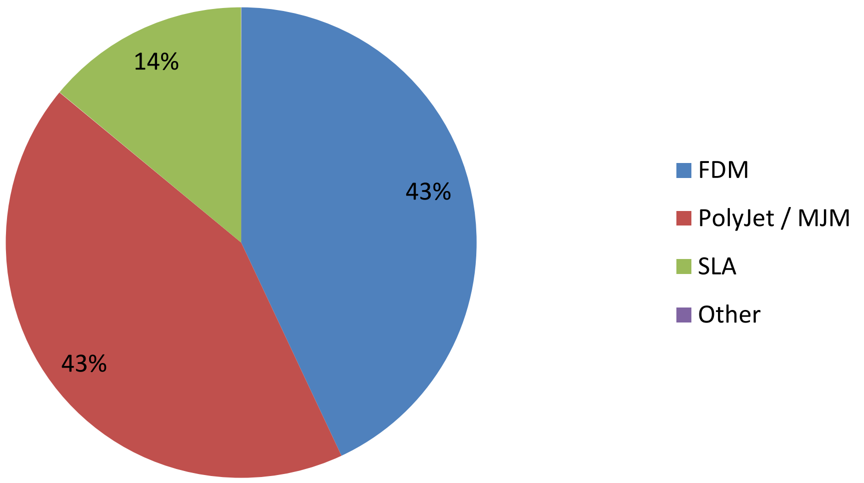


Figure 18: Technologies of owned machines by percentage

Purchasing any sort of machinery should be preceded by a careful examination of needs of the company and the options available to fulfill those needs. In the case of procuring machinery, the need is usually the ability to produce prototypes quickly and cost-effectively. A solution that leads to the procurement of an AM machine is that the company decides that the best solution to the need is to buy an AM machine. Further, the type of machine has to be decided on, which is where knowledge of the AM field becomes very important.

A general understanding of all AM technological categories is required along with an in-depth knowledge on the possibilities of their applications. After an AM technology category has been selected, it is equally important to know what kind of machines exist in that category, who manufactures them, how much do they cost to procure and maintain, what sort of maintenance and warranty deals does the manufacturer offer, what materials can the machine use, what special abilities do different machines offer and a complete view of its technical specification.

As an example of such a process, the AM category of powder bed fusion can be divided into subcategories by material or power source. The material subcategory can be divided into plastics and metals. The plastic sub-subcategory can be divided into machines that are able to create parts out of Nylon 11 and 12 mixed with fibers of different sorts, machines that can only handle Nylon 11 and machines that work with all the aforementioned plastics and PEEK in addition. In the metal sub-subcategory the choice is larger with machines that can handle everything from gold to titanium to machines that only work with certain types of metallic powder.

The power source category can be divided into laser, thermal printhead, and electron beam power sources. While machines that use a thermal printhead and an electron beam are proprietary and manufactured only by Blueprinter ApS [35] and Arcam AB [36] respectively, machines that use a laser are provided by EOS GmbH [37], 3D Systems [38], ReaLizer GmbH [39], SLM Solutions [40], Concept Laser GmbH [41], AFS Co. Ltd. [42], Shaanxi Hengtong [43], Trump Precision Machinery Co. [44] Wuhan Binhu Mech. & Elec. [45], Renishaw [46], and Matsuura [47]. A company has to look into each machine provider and evaluate it and its product. This includes finding the machines’ speed, power consumption, maintenance rate among other technological specifications.

As can be seen, the process of procuring an AM machine is fairly long and requires a lot of information on the field of AM and specific technological knowledge. As AM as a field is relatively new and progressing fast, companies are hard pressed to find employees among their ranks with enough knowledge to be able to make an educated procurement. This is where familiarity of technologies plays a large role as, according to the interviews, companies often buy a machine from a technology category they are familiar with. Low levels of knowledge of AM also make the companies more susceptible to the marketing of AM machine manufacturers. Some companies are satisfied with the amount of information they get from a machine importer at a trade show to purchase an AM machine.

5.4.2 Operating AM machinery

AM machinery is highly automatized when it is operating but can also be labor intensive during set-up and part removal phases. The presence of a machine operator is needed in the phase of machine set-up, when the machine is inspected and made sure that it is completely operational, .STL files are prepared to be included in the build, and the machine is started. The presence of an operator is also required when the build is finished. The parts have to be taken out of the machine and the machine has to be cleaned and maintenance conducted. The demand of post processing varies greatly between technologies but more often than not it takes several hours to remove all the support material from a full build and to finalize the parts. Operator presence is also required during the time a machine is running in case it stops or produces an error for any reason. Failure to intervene in such cases often means the loss of the entire build and damage to the machine.

The question of who is operating the AM machine is vital. The two most common ways to organize the usage of an AM machine are:

1. Letting the personnel responsible for 3D modeling use the machine themselves
2. Appointing an operator for the machine

The amount of companies using an appointed person to operate the machines is equal to the amount of companies using an open access policy. According to the interviews, the companies using the open access policy have been having frequent stand-stills, lowered build success rate, and an overall drop in appreciation of AM among the users.

5.4.3 Utilization rate

As AM machines are fully automatic during operation save for failures and errors, they should be able to run close to 24 hours per day. Companies owning an AM machine have a utilization rate averaging 47.25 hours per week. This utilization rate is relatively low presuming that the machine could be operated without a break except for maintenance and setup breaks. The percentage per week has been calculated for a full 168 hour week.

Table 5: Utilization rate

Utilization rate	**Average**	**25th percentile**	**50th percentile**	**75th percentile**
Hours per week	47 h	25 h	38 h	60 h
Percentage of week (168 h)	28%	15%	23%	36%

It is worth noting that the utilization rate alone does not represent how efficiently the company is running it. In most AM technologies the amount of time needed to produce one part cannot be linearly interpolated to calculate the time needed to produce multiple parts. In fact, the more parts there are in the build the less time the process takes to manufacture each part. This is due to the fact that the process time does not consist only of directly solidifying, growing, or cutting out a cross-section of the part on a layer, but it also takes time to go from one layer to another. An example of this is distributing a new layer of powder in selective laser sintering, which requires the build platform to move down, the material reservoir to move up, and a roller or blade to take the powder from the reservoir to the build bed. This process of moving from one layer to another takes an equal amount of time regardless of how many parts are in the build or how much of the surface needs to be worked. Thus, the time is calculated for each part decreases as their amount increases. Some technologies are less prone to this effect, such as fused deposition modeling, in which an extruder works on each piece individually and the only common process is lowering the bed by the thickness of a layer but even in this case the effect is noticeable enough for it to be worth to maximize the build. The set-up time needed for starting the machine is also approximately the same regardless of the amount of parts to be produced.

Let us call the time needed to produce the cross-sections of part 1 T_{p1}, part 2 T_{p2}, the accumulated time to move from one layer to another T_l, the set-up time T_s and the amount of time needed for the entire build T_b. The formula for calculating the time needed to produce an entire build is (1).

$$T_{p1} + T_{p2} + T_s + T_l = T_b \qquad (1)$$

In case only one part is printed, Formula (2) applies to calculate the relative time used to produce a part compared to how long the entire build took. F_{p1} is defined as the fraction of total build time part 1 is being produced.

$$\frac{T_{p1}}{T_{p1}+T_s+T_l} = F_{p1} \qquad (2)$$

If two parts are being produced, F_{pb} is the fraction of total time both parts are being produced and the following applies:

$$\frac{T_{p1}+T_{p2}}{T_{p1}+T_{p2}+T_s+T_l} = F_{pb} \qquad (3)$$

Even though in the second case the build time is longer, the time used on directly producing parts is higher in comparison to the entire process. The range of the fraction of time used on parts compared to the total build time is from 0 to 1. The closer the result is to 1, the more efficient the process.

Additionally, in processes such as SLS, all material that is not used for the part cannot be recycled, thus producing more waste the less of the build volume is used for parts. In the process, it is general practice to mix 50% of fresh powder with 50% used powder until the powder is no longer usable due to causing faults in parts [48].

It is possible to calculate the amount of powder not used in the process that suffers from degradation. Let us assume two parts of the same height and call the volume of part V_{p1}, volume of part 2 V_{p2}, the volume of the build V_b, and the unused volume V_u. The following formulae apply:

$$V_{p1} + V_{p2} + V_u = V_b \tag{4}$$

$$V_u = V_b - V_{p1} - V_{p2} \tag{5}$$

As V_b remains the same regardless if one or two parts are included in it, the following is true:

$$V_b - V_{p1} > V_b - V_{p1} - V_{p2} \tag{6}$$

Even though SLS is the most extreme example of the economies of scale of producing multiple parts with AM simultaneously, they apply to every other technology in the form of used electricity and operator wages.

As there are considerable time and cost benefits in producing more parts at once, downtime for the machine is acceptable if the operator is in the process of waiting for more CAD files to come to maximize the efficiency of the machine. Therefore, it is important to look into how companies handle gathering enough parts to run the machine at full capacity, or indeed if they have enough parts to fill an entire build.

The companies that do not have an operator do not have a formal build filling program in place. As many people are allowed to use the machine without informing others, the machines are often running few parts and any parts that arrive during the machine running are placed in a queue.

The companies that employ an operator for their AM machines have rules on how and when the machine should be run. Most commonly the machine is run in two cycles: one starting in the morning and one starting in the afternoon. The intention is to make sure that one cycle ends before the other one begins and that there is sufficient time between them to make the set-up preparations. In case there are not enough parts to warrant such a rigid program, a certain volume limit can be set and it could be prohibited to start the machine until it is reached. If there is a recurring problem reaching the limit it can be lowered or a timer can be put in place to allow starting the machine after a certain time the first part has been submitted.

5.4.4 Maintenance of machinery

In order for any machine to function properly it needs to be maintained on regular basis. It is noteworthy that preventive maintenance of AM machinery is extremely important due to their sensitivity to failure. Preventive maintenance and upgrades of AM machines is usually done by the manufacturer or by a certified retailer or maintenance bureau closer to the customer. It is common to make a yearly service contract with one of these entities that includes a finite number of upgrades and visits. These contracts are generally perceived as expensive but worth the investment as in some cases they cost less than even a single fatal machine failure. 80% of the companies are doing preventive maintenance which is a relatively high percentage. However, only 40% of the companies report having a service agreement for preventive maintenance. The preventive maintenance practices by percentage are presented in Figure 19.

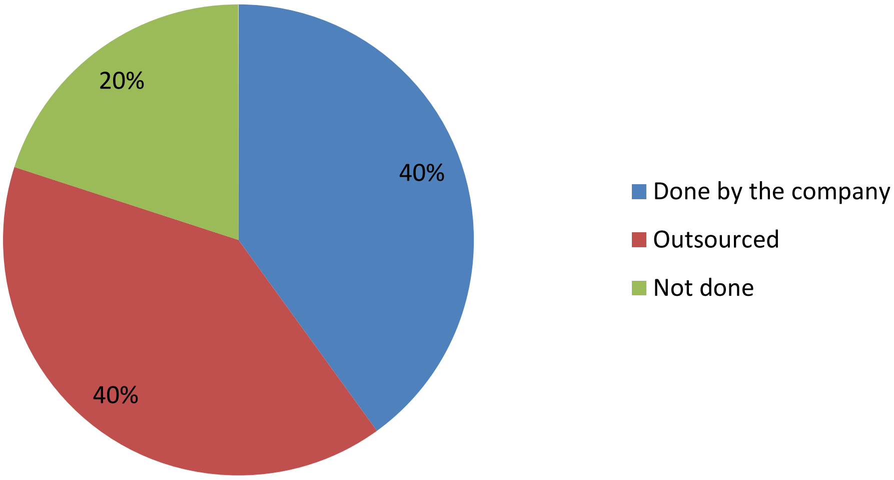


Figure 19: Preventive maintenance practices by percentage

According to the interviews, companies that do not perform preventive maintenance on their machines suffer from prolonged down times and constant failures in parts. This has led to frustration among the users and degradation in confidence that users have in AM. When a machine is not performing properly, the company either outsources the AM parts or avoids the usage of AM altogether.

5.4.5 Part production time

As explained in subchapter 5.4.3, the build time in AM consists of the actual part production and of time spent on general process actions such as set-up and moving from one layer to another. This means that a high utilization rate can be interpreted as detrimental and beneficial to the part production. In case of a high utilization rate, the machine is running often but there is a possibility of a queue forming thus extending the part production time. Nevertheless, if the utilization rate is low due to the fact that the machine is often waiting for a certain volume limit to be fulfilled, parts have a better chance to enter the build making the part production time of some parts longer but lowering it on average. However, if there is heavy demand for AM parts to be produced with the machine, which would be signified by a constant high utilization rate, the average part production time would grow longer. 50% of the companies report the average part production time to be less than a day and another half report it being approximately a day. Both times are extremely good with current technologies and imply a very low waiting time. This means that there is no case of a high demand and high utilization rate, and it is backed by the fact that the average utilization rate is relatively low. The distribution of average part production times is shown in Figure 20.

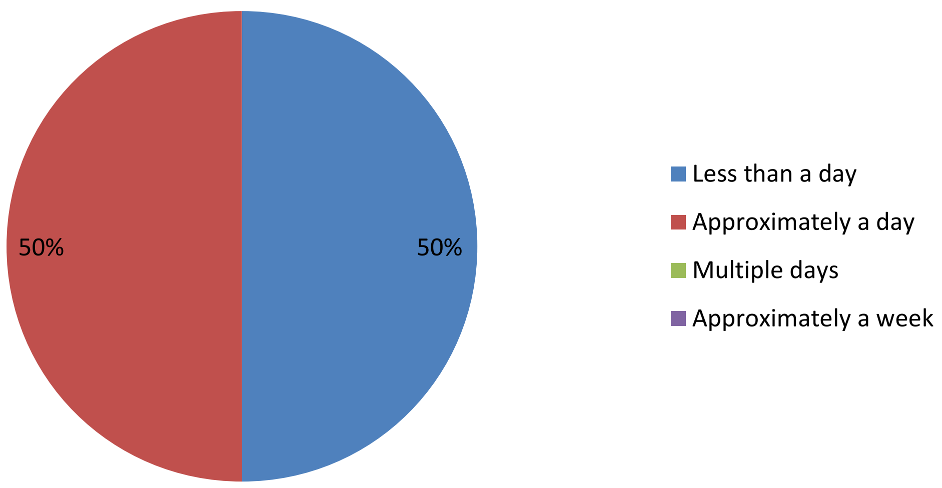


Figure 20: Part production time

5.4.6 Monitoring production costs

Costs of AM machinery can be divided into fixed costs and variable costs. Fixed costs consist of the initial investment cost of the machine and peripherals, post processing equipment, a yearly service agreement and rent of space needed for the machine.

Variable costs include material costs, labor, and electricity. Oftentimes the only costs companies consider when procuring machinery is the costs of the machine, post processing and the material cost. The costs of the service agreement and labor are often ignored or understated. This can lead to not hiring a separate operator for the machines which in its part leads to downtime and raised costs.

Monitoring costs of parts built with in-house AM machinery is strongly in relation to the size of the company. Smaller companies monitor the price of every part and the production decision is made based on that. In bigger companies the fabrication costs are either budgeted annually or not monitored at all. Commonly the costs are only calculated at the investment stage and not calculated at a later point. Nevertheless, the only companies reporting to suffer from inflated costs in relation to AM are the ones that do not perform preventive maintenance and suffer from constant breakdowns of machinery and lost labor caused by them. Figure 21 presents the distribution of companies' different monitoring practices.

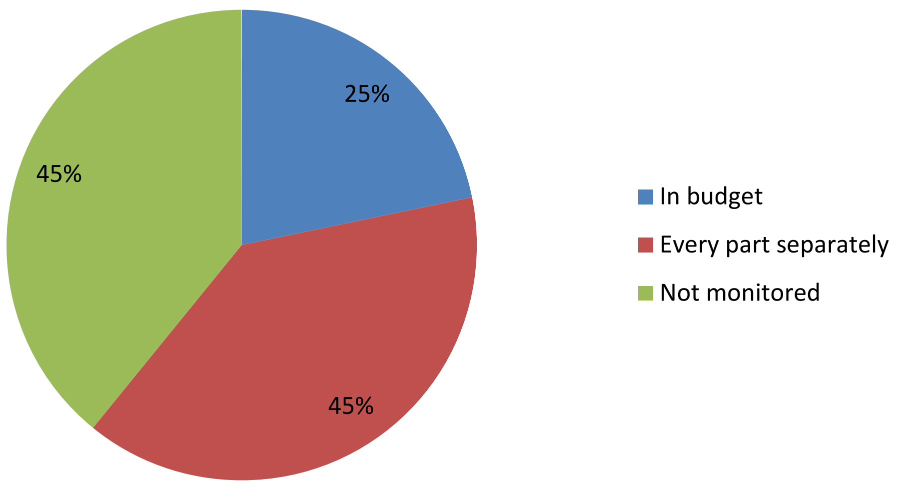


Figure 21: Monitoring costs in own production

5.5 Practices in outsourcing of AM services

Companies are increasing the amount of outsourcing because the opportunities of AM have become more widely known and accessible. In the case a machine is overloaded and the company does not own a second machine, outsourcing is a faster way to get all the parts. Oftentimes the quality of the in-house machine is insufficient in regards to the surface quality, the durability of the material, or producing finer details such as snap on parts. Usually outsourcing also includes post processing as it is perceived that service bureau employees are more capable of handling it than company employees.

Larger quantity series consisting of over twenty parts are usually outsourced. The size of the part intended for production matters if its size exceeds the maximum build envelope of the in-house machine. Silicon molds and parts made using silicon molds are outsourced in the majority of cases. On rarer occasions, especially when a company is thinking of buying a machine of their own, it is willing to try out a new to technology which leads to the outsourcing of test parts.

Several companies outsource higher quality parts and produce lower quality parts in-house. The same distinction applies with functional prototypes and visual prototypes.

Table 6: Outsourcing compared to all AM usage

Type of measurement	**Average**	**25th percentile**	**50th percentile**	**75th percentile**
Percentage of all AM usage	56%	25%	53%	100%
Currency	41,000 €	10,500 €	25,000 €	45,000 €

5.5.1 Quality assurance

Unlike the practice of specifying surface quality and dimensional tolerances in traditional manufacturing, companies often order parts from service providers according to the specifications of the machines. It is reasonable to expect outsourced parts to represent the specifications given by the machine supplier but as with all manufacturing processes, producing parts with AM is subject to many variables that affect the quality of the product. For example, the heat distribution in SLS builds is not even and can vary from build to build which leads to varying results in material strength and dimensional accuracy of the part. Therefore, it is not always guaranteed that the produced part is exactly of as high a quality as advertised.

In the case of outsourcing parts without post processing, companies trust the service provider to perform quality assurance tests in order to comply with the requirements, but as there often are no explicit requirements the test commonly consist of only verifying if a fault in the process caused a defect in the part.

When ordering parts with post processing, or with the use of rapid tooling, companies are more precise in defining the desired qualities of the part. These processes require manual labor and as such are subject to more variables than a part that is produced directly with a machine.

Most companies trust that the service providers perform the quality assurance tests and perform simple visual checks of the ordered parts. This applies especially to service providers that have been used extensively in the past. When ordering from less known service providers, a more rigid approach to quality assurance is taken. A small percentage of the companies inspect the parts’ dimensions and material properties. The distribution of companies’ practices in quality assurance of outsourced parts is presented in Figure 22.

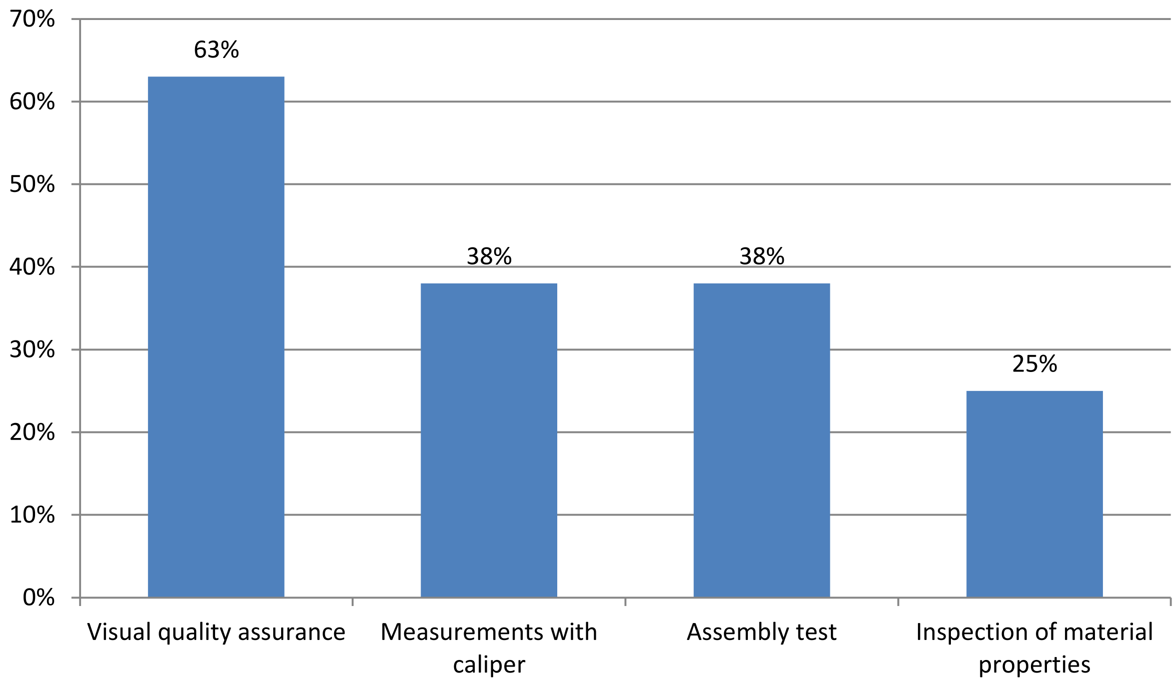


Figure 22: Distribution of quality assurance in outsourcing

5.5.2 Information security of CAD files

The importance of CAD file security varies from field to field. In consumer electronics, a part the company is working on can contain several innovations and be crucial to the overall value perceived by the customer. A leak of the design of such a part can be damaging to the company so strict measures are taken to protect them. In the machine building industry, a part is a part of a much larger assembly and a leak of a CAD file of a part of the machine, while not desired, is not detrimental to the success of the final product.

Most companies rate their service providers and only work with those who are trustworthy and willing to sign an NDA agreement. A problem with security on the service providers' side can lead to a leak and subsequent copies of the product being made.

Sending CAD files to a trusted service provider is not a problem but sending the files to anyone else is avoided in case of leaks. If the files are secret, the company produces the part in-house with available technologies.

In order to produce parts with AM machines, the CAD files have to be transformed into .STL format. In many cases the change of file format causes unexpected errors and the file needs to be processed for it to be accepted by the machine. Most service providers in the AM field offer a service of transforming CAD files into .STL or fixing them. The Additive Manufacturing File Format (.AMF) has attracted the interest of a small percentage of the companies because of its ability to store color, materials, lattices and constellations unlike the .STL file format.

An equal amount of interviewees perceived outsourcing of post processing of .STL files as useful. The distribution of the degree of secrecy in the companies is shown in Figure 23.

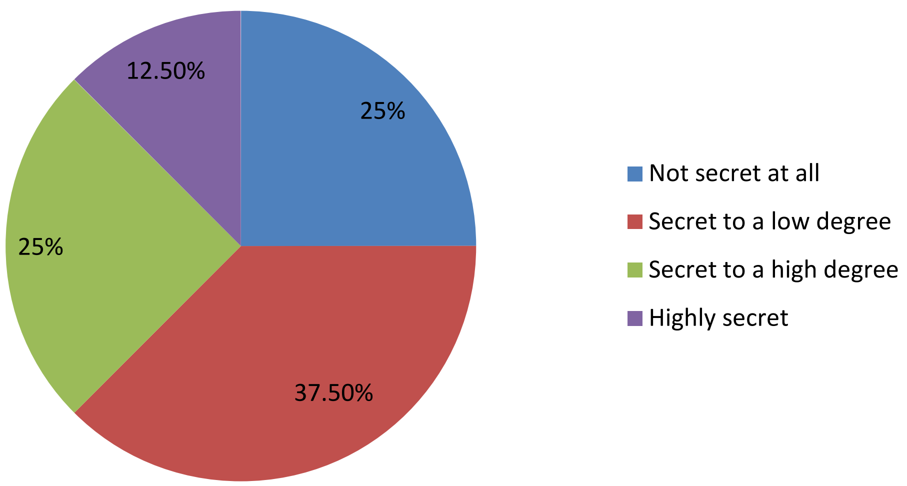


Figure 23: Degree of secrecy of CAD files

5.5.3 Order lead time

The order lead time is the time it takes from the order being placed to the customer receiving the part. This time includes the service provider processing the order, evaluating the CAD file or .STL and producing the part, and the time it takes to ship the part from the service provider to the customer.

A small part of the companies receive parts from the supplier in approximately a day. 86% of the companies receive the parts from days to approximately a week. The distribution of the average order lead time is presented in Figure 24.

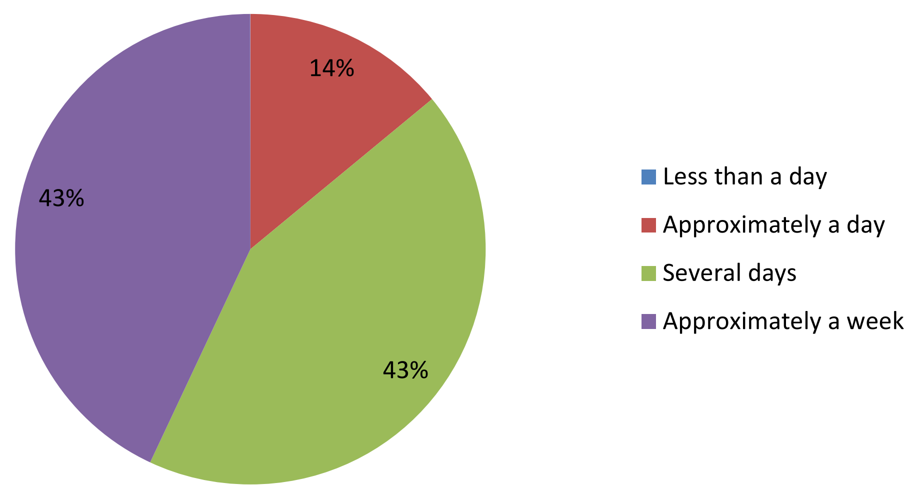


Figure 24: Order lead time

The times presented in Figure 24 are much longer than when companies produce parts with their own machines. A comparison of part production time and outsourcing lead time is presented in Figure 25.

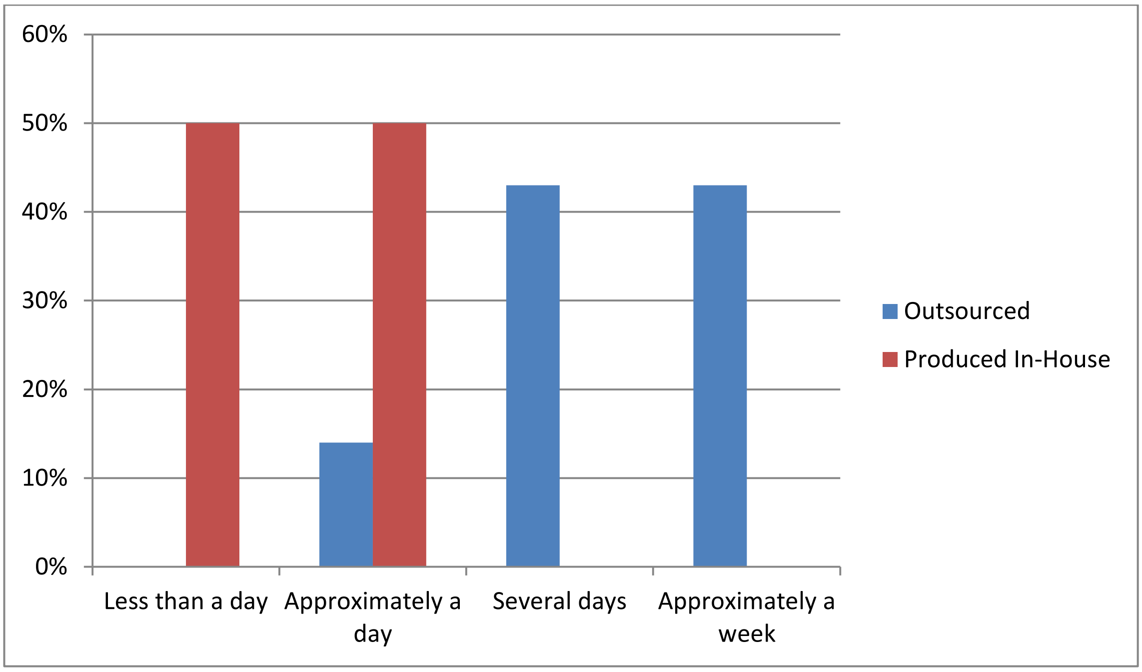


Figure 25: Comparison of part production time in-house and outsourcing lead time

5.5.4 Maximum benefit threshold

The maximum benefit is the threshold in delivery time after which there is no benefit in being faster. For most of the companies the threshold is set at approximately days to a week. Some companies have the threshold set at approximately a day. At the moment the delivery times are slightly longer than the maximum benefit threshold but according to the interviews it is not seen as problematic. The maximum threshold distributed by company is shown in Figure 26.

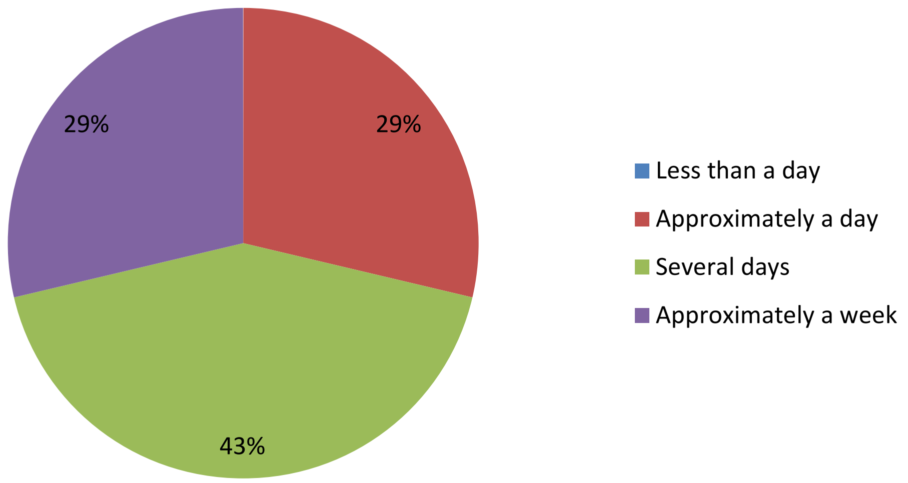


Figure 26: Maximum benefit threshold

5.5.5 Monitoring outsourcing costs

Most companies monitor costs for each order separately. Larger companies have a budget for the usage of AM on a yearly level. None of the companies reported being surprised by hidden costs of outsourcing and have been satisfied with the pricing. The practices of monitoring costs in outsourcing are presented in Figure 27.

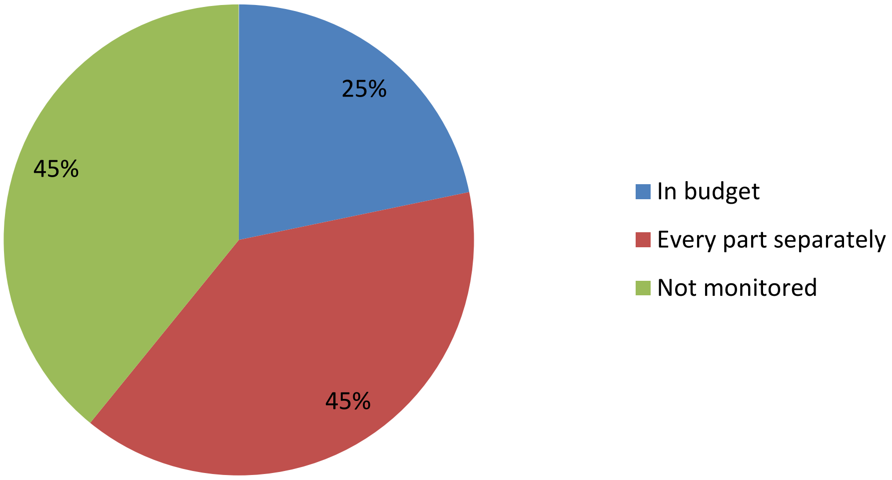


Figure 27: Monitoring costs in outsourcing

5.6 Importance of factors related to AM

In the last part of the questionnaire, general factors that are related to AM were examined. The interviewees were told to rate the importance of the listed factors from 1 to 5 and to expand on their answer. The acquired data is presented in Table 7.

Fast access to AM parts and their accuracy were seen to be the most important factors among the interviewed companies. The suitability of material and general knowledge of AM were seen as relatively important on average but the spread between companies was large. For some companies it is very important to have the part created out of a certain material for it to perform as wanted and for some is it of no real importance. The need for parts to have a certain material commonly comes from their functionality and for this reason the companies that rated the importance of material low are highly likely to be the ones that generally produce or outsource visual prototypes.

Security of CAD files was not an issue for most of the companies either because they are in a business where the leak of one file does not pose a threat to the final assembled product, or they are confident enough in their service providers. The optimality of technology was rated low among all but a few companies. This means that most companies are not concerned with which methods are used to produce the parts as long as they are made of the correct material and are able to serve the desired purpose.

Additive manufacturing is seen as an important tool in presenting conceptual models to engineers but showcasing AM models to shareholders is not perceived as useful as the parts are too rough to present the commercial value of the final product.

Table 7: Importance of factors related to AM, range 1-5, 1 is lowest, 5 is highest

Factor	**Average**	**25th percentile**	**50th percentile**	**75th percentile**
Fast access to part	4,09	4	4	5
Accuracy of part	4,27	4	4	5
Suitability of material	3,64	2,5	4	5
Security of CAD files	3,18	2,5	3	3,5
Optimality of technology	2,82	1,5	3	4
General knowledge of AM	3,64	2,5	4	4,5

6 Summary and conclusions

A need was identified to examine of the needs and practices of AM in the Finnish industry in order to understand what the situation is and how it is in relation to the rest of the world. In order to accomplish this, a survey consisting of eight companies and fifteen persons was conducted.

The surveyed fields were chosen according to the criterion that they needed to be industrial and with potential in AM usage, which led to the selection of the automotive, aerospace, industrial machines, and consumer products fields. From these fields 28 companies were asked to participate out of which eight agreed to be a part of the survey, giving a 29% response rate. The companies that decided to participate were from the industrial machines and consumer products fields. The position in the company of the interviewed persons ranged from CAD designer to CEO.

The goals set for the survey were mapping out the usage and familiarity of different AM technologies, understanding how companies procure machinery, and understanding their practices in outsourcing AM parts.

A five-part questionnaire consisting of qualitative and quantitative questions was designed and presented to the interviewees during the interviews which lasted from one to two hours each. The questionnaire was laid out in the way that would draw information to the subchapters of Chapter 5.

The results to the question of how familiar different technologies were were close to expectations and previous research worldwide considering the restrictions of the surveyed fields. FDM, SLS, and stereolithography were the most recognized and used technologies, SLM and LOM were known but not used, PolyJet was used to a moderate degree, and the rest of the technologies were poorly recognized and not used.

The knowledge of FDM machines was heavily skewed towards the lower end and mid range machines and higher end machines did not have a large presence in the industry.

SLS was known for its material properties and high degree of freedom in design and was often used for outsourcing even though none of the companies owned an SLS machine. Stereolithography was the most associated with high quality AM parts but a trend can be seen according to which it is losing ground to other AM technologies. PolyJet machines were seen as sufficient for the purposes for the companies but costly to maintain.

The average distribution of applications of AM, rapid prototyping, rapid tooling, and rapid manufacturing, were 84%, 6%, and 10% respectively. These results are radically different from the previous surveys, which was partly due to the different approach taken in this survey. In the previous surveys service providers were surveyed whereas in this survey it was the companies that needed AM parts. As some companies use their machines for the faster rapid prototyping applications more than for rapid manufacturing, the percentaged is skewed in the favor of the former. Additionally, the majority of the companies were from the consumer products field in which the volumes are so high that rapid manufacturing is not viable. However, these factors are not enough to account for the entire difference in the distribution between the surveys leading to the conclusion that Finland is behind other countries in rapid tooling and rapid manufacturing.

62.5% of the surveyed companies owned at least one AM machine and 50% of the companies owned an industrial AM machine. 43% of the machines were using FDM technology, 43% Polyjet or MJM, and 14% stereolithography. Procurement of an AM machine is a lengthy process due to the wide spectrum of technologies and it was found that most companies do not do enough preparations and evaluate their needs in enough detail to acquire a machine best suited for them.

The practices in operating AM machinery turned out to be an important topic as two ways of operation were identified. The first one was to let the designers use the machines themselves and the second one to appoint an employee to exclusively operate the machinery. There were multiple problems found with the first approach including lack of maintenance and lowered build success rates. The second approach is recommended to be used.

The average utilization rate of AM machinery was found to be 47 hours per week. A 28% utilization rate was calculated using a full 168 hour week as the machines can theoretically be used around the clock with the exception of set-up times and maintenance breaks. As was demonstrated in Subchapter 5.4.3, the utilization rate is not the direct measure for the efficiency of AM machinery usage, as the duration of a build is not linearly dependent of the amount of parts in the build.

Maintenance of machinery was found to be very important and according to the interviews the lack of it led to prolonged down times and constant failures in parts. 80% of the companies reported doing preventive maintenance and 20% reported only doing corrective maintenance.

Part production time varied from less than a day to approximately a day. The part production time is related to the utilization rate and because it is fast, implies that the waiting times and a utilization rates are low. When outsourcing, the lead time was found to be between several days and approximately a week on average. This presents a difference between the two but companies reported that they are willing to wait for outsourced parts longer than in-house parts. The maximum benefit threshold for outsourced parts was divided between approximately a day, several days, and approximately a week in the distribution of 29%, 43%, and 29% respectively.

The amount of outsourced parts differs between companies as some prefer to do all of their own production and some prefer to outsource all of it. The average percentage of outsourcing was found to be 56% with the 25th percentile being 25% and the 75th percentile being 100%. The average annual budget for outsourcing was 41,000€.

Rigorous quality assurance was not performed on most parts in most companies because the service providers were trusted to handle the process. For the most part, companies settled on inspecting the parts visually in case of major failures. It was also discovered that most parts are not ordered with specifications to quality. The matter of CAD file security concerns some companies and is seen as non-consequential by others. The perceived benefit of post processing of .STL files by service providers is equally divided as some companies prefer to do finalize their own files and others would pay for the post-processing.

The practices of monitoring costs of AM vary depending on the size of the company and generally do not depend on outsourcing or producing parts in-house. 25% of the companies have a budget for outsourcing, 40% monitor the cost of every part, and 40% do not perform any sort of monitoring. Smaller companies monitor their AM expenditure more than larger companies.

References

[1] I. Gibson, D. W. Rosen and B. Stucker, Additive Manufacturing Technologies: Rapid Prototyping to Direct Digital Manufacturing, Springer, 2010.

[2] N. Hopkinson, R. Hague and P. Dickens, Rapid manufacturing : an industrial revolution for the digital age, Loughborough: John Wiley & Sons, Ltd, 2006.

[3] I. Campbell, D. Bourell and I. Gibson, "Additive manufacturing: rapid prototyping comes of age," *Rapid Prototyping Journal,* vol. 18, no. 4, pp. 264-280, 2102.

[4] B. Vayre, F. Vignat and F. Villeneuve, "Designing for Additive Manufacturing," in *45th CIRP Conference on Manufacturing Systems*, Grenoble, 2012.

[5] "Interpro," 2014. [Online]. Available: http://www.interpromodels.com/services/dmls-direct-metal-laser-sintering/. [Accessed 29 January 2014].

[6] Wohlers Associates, Inc., "Wohlers Report 2013," Wohlers Associates, Inc., Fort Collins, 2013.

[7] A. Borille, J. Gomes, R. Meyer and K. Grote, "Applying decision methods to select rapid prototyping technologies," *Rapid Prototyping Journal,* vol. 16, no. 1, pp. 50-62, 2010.

[8] T. Brajlih, B. Valentan, J. Balic and I. Drstvensek, "Speed and accuracy evaluation of additive manufacturing machines," *Rapid Prototyping Journal,* vol. 17, no. 1, pp. 64-75, 2011.

[9] ASTM, "Standard F2792 – 12a “Standard Terminology for Additive

Manufacturing Technologies"," ASTM International, West Cnshohocken, 2012.

[10] "Custompartnet: Fused Deposition Modeling," 2008. [Online]. Available: http://www.custompartnet.com/wu/fused-deposition-modeling. [Accessed 29 January 2014].

[11] E. O. Olakanmi, K. W. Dalgarno and R. F. Cochrane, "Laser sintering of blended Al-Si powders," *Rapid Prototyping Journal,* vol. 18, no. 2, pp. 109-119, 2012.

[12] Y. Chen and C. Zhezheng, "Joint analysis in rapid fabrication of non-assembly mechanisms," *Rapid Prototyping Journal,* vol. 17, no. 6, pp. 408-417, 2011.

[13] "Custompartnet: Selective Laser Sintering," 2008. [Online]. Available: http://www.custompartnet.com/wu/selective-laser-sintering. [Accessed 29 January 2014].

[14] "Custompartnet: Stereolithography," 2008. [Online]. Available: http://www.custompartnet.com/wu/stereolithography. [Accessed 29 January 2014].

[15] S. Upcraft and R. Fletcher, "The rapid prototyping technologies," *Assembly Automation,* vol. 23, no. 4, pp. 318-330, 2003.

[16] J. A. McDonald, C. J. Ryall and D. I. Wimpenny, Rapid Prototyping Casebook, Trowbridge: Professional Engineering Publishing Limited, 2010.

[17] K. T. Ulrich and S. D. Eppinger, Product Design and Development, 5th ed., Singapore: McGraw Hill, 2012.

[18] Y. Dang-guo, Z. Zheng-yu and Z. W.-j. Sun Yan, "A preliminary design and manufacturing study of hybrid lightweight high-speed wind-tunnel models," *Rapid Prototyping Journal,* vol. 17, no. 1, pp. 45-54, 2011.

[19] I. Ilyas, C. Taylor, K. Dalgarno and J. Gosden, "Design and manufacture of injection mould tool inserts produced using indirect SLS and machining processes," *Rapid Prototyping Journal,* vol. 16, no. 6, pp. 429-440, 2011.

[20] "Industrie Anzeiger," 11 January 2011. [Online]. Available: http://www.industrieanzeiger.de/fertigung/-/article/32571342/35405609/Konturnah-k%C3%BChlt-sich%26%2339%3Bs-doch-besser/art_co_INSTANCE_0000/maximized/. [Accessed 29 January 2014].

[21] "Innomia," 2012. [Online]. Available: http://www.innomia.cz/sluzby/konformni-chlazeni. [Accessed 29 January 2014].

[22] K. Altaf, A. M. A. Rani and V. R. Raghavan, "Prototype production and experimental analysis for circular and profiled conformal cooling channels in aluminium filled epoxy injection mould tools," *Rapid Prototyping Journal,* vol. 19, no. 4, pp. 220-229, 2013.

[23] X. Gu, J. Zhu and W. Zhang, "The lattice structure configuration design for stereolithography investment casting pattern using topology optimization," *Rapid Prototyping Journal,* vol. 8, no. 5, pp. 353-361, 2013.

[24] M. Chhabra and R. Singh, "Rapid casting solutions: a review," *Rapid Prototyping Journal,* vol. 17, no. 5, pp. 328-350, 2011.

[25] "Modern Machine Shop," 23 January 2013. [Online]. Available: http://www.mmsonline.com/articles/adding-to-your-tooling-options. [Accessed 29 January 2014].

[26] E. Bassoli and E. Atzeni, "Direct metal rapid casting: mechanical optimization and tolerance calculation," *Rapid Prototyping Journal,* vol. 15, no. 4, pp. 238-243, 2009.

[27] "Custompart.net Investment Casting," 2014. [Online]. Available: http://www.custompartnet.com/wu/investment-casting. [Accessed 24 February 2014].

[28] K. Karunakaran, A. Bernard, S. Suryakumar, L. Dembinski and G. Taillandier, "Rapid manufacturing of metallic objects," *Rapid Prototyping Journal,* vol. 18, no. 4, pp. 264-280, 2012.

[29] J. Lohilahti, "An investigation of the state of the industry of 3D printing in Finland," Oulu University of Applied Sciences, Oulu, 2011.

[30] J. Gausemeier, N. Echterhoff and M. Wall, "Thinking ahead the Future of Additive Manufacturing - Innovation Roadmapping of Required Advancements," University of Paderborn, Paderborn, 2013.

[31] R. Campbell, D. d. Beer and E. Pei, "Additive manufacturing in South Africa: building on the foundations," *Rapid Prototyping Journal,* vol. 17, no. 2, pp. 156-162, 2011.

[32] R. Czaja, Designing surveys : a guide to decisions and procedures, London: Pine Forge Print, 2005.

[33] U. D. o. Energy, "Oak Ridge Institute for Science and Education," 2014. [Online]. Available: http://www.orau.gov/cdcynergy/soc2web/Content/activeinformation/tools/toolscontent/quantiativemethods.htm. [Accessed 2019 January 2014].

[34] "AN-CADsolutions, Blueprinter reseller in Finland," 2004. [Online]. Available: http://www.an-cadsolutions.fi/en/blueprinter-3d-printer. [Accessed 12 February 2014].

[35] "Blueprinter," 2013. [Online]. Available: http://www.blueprinter.dk/shs.html.

[Accessed 6 February 2014].

[36] "Arcam," 2014. [Online]. Available: http://www.arcam.com/technology/electron-beam-melting/. [Accessed 6 February 2014].

[37] "EOS GmbH SLS machines," 2014. [Online]. Available: http://www.eos.info/systems_solutions/plastic/systems_equipment. [Accessed 6 February 2104].

[38] "3D Systems industrial machines," 2014. [Online]. Available: http://www.3dsystems.com/3d-printers/production/overview. [Accessed 6 February 2014].

[39] "Realizer GmbH SLM machines," 2014. [Online]. Available: http://www.realizer.com/en/startseite/the-slm-machines. [Accessed 6 February 2014].

[40] "SLM Solutions GmbH SLM machines," 2014. [Online]. Available: http://stage.slm-solutions.com/index.php?slm-125_en. [Accessed 6 February 2014].

[41] "Concept Laser GmbH Lasercusing technology," 2013. [Online]. Available: http://www.concept-laser.de/en/technology/lasercusingr.html. [Accessed 6 February 2014].

[42] "AFS Co. Ltd. SLS machines," 2007. [Online]. Available: http://www.lyafs.com.cn/en/sls.html. [Accessed 6 February 2014].

[43] "CSITF2013 Additive Manufacturing Technology Global Summit," [Online]. Available: http://english.rp-china.com/zczz.aspx?id=1. [Accessed 6 February 2014].

[44] "Trump Precision Machinery Co. SLS machines," [Online]. Available:

www.trumpsystem.com/E_ELITE3500.asp. [Accessed 6 February 2014].

[45] "Wuhan Binhu Mechanical & Electrical Co., Ltd. SLS machines on China Commodity Net," [Online]. Available: http://ccne.mofcom.gov.cn/63030. [Accessed 6 February 2014].

[46] "Renishaw SLM machines," [Online]. Available: http://www.renishaw.com/en/laser-melting-systems--15240. [Accessed 6 February 2014].

[47] "Matsuura SLM machine," [Online]. Available: http://www.matsuura.co.jp/english/contents/products/lumex.html. [Accessed 6 February 2014].

[48] K. Dotchev and W. Yusoff, " Recycling of polyamide 12 based powders in the laser sintering process," *Rapid Prototyping Journal*, vol. 19, no. 2, pp. 192-203, 2009.

Materiaalia lisäävän valmistuksen tarpeet ja käyttö suomalaisessa teollisuudessa

Kontaktihenkilö:
Sergei Chekurov
sergei.chekurov@aalto.fi
+358451131137

6.11.2013
BIT-tutkimuskeskus
Integrated Design and Manufacturing -tutkimusryhmä
SuperMachines-projekti
Aalto-yliopisto

Aalto University

Sisällysluettelo

1. Raportin tarkoitus ja laajuus

Tämän raportin tarkoituksena on tutkia materiaalia lisäävän valmistuksen (AM-tekniikoiden) nykytilannetta Suomen teollisissa yrityksissä.

1.1 Haastattelujen laajuus

Tutkimuksessa haastateltiin kahdeksaa eri yritystä ja yhteensä viittätoista eri henkilöä. Yritysten yhteenlaskettu liikevaihto vuonna 2012 oli noin 3,2 miljardia euroa. Osallistuvat yritykset valittiin teollisten yritysten keskuudesta sillä perusteella, että niiden potentiaalinen tai toteutunut AM-tekniikoiden käyttö on suurta.

Haastattelututkimukseen osallistui kuusi suurta ja kaksi PK-yritystä. Haastateltavat henkilöt valittiin sen mukaan, ketkä yrityksessä vastaavat materiaalia lisäävän valmistuksen toiminnasta ja päätöksistä. Haastateltavat henkilöt olivat AM-laitteiden operaattoreita, CAD-mallintajia, tuotekehityspäälliköitä ja tuotantovastaavia.

1.2 Haastattelujen kysymykset

Haastattelu koostui neljästä osasta. Ensimmäisessä käytiin läpi kuinka hyvin haastateltava tuntee teknologiat ja millaisia kokemuksia hänellä on tietyistä teknologioista kyseisessä yrityksessä. Toisessa osassa selvitettiin laitteiden omistamista koskevat asiat, kuten hankintaperusteet ja toimintakäytännöt. Kolmannessa osassa selvitettiin ulkoistamisen käytännöt. Neljännessä osassa haastateltavaa pyydettiin antamaan arvo tietyille AM-tekniikoihin liittyville tekijöille.

1.3 Raportin rakenne

Raportti mukailee rakenteeltaan haastattelua. Jokaiselle haastattelun osalle on annettu oma kappale. Tutkimuksessa löydetty data on esitetty määrällisesti taulukoissa, joiden vieressä tai alla on niiden selitykset.

2. Teknologioiden tunnettavuus

Tutkimuksen ensimmäisessä osassa selvitettiin kuinka hyvin erilaiset AM-teknolgiat tunnetaan. ASTM-standardi jakaa ainetta lisäävät menetelmät seitsemään ryhmään, jotka on esitetty taulukossa 1. Tähän taulukkoon pohjautuen tutkimukseen valittiin jokaisesta kategoriasta edustavimmat teknologiat, jotka on myös esitetty taulukossa 1.

Taulukko 1. AM-kategoriat ja valitut kaupalliset nimet

Teknologia	Kaupallinen nimi
Binder jetting	Three Dimensional Printing (3DP)
Direct energy deposition	Laser Engineered Net Shaping (LENS)
Material extrusion	Fused Deposition Modeling (FDM)
Material jetting	Polyjet
Powder bed fusion	Selective Laser Sintering (SLS)
Powder bed fusion	Selective Laser Melting (SLM)
Powder bed fusion	Electron Beam Melting (EBM)
Powder bed fusion	Selective Heat Sintering (SHS)
Sheet Lamination	Laminated Object Manufacturing (LOM)
Vat photopolymerization	Stereolithografia (SLA)
Vat photopolymerization	Digital Light Processing (DLP)

Taulukossa 2 on esitetty haastatteluissa annetut vastaukset siitä, tunnetaanko teknologia vai ei. Prosenttimäärä kuvaa "kyllä"-vastausten määrää kaikista vastauksista.

Vastaajista 88,9 % tunsi FDM:n, SLS:n ja SLA:n. 77,8 % tunsi LOM:n ja SLM:n. Polyjetin tunsi 55,6% 3DP:n ja DLP:n tunsi 22,2% ja EBM:n ja SHS:n 11,1% LENS-teknologiaa ei tuntenut kukaan haastateltavista.
Yleisesti kaupallisista nimistä tunnetaan hyvin vain FDM, SLS ja SLA. Muita tunnetaan huomattavasti huonommin.

Taulukko 2. Teknologioiden tunnettavuus

Sija	Kauppa-nimi	Tunnet-tavuus
1.	FDM	88,9 %
-	SLS	88,9 %
-	SLA	88,9 %
4.	SLM	77,8 %
-	LOM	77,8 %
5.	Polyjet	55,6 %
6.	3DP	22,2 %
-	DLP	22,2 %
8.	EBM	11,1 %
	SHS	11,1 %
9.	LENS	0,0 %

2.1. Fused Depostition Modeling (FDM)

Selkeyden vuoksi on hyvä jakaa FDM-teknologia edullisiin loppukäyttäjälaitteisiin ja teollisiin laitteisiin. Näiden kahden raja on tässä raportissa asetettu 5000 euroon. Noin 15%:lla yrityksistä on käytössä muutama halvemman hintaluokan FDM-laite, jolla testataan R&D-iteroinnin nopeuttamista talon sisällä. Yleisesti tämän hintaluokan laitteet on havaittu erittäin epätarkoiksi ja epäluotettaviksi yritysten keskuudessa.

Korkeamman hintaluokan laitteen omistaa 25% yrityksistä ja keskimääräinen käyttöaste on 19 tuntia viikossa. Noin 8% yrityksistä ulkoistaa FDM-mallien valmistusta, mutta niiden kokonaismäärä kaikista ulkoistetuista kappaleista on hyvin vähäinen. Positiiviseksi on havaittu teknologian materiaalivalikoima, joka on käyttäjien mielestä tarpeeksi vahvaa ja kestävää. Positiivista on myös jälkityöstön helppous.

Korkean hintaluokan (100,000€ +) laitteistoja ei tunnettu kovin hyvin. Suurimmalle osalle yrityksistä tuli yllätyksenä, että laitteistoille on saatavissa mm. ULTEM-materiaali, ja että niillä päästään noin 100 mikrometrin kerrospaksuuteen.

2.2. Selective Laser Sintering (SLS)

Yhdelläkään tutkimukseen osallistuneella yrityksellä ei ollut SLS-laitteistoa. SLS-malleja ulkoistetaan hyvin paljon ja Alphaform on ylivoimaisesti suosituin SLS-mallien tarjoaja. Positiiviseksi on katsottu suhteellisen hyvä materiaalin kestävyys.

SLS-menetelmän tarkuus on jakanut mielipiteitä. Menetelmän käyttäjistä noin 50% ovat olleet täysin tyytyväisiä mittatarkkuuteen ja toiset 50% käyttävät SLS:ää, kun kappaleen ei tarvitse olla kovin tarkka. Pinnan karheus nähtiin ongelmana.

2.3. Stereolithografia (SLA)

Stereolitografialaitteita omistaa 12,5 % yrityksistä. Stereolitografiamallien tuotantoa ulkoistaa 50 % yrityksistä. Ulkoistetut kappaleet teetetään Alphaformilla tai kiinalaisilla alihankkijoilla. Silikonimuottien teettäminen stereolitografian avulla on käytössä 37,5 % yrityksistä. Ongelmana nähdään materiaalien heikkous muihin valmistusmenetelmiin verrattuna. Positiivisena nähdään materiaalien laaja kirjo ja erinomainen mittatarkkuus.

2.4. Selective Laser Melting (SLM)

SLM-laitteistoja ei ole yhdelläkään tutkimukseen osallistuneella yrityksellä eikä yksikään aktiivisesti ulkoista SLM-kappaleita. Menetelmää on kokeiltu muutamassa projektissa useassa yrityksessä vaihtelevalla menestyksellä.

Suurimpina ongelmina nähdään menetelmän kalleus, laatu ja hitaus. Pienempiä ongelmia ovat jälkityöstön tarve ja laitteistojen tarkkuus. 75% yrityksistä ilmaisi mielenkiintoa käyttää SLM:ää tulevaisuudessa.

2.5. Laminated Object Manufacturing (LOM)

Yhdelläkään yrityksellä ei ollut käytössä LOM-laitteistoa eikä yksikään yritys ulkoistanut LOM-mallien tuotantoa. Menetelmän erittäin hyvä tunnettavuus johtuu siitä, että se oli 90-luvulla laajasti käytössä.

2.6. Polyjet

Polyjet-laitteistoja tai niihin verrattavia Multijet Modeling (MJM)-laitteistoja on 37,5 %:lla yrityksistä. Laitteistot on koettu hyvin herkiksi ja on havaittu, että ne vaativat paljon jatkuvaa ennakkohuoltoa. Ongelmina on nähty se, että laitteiston käyttöaste on pidettävä korkeana tasaisen laadun saamista varten sekä jälkikäsittelyn manuaalinen vaativuus. Teknologialle ominainen kutistuma on myös nähty ongelmallisena. Positiivisena on nähty kappaleiden mittatarkkuus ja varsinkin erinomainen tasomaisuus. Materiaalit ovat olleet pääosin tarkoitukseensa riittäviä.

2.7. Three Dimensional Printing (3DP)

Yhdelläkään yrityksellä ei ollut käytössä 3DP-laitteistoa eikä yksikään yritys ulkoistanut 3DP-malleja. Ongelmana nähtiin materiaalin heikkous. Värillisten kappaleiden valmistamisen ei nähty tuovan lisäarvoa.

2.8. Digital Light Processing (DLP)

Yhdelläkään yrityksellä ei ollut käytössä DLP-laitteistoa eikä yksikään yritys ulkoistanut DLP-malleja. Teknologian tunnettavuus on alhainen.

2.9. Electron Beam Melting (EBM)

Yhdelläkään yrityksellä ei ollut käytössä EBM-laitteistoa eikä yksikään yritys ulkoistanut EBM-malleja. Teknologian tunnettavuus on alhainen.

2.10. Selective Heat sintering (SHS)

Yhdelläkään yrityksellä ei ollut käytössä SHS-laitteistoa eikä yksikään yritys ulkoistanut SHS-malleja. Teknologian tunnettavuus on alhainen. Muutama yritys ilmaisi mielenkiintoa SHS:n käytössä R&D-toimistossa, kunhan menetelmän laadusta saadaan varmaa tietoa.

2.11. Laser Engineered Net Shaping (LENS)

Yhdelläkään yrityksellä ei ollut käytössä LENS-laitteistoa eikä yksikään yritys ulkoistanut LENS-malleja. Teknologiaa ei tuntenut kukaan haastateltavista.

3. Käyttökohteiden osuus kokonaiskäytöstä

Tutkimuksessa jaettiin käyttökohteet kolmeen kategoriaan: rapid prototyping (RP), rapid tooling (RT) ja rapid manufacturing (RM).

Tässä raportissa on katsottu, että ulkoistettaessa käyttökohde määritellään sen mukaan, mikä on toimitettu lopputuote. Silikonimuottien ulkoistamisessa on katsottu, että käyttökohde on RP, mikäli toimitettu tuote on silikonimuotin avulla tehty malli, ja RT, mikäli toimitettu tuote on itse silikonimuotti. Yrityksistä 37,5 % käyttää silikonimuotteja, mutta suurin osa näistä muoteista pysyy toimittajan tiloissa.

Taulukossa 3 on esitetty käyttökohteen suuruus kaikesta vastanneiden yritysten AM:n käytöstä. Esitettäviksi arvoiksi on valittu keskiarvot sekä 25., 50. ja 75. persentiilit.

Taulukko 3. Käyttökohteet

Käyttökohde	Keskiarvo (%)	25. persentiili (%)	50. persentiili (%)	75. persentiili (%)
RP	84	80	90	90
RT	6	0	0	5
RM	10	1	10	20

RP on tällä hetkellä ylivoimaisesti haastateltujen yritysten suurin käyttökohde. 90 % yrityksistä tekee lähes pelkästään RP:a. Maailmaan verrattuna Suomessa käytetään hyvin vähän RT:a. Silikonimuotteja teetetään paljon, mutta usein yritys näkee prosessista vain lopputuotteen. Vahamuotteja tarkkuusvaluun on kokeiltu, mutta sen on nähty olevan liian kallista. Yrityksissä, joilla on tuotantoyksikkö, tehdään jigejä tuotantoon. RM:n kysyntä olisi muuten suurta, mutta sen hinta ja laatu ovat tähän mennessä olleet estäviä tekijöitä. Joillakin yrityksillä AM on ainoaa valmistusta Suomessa, kun kaikki muu on ulkoistettu ulkomaille.

4. Laitteiden omistaminen ja käytännöt

Taulukossa 4 on esitetty kuinka iso osa yrityksistä omistaa laitteita. Yhden laitteen omistavia yrityksiä on yhtä monta, kuin yrityksiä, joilla ei ole laitteita. 25 %:lla on omistuksessa useampi kuin yksi laite.

Taulukko 4. Omistettujen laitteiden määrä

Laitteiden määrä	Määrä (%)
Ei laitteita	37,5
Yksi laite	37,5
Useampi kuin yksi laite	25

Taulukko 5. Laitteiden määrä yrityksissä

Teknologia	Omistavien yritysten prosentti (%)
FDM	42,8
Polyjet / MJM	42,8
SLA	14,3

4.1. Laitteiden hankintaperusteet

Oman laitteen hankintaa on usein edeltänyt mittava ulkoistaminen. Oma laite on haluttu hankkia, koska toimitusaikojen poistaminen nopeuttaa tuotekehitystä ja madaltaa käyttäjien kynnystä käyttää AM:ää. Syynä oman laitteen hankkimiseen on myös kustannustehokkuus, sillä omalla laitteella on halvempaa tuottaa kappaleita ja ulkoistuksen piilokustannukset ovat tiedossa.

Tietty laite on hankittu erilaisin perustein eri yrityksissä. Selkeästi yritykset ovat halunneet koneen, jolla saa riittävän isoja ja tarkkoja kappaleita, jotka ovat myös helppoja käyttää. Usein kone on valittu valmiiden mallien perusteella, joissa on kiinnitetty huomiota materiaaliin. Nopea jälkikäsittely on ollut kaikille prioriteettina. Osa yrityksistä on nähnyt, että ostettu laite on hankittu kevein perustein.

4.2. Laitteiden operointi

Laitteiden käytössä on oleellista, kuka niille toimii operaattorina. Yleisimmät tavat järjestää asia ovat:

1. Annetaan 3D-mallinnuksesta vastaaville työntekijöille mahdollisuus käyttää laitetta itse
2. Nimetään laitteille tarkoitukseen palkattu operaattori

Taulukossa 6 on esitetty missä suhteessa yritykset käyttävät yllä mainittuja käytäntöjä. Ainoastaan laitteita omistavat yritykset ovat taulukon tiedoissa mukana.

Yhtä monta yritystä antaa mallintajien käyttää laitteistoa kuin käyttää nimettyä henkilöä. Haastattelujen perusteella on huomattu, että operaattorin käyttäminen voi nostaa koneen käyttöastetta ja laskea toimettomana seisomista.

Taulukko 6. Käytäntöjen jakauma

Käytäntö	Määrä kaikista (%)
Tarpeen mukaan	50
Nimetty henkilö	50

4.3. Käyttöaste

Yrityksissä, joilla on omistuksessaan AM-laite, käyttöaste on ollut keskimäärin 47,25 tuntia viikossa. Tämä käyttöaste on verrattaen alhainen olettaen, että laite voisi olla käynnissä tauotta asetusaikoja ja huoltotaukoja lukuunottamatta. Prosentuaalinen käyttöaste on laskettu täydelle 168 tunnin viikolle.

Taulukko 7. Laitteiden käyttöaste

Käyttöaste	Keskiarvo (h)	25. persentiili (h)	50. persentiili (h)	75. persentiili (h)
Tunteina viikossa	47	25	38	60
Prosentteina viikosta (168 h)	28 %	15 %	23 %	36 %

4.4. Laitteiden huolto

Ennakoivaa huoltoa tekee 80 % yrityksistä, mikä on melko korkea aste. On huomionarvoista, että AM-laitteiden ennakoiva huolto on äärimmäisen tärkeää niiden herkkyyden takia.

Taulukko 8. Ennakoiva huolto

Ennakoiva huolto	Määrä kaikista (%)
Tehdään itse	60
Ulkoistetaan	20
Ei tehdä	20

4.5. Valmistusaika

Yrityksistä 50 % saa kappaleen valmiiksi alle päivässä ja toiset 50 % noin päivän sisällä. Kummatkin ajat ovat nykytekniikoilla erittäin hyviä ja viittaavat hyvin lyhyeen odotusaikaan. Tämä johtuu osittain alhaisesta käyttöasteesta

Taulukko 9. Oman koneen kappaleenvalmistusaika

Valmistumisaika	Prosenttimäärä (%)
Alle päivä	50
Noin päivä	50
Useita päiviä	0
Noin viikko	0

4.6. Kustannusten valvonta

Omalla koneella valmistettavien osien kustannusten seuranta riippuu suuresti yrityksen koosta. Pienemmät yritykset seuraavat jokaisen kappaleen hintaa ja päättävät sen mukaan tehdäänkö kappale. Suuremmissa yrityksissä materiaalikulutus on joko budjetoitu vuositasolla tai sitä ei seurata ollenkaan. Usein kustannuksia lasketaan vain investointivaiheessa, mutta ei lasketa enää sen jälkeen.

Taulukko 10. Kappaleiden valmistuksen kustannusten seuranta

Kappaleiden valmistuksen kustannusten seuranta	Prosentti yrityksistä (%)
Budjetoitu	20
Jokainen kappale erikseen	40
Ei seurata	40

5. Ulkoistaminen

Yritykset ulkoistavat yhä enemmän, koska ollaan tultu tietoisiksi AM:n mahdollisuuksista. Yrityksille, joilla on oma laite, ulkoistamispäätös on usein harkittu.

Mikäli oma kone on ylikuormitettu eikä konsernista löydy toista konetta, ulkoa tilaaminen on joskus nopeampaa. Usein oman koneen laatu ei riitä pintalaadun, materiaalin kestävyyden tai kuluvuuden tai esimerkiksi snap-on-yksityiskohtien valmistukseen, jolloin ulkoistetaan. Usein ulkoistukseen kuuluu myös jälkikäsittely, sillä nähdään, että AM-toimittajat ovat siinä kokeneempia kuin oman talon työntekijät. Isot yli 20 kappaleen sarjat yleensä ulkoistetaan. Kappaleen koko ratkaisee ulkoistuksessa, jos omistetun koneen valmistustilavuus on pienempi kuin haluttu kappale. Silikonimuotit ja niiden kautta valmistetut kappaleet ulkoistetaan lähes kaikissa tapauksissa. Harvemmissa tapauksissa, varsinkin oman laitteen hankkimista suunniteltaessa, yritys haluaa kokeilla tekniikkaa, jota sillä ei ole, jolloin se luonnollisesti ulkoistaa.

Usealla yrityksellä on mentaliteettina, että laadukkaat osat ulkoistetaan ja talon sisällä valmistetaan heikompilaatuisia malleja. Sama jako pätee myös siinä, että toiminnalliset prototyypit ulkoistetaan ja visuaaliset prototyypit tehdään omalla laitteella.

Taulukko 11. Ulkoistamisen määrä kokonaistoiminnasta

Mittaustapa	Keskiarvo	25. persentiili	50. persentiili	75. persentiili
Prosentteja kokonaiskulu-ista	56 %	25%	53 %	100%
Euroja	41,000 €	10,500€	25,000€	45,000€

5.1. Laadunvalvonta

Tilatun osan laadun tarkistaminen suoritetaan yleensä vain visuaalisesti ja kokeilemalla kokoonpantavuutta. Yleisesti luotetaan toimittajaan ja jätetään kappaleen laatu tämän vastuulle. Muutama yritys mittaa kappaleiden mittatarkkuuden ja materiaaliominaisuudet.

Taulukko 12. Laaduntarkastuskäytännöt

Laaduntarkastusmenetelmä	Prosentti yrityksistä (%)
Visuaalinen tarkastus	63
Mittatarkkuuden mittaus työkalulla	38
Kokoonpantavuustesti	38
Materiaalin ominaisuuksien tarkastus	25

5.2. CAD-tiedostojen tietoturva ja käsittely

Luotetuille toimittajille tiedostojen lähettäminen ei ole ongelma, mutta muille tiedostoja ei usein lähetetä tietovuotojen varalta. Mikäli tiedostot ovat salaisia, laitteen omistavat yritykset valmistavat kappaleen itse.

Taulukko 14. .STL-tiedoston jälkikäsittely toimittajalla

Nähdään hyödyllisenä	Prosent-timäärä (%)
Kyllä	50
Ei	50

Taulukko 13. CAD-tiedostojen salaisuus

Salaisuusaste	Prosenttimäärä (%)
Ei lainkaan salaisia	25
Jonkin verran salaisia	37,5
Suurimmaksi osaksi salaisia	25
Hyvin salaisia	12,5

5.3. Toimitusaika

Pieni osa yrityksistä saa kappaleet toimittajalta noin päivässä. 86 %yrityksistä odottavat toimitusta useista päivistä noin viikkoon.

Taulukko 15. Ulkoistettujen kappaleiden yleisin toimitusaika

Toimitusaika	Prosenttimäärä (%)
Alle päivä	0
Noin päivä	14
Useita päiviä	43
Noin viikko	43

5.4. Maksimaalisen hyödyn raja

Maksimaalisen hyödyn raja on se toimitusnopeus, jolla ylimääräinen nopeus ei tuota hyötyä. Suurrimmalla osalla yrityksistä maksimaalisen hyödyn raja on muutamista päivistä noin viikkoon, mutta muutamalla yrityksellä maksimaalisen hyödyn raja on noin päivä. Tällä hetkellä toimitusajat ovat hieman maksimaalisen hyödyn rajaa pidempiä.

Taulukko 16. Maksimaalisen hyödyn raja

Ajanmääre	Prosenttimäärä (%)
Alle päivä	0
Noin päivä	29
Useita päiviä	43
Noin viikko	29

5.5. Kustannusten seuranta

Kustannuksia seurataan suurimmassa osassa yrityksistä jokaisen tilauksen kohdalla erikseen.Isommat yritykset ovat budjetoineet AM-tekniikoiden käytön vuo-sitasolla

Taulukko 17. Ulkoistamisen kustannusten seuranta

Ulkoistamisen kustannusten seuranta	Prosentti yrityksistä (%)
Budjetoitu	25
Jokainen tilaus erikseen	50
Ei seurata	25

6. Yleistä ja tulevaisuusnäkymät

Taulukko 18. Materiaalia lisäävään valmistukseen liittyvien tekijöiden subjektiivinen tärkeys asteikolla 1-5, jossa 1 = ei lainkaan tärkeä ja 5 = hyvin tärkeä

Tekijä	Keskiarvo	25. persentiili	50. persentiili	75. persentiili
Saada kappale nopeasti käsiin	4,09	4	4	5
Kappaleen mittojen tarkkuus	4,27	4	4	5
Materiaalin sopivuus	3,64	2,5	4	5
CAD-tiedostojen tietoturva	3,18	2,5	3	3,5
Menetelmien optimaalisuus	2,82	1,5	3	4
Yleinen tietämys AM-tekniikoissa	3,64	2,5	4	4,5

Materiaalia lisäävä valmistus nähdään tärkeänä esitettäessä konseptimalleja insinööreille. Osakkeenomistajille pikavalmistetut mallit nähdään liian karkeina. Selkeänä trendinä yritykset haluavat valmistaa isompia kappaleita. Kiinnostus SLM:ää kohtaan on suurta. Toimitusaika on suurimman osan mielestä hyväksyttävä ja palveluun yleisimmiltä toimittajilta ollaan oltu tyytyväisiä. Suoraan eri väreillä toimivat valmistusmenetelmät ovat saaneet jonkin verran huomiota, mutta suurin osa yrityksistä mieluummin maalaa mallit jälkeenpäin. Pikavalmistettujen kappaleiden pinnanlaatuun ei olla tyytyväisiä, vaan sen pitäisi olla parempaa. Omien laitteiden nopeus on tällä hetkellä hyväksyttävä, mutta tulevaisuudessa toivotaan laitteiden olevan monta kertaa nopeampia.

Uuteen .ATF-formaattiin on kiinnitetty jonkin verran huomiota ja osa yrityksistä toivoo saavansa käännettyä tulevaisuudessa CAD-tiedoston .ATF-tiedostoksi. Tarkkuusvaluille (investment casting) on kysyntää ja toivotaan, että Suomeen tulisi tarkkuusvaluja tekevä toimittaja. Malleja käytetään harvoin sellaisinaan, vaan ne viimeistellään varsinkin reikiä aventamalla.

Edistyneimmät käyttäjät ovat aloittaneet RM:n käytön ja trendin mukaan tulevaisuudessa sitä tullaan käyttämään Suomessa enemmän kuin nyt. Kokonaistietämys materiaalia lisäävän valmistuksen ympäriltä vielä suhteellisen alhaista.

ISF mini -projektin loppuraportti 2013-2014

Aalto-yliopisto, Pekka Lehtinen, pekka.a.lehtinen@aalto.fi

Johdanto

Pikavalmistus (Additive Manufacturing, Rapid Prototyping) tarjoaa valmistusmenetelmiä, joilla voidaan joustavasti valmistaa monimutkaisia geometrioita sisältäviä kappaleita. Näiden kappaleiden valmistaminen perinteisillä menetelmillä on usein kallista, työlästä tai jopa mahdotonta. Pikavalmistuksessa fyysinen kappale valmistetaan materiaalia lisäävällä menetelmällä suoraan CAD-mallin pohjalta kerros kerrokselta nopeasti ja automaattisesti. Pikavalmistuksen tehokkuus ja mahdollisuudet tulevat esille etenkin pienten tuotemäärien valmistuksessa. Valmistusmuotteihin ja muihin työkaluihin ei tarvitse investoida, sillä tuote voidaan valmistaa suoraan yhdellä pikavalmistuslaitteella.

ISF mini –projektissa tavoitteena on kehittää pienien ohutlevykomponenttien painomuovaamiseen soveltuva tutkimuslaitteisto ja kerätä tietotaitoa pienten kappaleiden muovaamisesta ja muovattavuudesta. Lyhenne ISF tulee sanoista Incremental Sheet Forming. Kyseessä ei siis ole materiaalia lisäävä menetelmä, sillä levyn massa pysyy samana koko prosessin ajan. Muovausperiaate tapahtuu kuitenkin kerros kerrokselta ja tietokoneohjauksella.

Laitteisto

Tutkittavien metallievyjen muovaamista varten hankittiin levynkiinnitysteline ja muovauskärkiä. Teline on esitetty kuvassa 1a. Muovauskärki on kovametallitappi, jonka päässä on puolipallon muotoinen kärki. Kärjen halkaisija vaihtelee 3 mm ja 10 mm välillä.

Levy kiinnitetään telineessä (kuva 1a) näkyvän aukon kohtaan. Teline koostuu alumiiniprofiileista tehdystä kahdesta kehikosta, joiden väliin levy voidaan kiinnittää puristimilla. Kuvassa 1b näkyy telineeseen kiinnitetty metallilevy. Levy on siis kiinnitetty neljältä sivulta. Levyn alla ei ole tukia, vaan telineen alumiiniprofiilit toimivat tukipisteinä. Tämä muovaustapa, jossa muovattavan levyosuuden alla ei ole tukia tunnetaan nimellä Single Point Incremental Sheet Forming.

Ensimmäiset kokeet suoritettiin pylväsporakoneella kesällä 2013. Kovametallitappi kiinnitettiin koneeseen ja metallilevy telineeseen. Pöytää liikutettiin käsipyörien avulla. Pöydän liikkuessa metallikärki piirsi levyyn uran. Kitkan vähentämiseksi levylle levitettiin voiteluöljyä. Jokaisen kerroksen jälkeen karaa laskettiin kerrospaksuuden verran alaspäin, minkä jälkeen piirrettiin uusi kuvio metalliin. Prosessia jatkettiin kunnes haluttu muoto oli saatu metallilevyyn. Näillä alustavilla kokeilla oli tarkoitus selvittää, metallilevyn paksuuden, kerrospaksuuden ja voitelun vaikutus lopputuotteeseen.

Joulukuussa 2013 otettiin käyttöön CNC-kone KX3-Mach, joka on esitetty kuvassa 1b. Samoja muovauskärkiä ja levynkiinnitystelinettä käytettiin tämän koneen ja pylväsporakoneen kanssa. Muovausprosessi on kuitenkin erilainen. Aluksi suunnitellaan CAD-malli siitä muodosta, joka halutaan muovata metallilevyyn. Tämä malli käsitellään CAM-ohjelmalla, jotta CAD-malli saadaan muutettua G-koodiksi. G-koodi on komentokieli, jota käytetään CNC-koneiden ohjaamiseen. CAD-malli siis muutetaan CNC-koneen ymmärtämiksi liikkumiskomennoiksi. G-koodi ladataan CNC-konetta ohjaavaan Mach-ohjelmaan, jolla voidaan hallita koneen liikkeitä ja käynnistää muovausprosessi.

(a) Teline metallilevyn kiinnittämistä varten.

(b) CNC-kone KX3-Mach.

Kuva 1: Metallilevyjen muovaukseen käytetty laitteisto.

Testatut materiaalit ja parametrit

Metallilevyjen muovaus tapahtuu painamalla kovametallikärki levyn pintaa vasten ja kuljettamalla kärkeä halutun muodon mukaisesti. Prosessiin vaikuttavat monet parametrit. Muovattavan radan muoto vaikuttaa merkittävästi lopputulokseen. Terävät kulmat ovat usein vaikeampia valmistaa onnistuneesti kuin pyöreät muodot. Muovauskärjen koko rajoittaa kulmien terävyyttä ja yksityiskohtien tarkkuutta. Myös muovauskärjen varren pituudella, pyörimisellä ja kärjellä on merkitystä. Pitkä varsi on joustava, jolloin muodot pyöristyvät. Pyöriminen puolestaan hioo levyn pintaa samalla kun kärki piirtää haluttua kuviota levyyn. Kokeissa selvitettiin myös miten kuulakärkikynämäinen ratkaisu toimii muovausprosessissa. Muovausnopeuden kasvattaminen pyöristää kulmia, mutta nopeuttaa valmistusprosessia. Kerrosten välinen z-askel vaikuttaa pinnan laatuun, sillä pieni z-askel vähentää pinnan aaltoisuutta, joka muodostuu kerrosten välisestä askeleesta. Askeleen suurentaminen nopeuttaa prosessia, mutta kärjen liikuttamiseen tarvitta voima kasvaa huomattavasti. Muovaus tapahtuu käyttämällä levyn materiaalia joten erittäin syvät ja jyrkkäseinäiset muodot eivät ole mahdollisia. Levyn materiaali ja paksuus ovat tärkeitä parametreja, jotka tulee ottaa huomioon muodon suunnittelussa. Jäykkä materiaali hajoaa helpommin kuin joustava materiaali. Paksuus puolestaan lisää materiaalin määrää, jolloin murtumat ovat epätodennäköisempiä, mutta samalla levyn jäykkyys kasvaa.

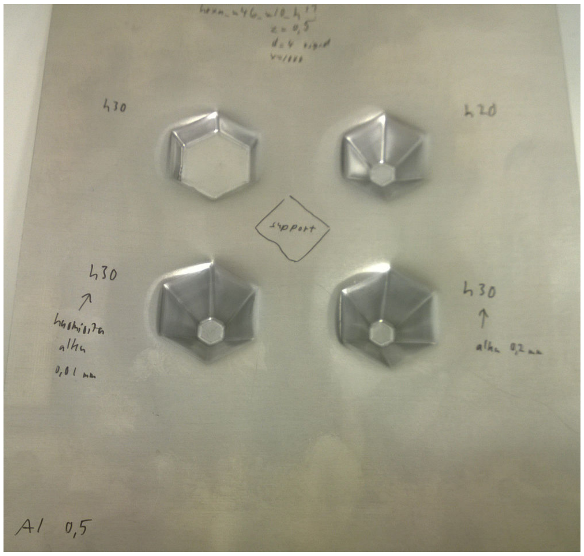
Tässä projektissa käytettiin seuraavia materiaaleja: alumiini, kupari, teräs (kylmävalssattu), syvävetoteräs (DC04) ja duralumiini. Näiden materiaalien levyjen paksuudet vaihtelivat pääsääntöisesti välillä 0,5 mm ja 1 mm. Muovauskärkenä toimi kiinteä puolipallo tai kuulakärkikynän tapainen pallo. Pallon halkaisija vaihteli välillä 3 mm ja 10 mm. Muovausnopeus valittiin väliltä 500 mm/min ja 2000 mm/min. Muovattavia muotoja oli kattavasti erilaisia. Pääsääntöisesti kuviot olivat erikokoisia kartiomaisia syvennyksiä, joilla oli vaihteleva pohjan muoto ja seinän jyrkkyys. Seinän kaltevuus on mitattu asteina siten että 0° on tasainen levy ja 90° on pystysuora seinä.

Tulokset

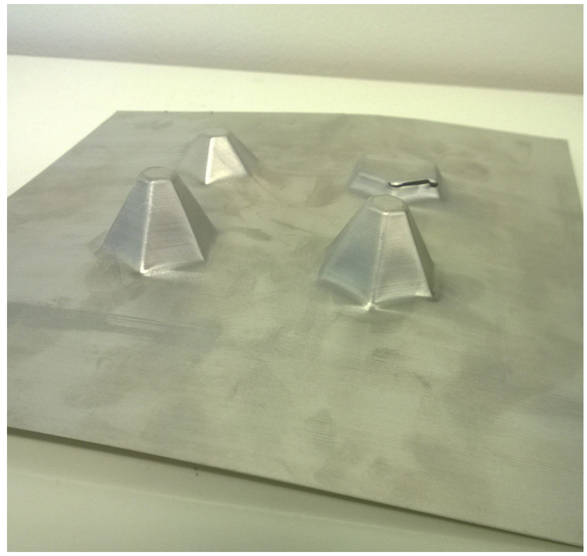
Edellisessä luvussa mainittuja ominaisuuksia tutkimalla saatiin selville eri materiaalin valinnan ja muovausparametrien vaikutukset valmistusprosessiin. Laadukkaan lopputuloksen saaminen ei salli mielivaltaisten parametrien käyttöä, vaan on käytettävä hyväksi havaittuja arvoja. Kuvissa 2 - 6 on esitetty valmistettuja muotoja käyttäen eri parametreja. Jokaiseen levyyn on kirjoitettu millaisilla parametreilla kyseinen muoto on tehty. Levyistä löytyvät seuraavat tiedot

muoto_wα_wβ_hγ, z, d ja v,

missä wα ja wβ ovat muodon leveys levyn pinnassa ja pohjalla, hγ on muodon syvyys, z on kerrosten välisen z-askeleen suuruus, d on muovauskärjen halkaisija ja v on muovausnopeus (mm/min). Kaikki numeroarvot ovat ilmoitettu millimetreissä. Esimerkiksi kuvassa 6a olevaan levyyn on kirjoitettu circle_w??_w10_h40; z=0,5; d=6 rigid; v=1000. Eli kyseessä on ympyräkartio, jonka suurempi halkaisija on 40, 42, 44 tai 46 mm (levyyn on muovattu neljä eri kuviota). Pohjalla olevan ympyrän halkaisija on 10 mm. Kuvion syvyys on 40 mm. Z-askel on 0,5 mm. Käytettävän muovauskärki on kiinteä (ei kuulakärkikynä) ja halkaisijaltaan 6 mm. Muovausnopeus on 1000 mm/min.

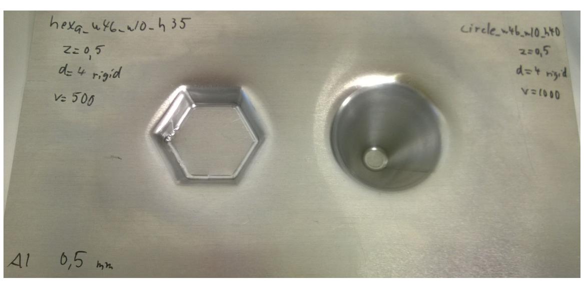


(a) Yläpuoli

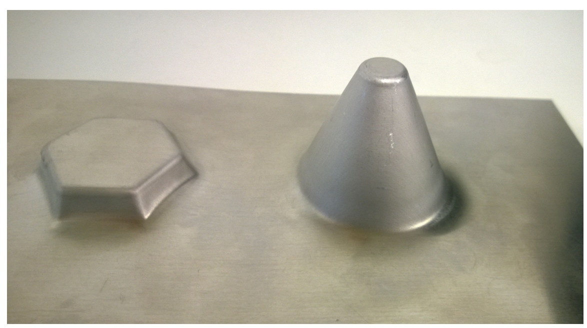


(b) Alapuoli

Kuva 2: Alumiinilevy 0,5 mm hexa_w46_w10_h??.

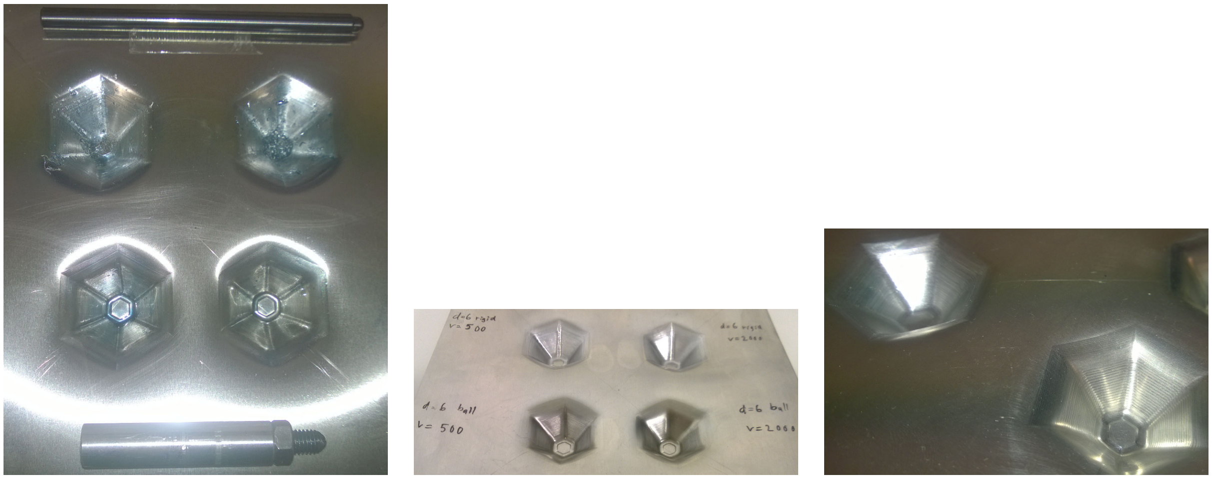


(a) Yläpuoli



(b) Alapuoli

Kuva 3: Alumiinilevy 0,5 mm, jossa vasemman puoleinen on epäonnistunut (levy murtunut kesken muovauksen) ja oikean puoleinen on onnistunut (ehjä levy).



(a) Kiinteä kärki on rouhinut metallin pintaa ja jättänyt kuvioon metallilastuja.

(b) Eri kärjillä tehdyt kuviot.

(c) Pinnan sileys on erilainen käytetystä kärjestä riippuen. Ylhäällä kiinteällä kärjellä tehty kuvio.

Kuva 4: Kiinteän puolipallon ja kuulakärkikynämäisen kärjen muovaamia kuvioita. Ylärivin kuviot on tehty kiinteällä kärjellä. Alarivin kuviot on tehty kuulakärkikynäkärjellä. Kärjet näkyvät (a) kuvan ylä- alareunassa.

(a) Kuparille circle_w46_w10_h??

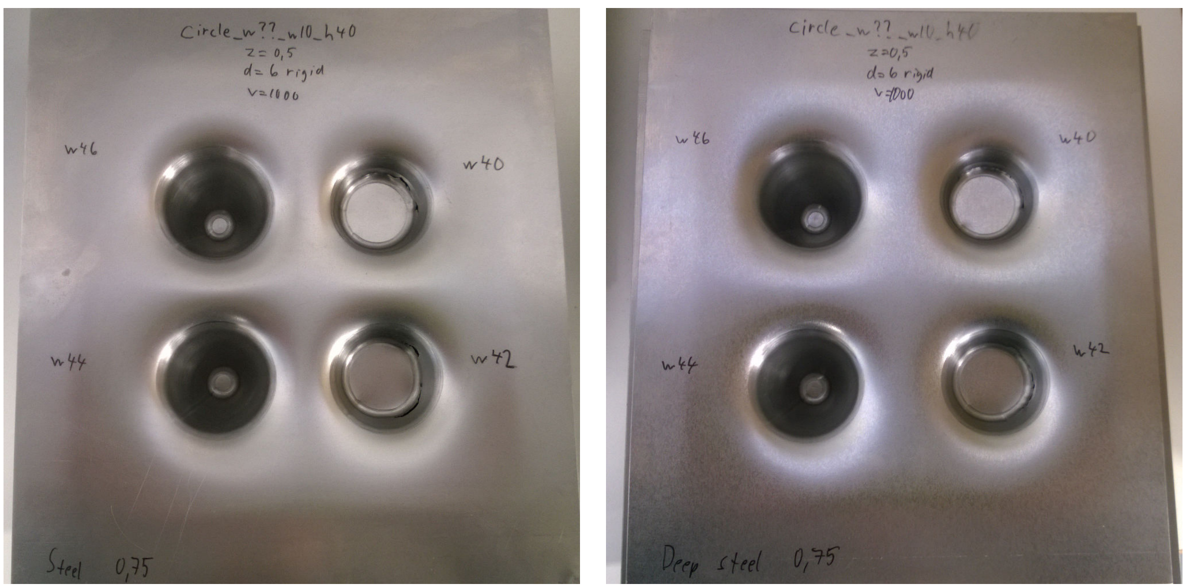
(b) Alapuoli kuvan (a) levystä.

(c) Kulmien pyöristämisen vaikutus.

Kuva 5: Kuparilevy 0,5 mm, jolle on tehty useita eri kuvioita.

Taulukko 1: Muovauksessa hyvin toimivat parametrit

Materiaalit	**Parametreja**
Alumiini 0,5 mm	Muovauskärjen halkaisija 4 - 6 mm
Kupari 0,5 mm	z-askel 0,5 mm
Teräs 0,5 mm	Nopeus 500 – 1 000 mm/min
Syvävetoteräs 0,75 mm	Seinän kaltevuus alumiinille $< 65°$
	Seinän kaltevuus kuparille ja teräkselle $< 68°$



(a) Teräs (b) Syvävetoteräs

Kuva 6: Vertailua teräksen ja syvävetoteräksen välillä.

Taulukkoon 1 on koottu useimmiten käytettyjen materiaalien osalta suositeltavat parametrit ja rajoitteet. Parhaat testitulokset saatiin 0,5 mm paksuilla alumiini-, kupari- ja teräslevyillä. Kokeiden kannalta huonoin materiaali oli duralumiini, sillä se murtui hyvin herkästi. Suurta eroa ei huomattu syvävetoteräksen ja kylmävalssatun teräksen välillä, vaikka syvävetoteräksellä on alhainen myötölujuus ja se on suunniteltu juuri muovausprosesseja varten. Kuvasta 6 käy ilmi, että samat kuviot ovat epäonnistuneet ja onnistuneet samankaltaisesti molemmilla teräslaaduilla. Luotettavaa vertailua haittasi se, että toistettavuus ei ollut paras mahdollinen. Huono toistetettavuus käy ilmi kuvasta 5a, jossa yksi arvolla h40 valmistettu kuvio on epäonnistunut ja kaksi on onnistunut.

Yhteenveto ja jatkosuunnitelmat

ISF mini -projektissa onnistuttiin painomuovaamaan pieniä ohutlevykomponentteja tutkimuslaitteistolla. Koetulosten avulla löydettiin metallilevyn muovauksessa hyvin toimivat parametrit. Erilaisia muotoja painomuovattiin käyttäen useita eri materiaaleja. Tälle laitteistolle sopivat erityisen hyvin 0,5 mm paksuiset alumiini, kupari ja teräslevyt. Muovauskärjen halkaisi oli 4-6 mm, ja muovausnopeus oli yleensä 1000 mm/min. Seinän kaltevuuden tulee olla alle 65°, jotta levyn repeämiseltä vältyttäisiin.

Muovausprosessissa ilmeni kuitenkin joitain ongelmia. Toistettavuus ei ollut paras mahdollinen. Suurilla seinän kaltevuuden arvoilla tehdyt kuviot saattoivat onnistua tai epäonnistua, vaikka laitteistoon ei tehty muutoksia. Tukipisteiden etäisyyksiä muovattavaan kuvioon ei ollut tarkoin määritelty, mikä saattaa selittää epäjohdonmukaisuutta. Merkittävä tekijä on todennäköisesti myös metallin laatu. Metallilevyn muovattavuuteen vaikuttavat sen raerakenne ja tekstuuri. Kaikki kokeet on suoritetu huoneenlämmössä, joten lämpötilan vaikutus on selvittämättä. Terävien kulmien muovaaminen on haasteellista ja käytettävien työkalujen valinnalla on merkitystä. Esimerkiksi kolmion kulmat ovat jo niin teräviä, että levy helposti murtuu niiden kohdalta.

Lämpötilan vaikutusta voidaan tutkia käyttämällä tehokasta laserlaitteistoa. Tässä projektissa käytettyyn KX3-Mach-laitteistoon on yhdistetty laser Hämeenlinnan Ammattikorkeakoulun toimesta. Laser lämmittää metallilevyä sen alapuolta. Tutkimuksen tavoitteena on selvittää miten levyn lämmittäminen paikallisesti laserilla vaikuttaa levyn muovattavuuteen.

Teknologiaosaamisen koulutus- ja tutkimuskeskus
Tapio Väisänen

18.8.2014

TUTKIMUSRAPORTTI

Laseravusteinen numeerinen painomuovaus

Tämä tutkimusraportti liittyy Aalto-yliopiston SuperMachines-hankkeeseen. Raportti sisältää (1) Laseravusteisen numeerisen painomuovauksen englanninkielisen kirjallisuuskatsauksen sekä (2) HAMKissa tehtyjen kokeiden kuvauksen ja tulokset.

1. Kirjallisuuskatsaus

LASER-ASSISTED INCREMENTAL FORMING

Introduction

Laser-assisted Incremental forming is a process where laser is used to heat material during the incremental forming process. The key idea is to create a heated spot in the dynamic contact zone between tool and sheet, while keeping the rest of sheet at near the ambient temperature. This process leads to reduced process forces, improved dimensional accuracy of parts and increased formability for a range of materials.

Laser-assisted incremental forming is being developed for the aim of forming high-strength materials flexibly and cost-effectively. Magnesium and titanium alloys are suitable materials in this process as it is difficult to form these materials at room temperature. In addition, aluminium alloys and different steels have also tested. Local heating is used to improve the formability of materials that cannot, or can be formed difficultly at room temperature. The forming area is heated by a laser beam before the tool. (Callebaut 2009)

Researches of the laser assisted incremental forming

Laser assisted incremental forming system created by J.R. Duflou is shown in Figure 1. 500W Nd:YAG laser was used in the back side of the sheet by a 3-axis X-Y-Z system. The laser was used to heat the CNC-controlled tool position and cooling system was used to ensure that material stays at low temperature.

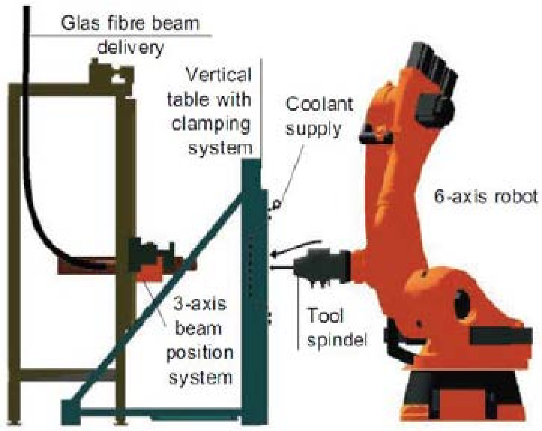


Figure 1. Laser assisted incremental forming system (Duflou et al. 2011)

Force reduction

Duflou, Callebaut, Verbert and De Baerdemaeker have demonstrated the effect of a area temperature increase to reduce axial force on the process. A backing plate with diameter 180 mm was used to support 1.25 mm thick aluminium blank of size 225*225 mm. The backing plate cones with an original outer diameter of 140 mm, a depth of 20 mm and a wall angle of 40° have been formed. Step size was 0.5 mm, and diameter of a tungsten carbide tool was 10 mm. (Duflou, Callebaut, Verbert & Baerdemaeker 2011.) In their experiment, in order to improve absorption, they used a graphite 33 coating in the laser side of the blank and 8 and 12 mm spot laser were chosen with forward offset of 2.4 mm. Feed rate were varied in the test. The test results in Figure 2 show that force decreases when temperature increases.

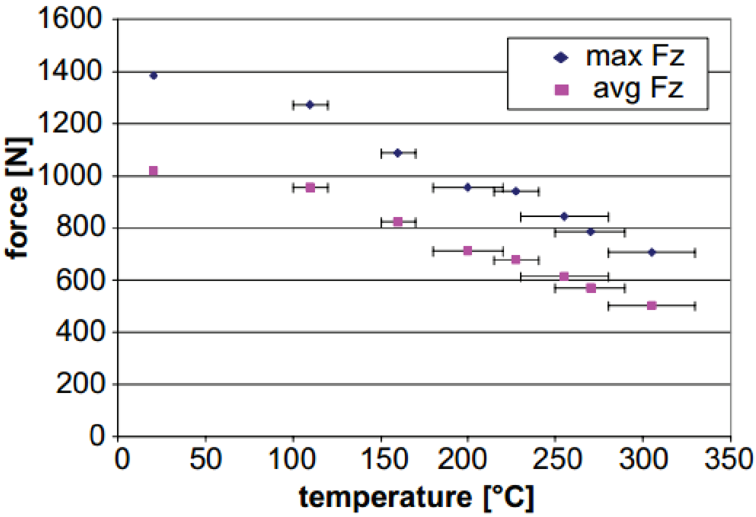


Figure 2. Maximum and average axial forces as a function of heating temperature (Duflou et al. 2011)

Accuracy improvement

In order to reduce springback, reduction of unwanted plastic deformation will be beneficial from reducing process forces. Duflou et al. used 65Cr2 steel blanks of 0.5 mm thickness to compare the accuracy in a cold and a dynamically heated forming test by using 10 mm tungsten carbide tool to form conical shapes with outer diameter of 160 mm, a depth of 40 mm and a slope angle of 50°. A 180 mm diameter backing plate was used. A tool path with a discrete step down size of 0.5 mm was used. Feed rate of the robot was 1500 mm/min for the cold situation and 2000 mm/min for the laser assisted run (Duflou et al. 2011.) The results in Figure 3 show that heated part have better accuracy than non-heated part.

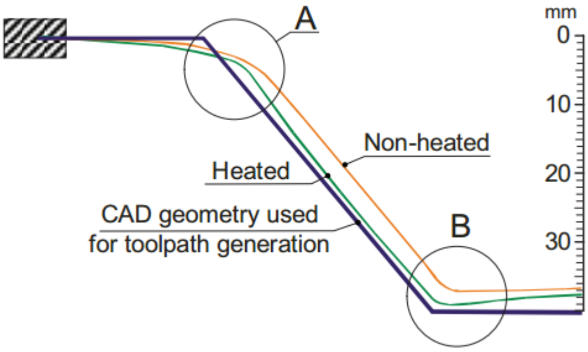


Figure 3. Obtained workpiece geometry for heated and non-heated process variants. (Duflou et al. 2011)

Formability increase

In order to compare the formability behaviour, Duflou et al. used 0.6 mm thickness TiAl6V4 sheets under dynamically heated conditions and at room temperature. A high temperature resistant coating 10 mm tool was used to form the conical shape with outer diameter 140 mm and increasing wall angle. A 180 mm backing plate supported the work piece. Many research teams have used similar setup to determine the formability of different materials. In order to adapt the test with low wall angle in room temperature, maximum depth for the cones was limited to 30 mm. Incremental step of 0.5 mm of toolpath was used. (Duflou et al. 2011.) The original feed rate of robot was 1000 mm/min. The test results are shown in Figure 4. Wall angle is increased from 32 degrees to 56 degrees when heated.

Non-heated		Heated			
wall angle [°]	obtained result	wall angle [°]	spot size [mm]	energy input [J/mm²]	obtained result
30	OK	45	12.0	0.875	OK
35	failed	50	12.0	0.875	OK
32	OK	55	12.0	0.875	failed
34	failed	53	12.0	0.740	OK
33	failed	55	12.0	0.740	OK
		57	12.0	0.740	failed
		56	12.0	0.740	failed
		56	14.0	0.740	OK
		57	15.0	0.740	failed

Figure 4. Formability test results for 0.6mm TiAl6V4 (Duflou et al. 2011)

As a summary, tests made by Duflou et al. demonstrated that laser-assisted incremental forming leads to reduced process forces, improved dimensional accuracy of parts and increased formability for a range of materials. The authors also concluded that appropriate settings of the local heating and cooling parameters leads to reduced residual stress level.

An experimental set-up (Figure 5) created by A. Göttmann has been used to test formability of Ti alloys. In this system, a variety of Ti alloys had been tested and 1700 W laser output was used. The dimension of laser spot was 15 mm*45 mm. Position of laser spot was forward of the tool (Figure 15) (Göttmann et al. 2011.) Test results are shown in table 1. Results show that with laser heating the formability of TiAl6V4 could be increased, but no improvement for Ti Grade 2 is found.

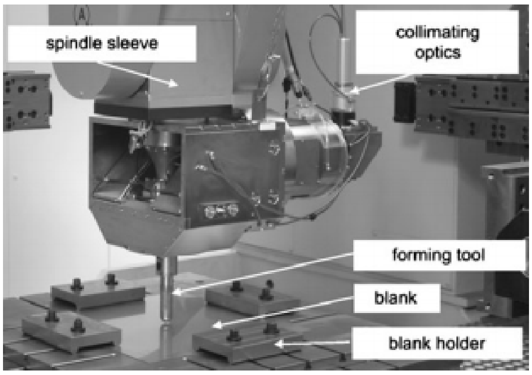


Figure 5 Experimental setup created by A.Göttmann (Göttmann et al. 2011)

Table 1. Experimental results (Göttmann et al. 2011)

Material	Laser output (W)	Tool diameter (mm)	Maximum depth (mm)	Failure mode
Ti Grade 2	1,700	20	94	Thermal failure
Ti Grade 2	1,700	30	60	Thermal failure
Ti Grade 2	1,700	30	38	Thermal failure
Ti Grade 2	0	20	110	–
TiAl6V4	1,700	20	98	Thermal failure
TiAl6V4	1,700	30	50	Crack
TiAl6V4	1,700	30	50	Crack
TiAl6V4	0	20	16	Crack

Mohammadi, Vanhove, Bael and Duflou have done the experiment of the influence of laser assisted single point incremental forming on the accuracy of the shallow sloped parts. Compare with the cold incremental forming, the test results for laser assisted forming show better accuracy of a part (reduction of 42.3% in the bulge height). Moreover, reduction in forming forces results in generation of more uniform part due to increasing the dynamic stiffness of the robot. The test results are shown in Figure 6. (Mohammadi et al. 2014)

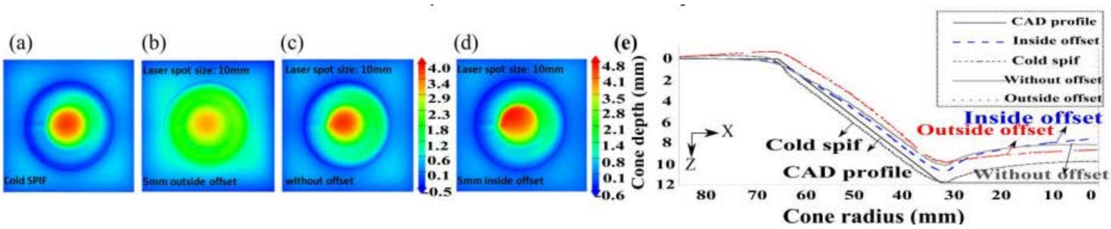


Figure 6. Influence of the laser positioning on the measured geometric accuracy a) cold SPIF, b) 5 mm outside offset, c) no lateral offset, d) 5 mm inside offset and e) accuracy comparison at the cross section parallel to X axis. (Mohammadi et al. 2014)

Sources:

Callebaut B., Sheet Metal Forming by Laser Forming and Laser Assisted Incremental Forming. 2009. Dissertation KuLeuven University, Leuven, Belgium.

Duflou J.R., Callebaut B., Verbert J., De Baerdemaeker H., Improved SPIF performance through dynamic local heating. 2008. International Journal of Machine Tools & Manufacture 48 (2008) 543–549.

Göttmann A., Diettrich J., Bergweiler G., Bambach M., Hirt G., Loosen P., Poprawe R., Laser-assisted asymmetric incremental sheet forming of titanium sheet metal parts. 2011. http://www.pdfdrive.com/laser-assisted-asymmetric-incremental-sheet-forming-of-titanium-e6859326.html

Mohammadi A., Vanhove H., Van Bael A., Duflou J.R., Influence of laser assisted single point incremental forming on the accuracy of shallow sloped parts. NUMISHEET 2014, International Conference and Workshop on Numerical Simulation of 3D Sheet Metal Forming Processes edition:9, Melbourne, Australia date:6-10 January 2014.
https://lirias.kuleuven.be/bitstream/123456789/424936/1/Influence+of+laser+assisted+single+point+incremental+forming+on+the+accuracy+of+shallow+sloped+parts.pdf

Other related literature:

Adams D.W., Improvements on single point incremental forming through electrically assisted forming, contact area prediction and tool development. 2013. Dissertation Queen's University, Kingston, Ontario, Canada.

Crina R., New configurations of the SPIF process- a review. 2010. Journal of Engineering Studies and Research – Volume 16 (2010) No. 4

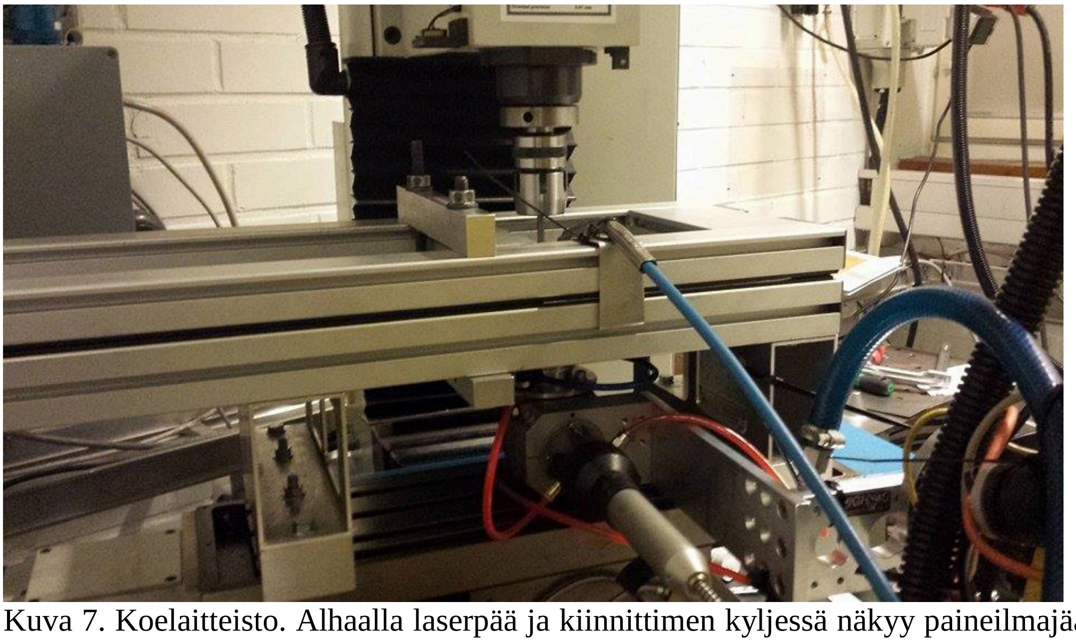
Duflou J.R., Callebaut B., Verbert J., De Baerdemaeker H., Laser Assisted Incremental forming: Formability and Accuracy improvement. 2007. Annals of CIRP Vol. 56/1/2007.

Kratky A., Laser Assisted Forming Techniques. 2007. Proc. SPIE 6346, XVI International Symposium on Gas Flow, Chemical Lasers, and High-Power Lasers, 634615 (8 May 2007)

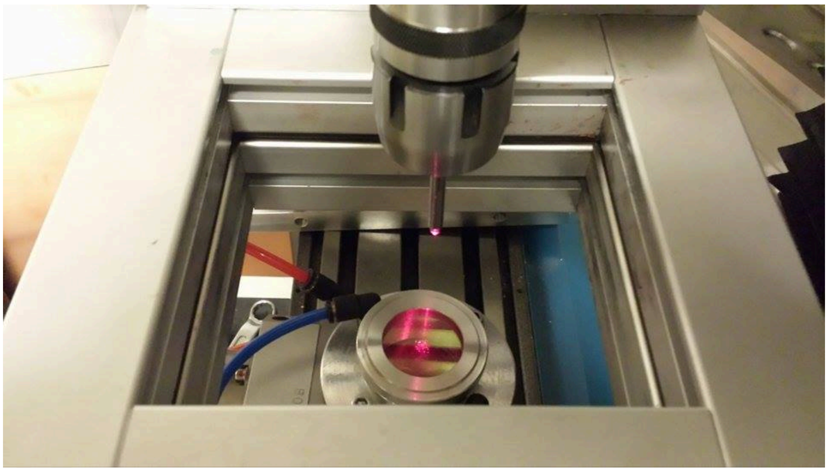
2. Laseravusteisen numeerisen painomuovauksen kokeet

Koejärjestelyt

Kokeet tehtiin Hämeen ammattikorkeakoulun Riihimäen yksikössä. Kokeissa käytettiin kuvan 7 mukaista laitteistoa. Työstörataa ohjattiin samoilla NC-ohjelmilla kuin ilman laseria tehdyissä kokeissa. Robotti kannatteli laserpäätä muovattavan levyn alla siten, että lasersäde osoitti ylöspäin. Teräkseen tehdyissä kokeissa säde asetettiin kohtisuoraan muovattavan levyn pintaa vastaan. Alumiinilla ja kuparilla säde asetetiin pieneen, noin 5 asteen kulmaan levyn pintaan nähden takaisinheijastuksen minimoimiseksi. Laserina käytettiin 1 kW kuitulaseria ja fokusoimattoman lasersäteen halkaisija oli noin 5 mm. Säteen keskipiste kohdistettiin mahdollisimman tarkasti työkalun keskipisteen kohdalle (kuva 8). Laserin tehona kokeissa käytettiin arvoja väliltä 70-350 W. Koekappaletta jäähdytettiin kokeen aikana paineilmalla, jotta kappale ei ylikuumenisi. Alumiinilla ja kuparilla kokeita tehtiin myös ilman jäähdytystä. Kappaleen lämpötilan vaikutusta muovaukseen testattiin myös lämmittämällä kappaletta kuumailmapuhaltimella laserin sijaan. Voiteluaineena käytettiin korkeita lämpötiloja kestävää kuparitahnaa. Kaikki kokeet tehtiin pyöreälle kartiomuodolle.



Kuva 7. Koelaitteisto. Alhaalla laserpää ja kiinnittimen kyljessä näkyy paineilmajäähdytyksen sininen letku.



Kuva 8. Säteen kohdistus työkaluun.

Kokeissa tutkittiin lähinnä muovautuvuutta, jossa mittarina käytettiin maksimi kartiokulmaa (vaakatason ja kartion seinän välinen kulma), mikä pystyttiin tekemään ilman kappaleen rikkoutumista. Tämän lisäksi havainnoitiin myös syntyvää pinnanlaatua.

Koetulokset

<u>Teräs (sekä tavallinen että syvävetoteräs)</u>

Laserin käyttö osoittautui pikemminkin haitaksi kuin hyödyksi. Muodot, jotka onnistuivat ilman lämmitystä, eivät onnistuneet laserin kanssa. Lisäksi työkalun puoleisesta pinnasta tuli karkea (kuva 9). Kokeita tehtiin myös lämmittäen kappaletta kuumailmapuhaltimella ja tulokset olivat vastaavat kuin laserilla lämmitettäessä.

Kuva 9. Laserin käytön vaikutus pinnanlaatuun. Vasemmalla esimerkki laserin käytöstä, oikealla ilman lämmitystä muovattu pinta.

Alumiini

Alumiinilla havaittiin lievä muovautuvuuden paraneminen. Alumiinilla onnistuttiin tekemään 61° kartiokulman kappale (ohjelma Circle 46-10-32) ja 62,8° (ohjelma Circle 46-10-35) kartiokulman kappale oli lähes onnistunut, kappale rikkoutui aivan viime sekunneilla muodon pohjasta. Ilman lämmitystä suurin onnistunut kartiokulma oli 59°. Kartion sisäpinnan laatu oli laseravusteisessa muovauksessa huonompi kuin ilman lämmitystä muovattaessa.

Kupari

Parhaimmat laseravusteisen muovauksen tulokset saavutettiin kuparilla. Kartiokulmat 68,2° (ohjelma Circle 46-10-45 ja laserteho 250 W) ja 70,1° (ohjelma Circle 46-20-36 ja laserteho 350 W) onnistuivat molemmat. Ilman laseria maksimi kartiokulma oli 65,8° ja 66,8° kartiokulma ei enää onnistunut. Kokeita ei tehty enää suuremmille kartiokulmille, koska suuri laserteho altistaa laitteen takaisinheijastusvaaraan. Laseravusteinen muovaus ei vaikuttanut heikentävästi kartion pinnanlaatuun (kuva 10).

Kuva 10. Laseravusteisesti painomuovatun kuparikartion pinta

Päätelmät

Laseravusteisesta painomuovauksen hyödyt ovat riippuvaisia muovattavasta materiaalista. Tehdyissä kokeissa teräksille ei saavutettu hyötyjä. Sen sijaan alumiinin ja kuparin muovattavuus parantui. Pinnankarheus heikentyi teräksillä ja alumiinilla. Löytämällä parempi voitelumenetelmä/-aine tai työkalumateriaali voisi ratkaista pinnanlaatuongelman. Työkalun ja kappaleen välisen kitkan pienentäminen parantaisi todennäköisesti myös muovattavuutta.

Epäonnistuneissa kokeissa kappale rikkoontui lähes aina noin 13 mm syvyydessä. Tällöin ilmeisesti saavutetaan lopullinen kartiokulma ja jos kappale kestää tämän, se kestää saman kulman loppuun asti. Vain parissa kokeessa rikkoontuminen tapahtui vasta kokeen loppupuolella.

Koelaitteisto asetti kokeille seuraavat rajoitukset. Lasersäteelle ei voitu määrittää ns. offsettia eli osoittamaan hieman työkalun etupuolelle kulkusuuntaan nähden. Lisäksi lasersäteen halkaisija oli vakio, noin 5 mm. Offset ja suurempi lasersäteen koko ovat lähdekirjallisuuden mukaan optimaalisempia parametreja laseravusteisessa painomuovauksessa. Lisäksi kaikkiin koetuloksiin (myös ilman laseria tehtyihin kokeisiin) vaikutti työkalun muoto. Työkalussa oleva olake osui kappaleen pintaan naarmuttaen sitä, kun kartiokulma oli riittävän suuri (> n. 65°).

Seuraavassa on joitakin huomioita ajatellen mahdollisia laseravusteisen painomuovauksen jatkotutkimuksia:

- käytetään olakkeetonta työkalua ja tutkitaan pinnoitettujen työkalujen soveltuvuutta
- testataan eri voitelumenetelmiä ja –aineita
- tehdään kokeita eri lasereilla ja erilaisilla säteen halkaisijoilla
- tutkitaan mahdollisuutta käyttää offsettia säteen ja työkalun välillä
- tutkitaan menetelmän soveltuvuutta materiaaleille, joiden pitäisi soveltua hyvin laseravusteiseen painomuovaukseen (esim. Titaaniseos TiAl6V4) ja joille on tarvetta teollisuudessa

Incremental forming

Test environment

HAMK
UNIVERSITY OF APPLIED SCIENCES

Bachelor's thesis

Mechanical engineering and production technology

Riihimäki 2013
RUI CHEN

RUI CHEN

ABSTRACT

Riihimäki
Degree Programme in Mechanical Engineering and Production Technology
Option

Author Rui Chen **Year** 2014

Subject of Bachelor's thesis Incremental forming(test environment)

ABSTRACT

The thesis was commissioned by Aalto University. The goal of the thesis was to introduce the current theory of incremental forming and describe two types of this process: Single and two point incremental forming. Laser assisted incremental forming would also be illustrated in the thesis.

The laser assisted incremental forming method was applied in the experiment. Compared to incremental forming, process force was reduced and dimensional accuracy of parts was improved apparently and the formability of the material increased in the laser assisted incremental forming process. This type of process is used to form high-strength materials like magnesium alloys and titanium by applying a Nd:YAG laser, CO2 laser or Diode laser. Some research was studied by Duflou to improve laser assisted incremental forming in the aspects of force reduction, accuracy improvement, formability increasing and residual stress reduction.

In conclusion, although there are many benefits of laser-assisted incremental forming, some improvement could be suggested. Compared to incremental forming, the laser assisted incremental forming process has advantages in terms of formability and accuracy.

Keywords incremental forming, laser-assisted, experiment set-up

Pages 18 p. + appendices 0 p.

1 INTRODUCTION

Nowadays, there are many sheet metal forming processes used in diverse fields. So it is inevitable that companies choose convenient and economical processes. In contrast to other processes, in terms of cost and time, incremental forming has advantages. “Incremental sheet forming (ISF) is a flexible sheet metal forming process with a high potential for small quantity production and for rapid prototyping applications” (Blaga, n.d.). (Figure 1) In this process, no dedicated die is required. There are two types of incremental forming, single point incremental forming(SPIF) which uses a spherical tool and two point incremental forming(TPIF) where a sheet is shaped by a die, a supported column or a second motion indenter. (Jackson & Allwood, 2009) In both cases, the tool path is controlled by a CNC program. (Figure 2)

There are many different incremental forming methods, such as laser-assisted incremental forming, dual robot assisted incremental forming and electrically assisted incremental forming. In the laser-assisted incremental forming process, the laser heats the material dynamically.

In this thesis, the goal is to introduce incremental forming and laser-assisted incremental forming, more importantly, to design a test device for a laser assisted incremental forming experiment.

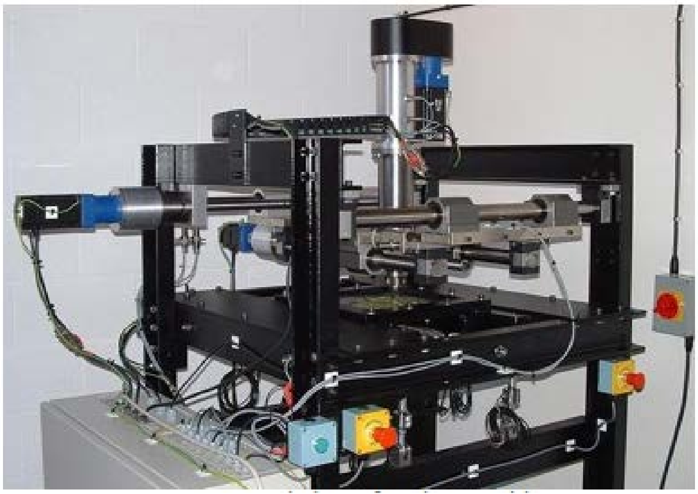


Figure 1 Incremental forming machine (Low Carbon Materials Processing. N.p., n.d.)

Figure 2 CNC Program (Hossmachine Homepage. N.p., n.d)

2 INCREMENTAL FORMING

2.1 Introduction

Incremental Sheet Forming (ISF) is a flexible forming process in which sheet metal can be formed into miscellaneous shapes and an expensive and dedicated tool is not needed in this process. (Brief Introduction to Incremental Sheet Forming, N.p., n.d.)
Tools under CNC-machine control allow the process to be more flexible in the manufacturing of metals without the demand for particular tools. The principle of the incremental forming process is shown by Figure.3

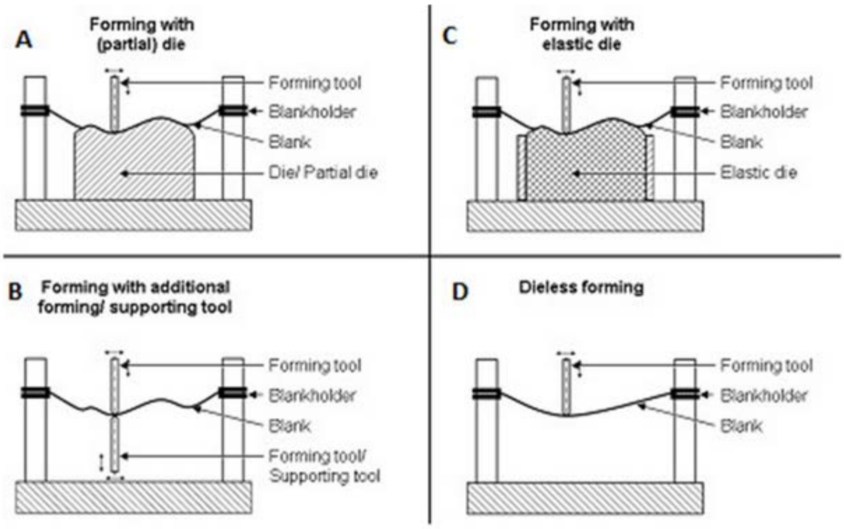


Figure 3 Process principles (Brief Introduction to Incremental Sheet Forming. N.p., n.d.)

The ISF can be applied in two areas:

· Fast forming for the vehicle industry, such as shapes for headlights, (Figure 4.1); heat/vibration shields (Figure 4.2); and surfaces for vans, (Figure 4.3) (Júri & João, 2009)

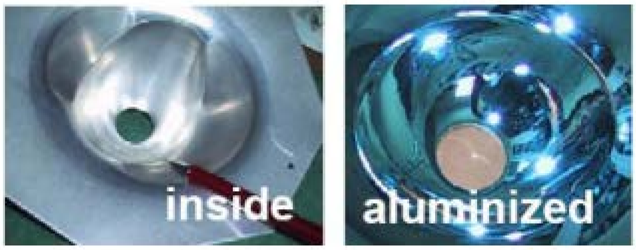


Figure.4.1 (Júri & João, 2009)

Figure.4.2 (Júri & João, 2009)

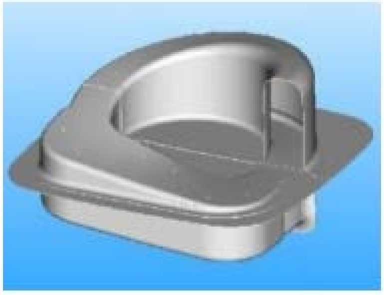


Figure.4.3 (Júri & João, 2009.)

• Other applications, for instance: seats of motorcycles, gas storage of motorcycle, manufacturing dies, surfaces of dies and medical applications. (Júri et al. 2009)

The main advantages of ISF:

- Due to the CNC-controlled toolpath, rapid prototyping is possible.
- In the ISF process, simple tools are needed to accomplish the process.
- Compared with other forming processes, the ISF process costs less
- ISF is a very flexible process
- Higher deformation can be achieved by the ISF process
- The ISF process is suitable for producing complex parts
- Dedicated dies are not required

Limitations:

- Lack of accuracy arises during processing elastic materials such as stainless steel.
- The material will break if the wall draft angle approaches 0°
- Because of the spring-back, there are some accuracy problems with a surface with a large radius of curvature.

2.2 Single Point incremental forming process

The Single point incremental forming (SPIF) process may be defined as a die-less sheet metal forming process, and is gradually growing in manufacturing application. A spherical tool controlled by a CNC program is used to form sheet metals in a gradual way without the demand of a dedicated die. This technique allows a relatively fast and economical production of a small series of sheet metal parts.

Figure 5 NC milling machine configuration used for forming a conical "cup" part (Production Processes, N.p., n.d)

In the SPIF process, a standard and round tool controlled by a CNC program is used to form sheet metals. The SPIF process begins with a common sheet metal, fixed on a rigid fixture and installed on the worktable of a CNC machine. The toolpath follows a programmed path, which is similar to a common milling process. The process chain of SPIF is shown in Figure 7.The main advantage of this process is:

- no requirement of die
- rapid prototyping
- small batch production.

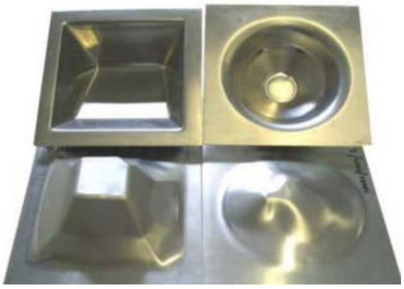


Figure 6 Sample of parts (Production Processes, N.p., n.d)

Figure 7 SPIF process (Bartolo, 2011)

In recent years, SPIF has been gradually developing. More theories are needed to describe the strain behavior of the SPIF process, to developing the knowledge of the relationship between process parameters for instance tool speed, tool size, tool path, pitch step and depth step which affect SIPF formability, wall thickness, accuracy and surface roughness.

2.3 Two point incremental forming

Two point incremental forming is a process in which metals are formed in a positive way. The tool process the outer surface of the metals and this process should be carried out with a stationary. Tolerances and dimensions of metals could be controlled better by this method. Z displacements of the tool guide the sheet fixing system in a way that the non-formed and formed zone of the sheet metal is always at the same level. This process can also be called Two Point Incremental Forming (TPIF). (MicroManufacturing N.p., n.d.)

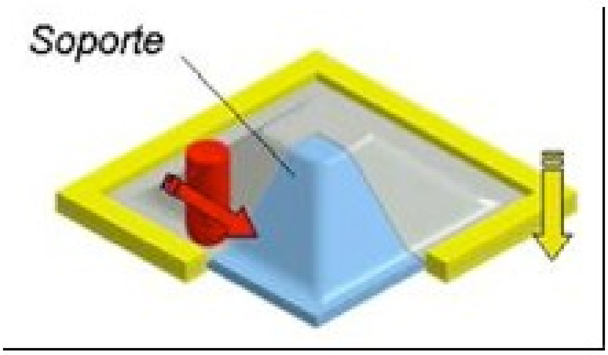


Figure 8 a TPIF example (MicroManufacturing N.p., n.d.)

TPIF may use the partial die or full die due to the lack of accuracy. Additionally, several repetitions involving the modification of the path of tool may be required before attaining a satisfactory part. FEM simulation can be used to decrease the number of repetitions. As a result, an optimized step to manufacture complex parts with TPIF technology can be obtained:

1.The process starts with a three-dimension model of the objective element.

2.A negative shape is obtained after subtracting the jaw from a prismatic (stock) block.

3.The tool path is generated by CAD/CAM software.

4.Simulation of the process is used to anticipate the results acquired with the path of tool brought out in Step 3 in combination with other process parameters such as blank dimensions and material.

5.Finally, if the outcomes acquired in Step 4 are satisfactory. The actual manufacturing of the component is realized. (Jorge & Bartolo, Innovative Developments.)

The main processes are described in Figure 9.

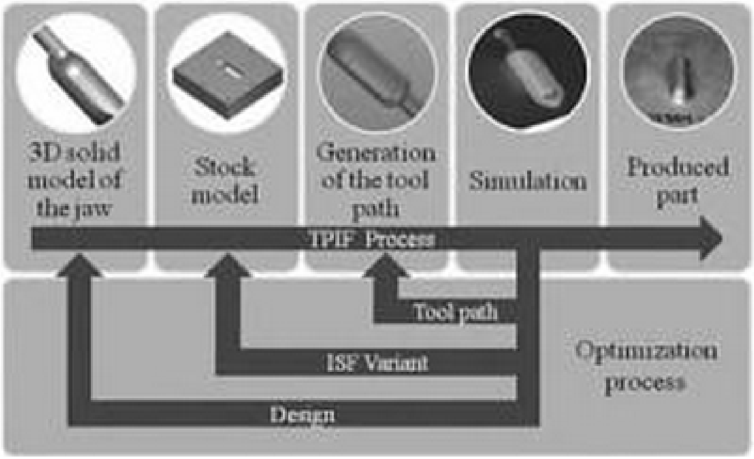


Figure 9 TPIF process map (Bartolo, 2011)

3 LASER-ASSISTED INCREMENTAL FORMING

3.1 Introduction

Laser-assisted ISF (laser + ISF) is a process in which a laser is used to heat material during the incremental process. Creating a heated point in the moving contact zone between a tool and metal is the main idea, while retaining the remaining metal at about the environmental temperature. This process results in a reduction of process forces, accuracy improvement of metals and formability increasing of materials.

3.2 State of the art

Laser-assisted ISF is being developed with the aim of forming high-strength materials flexibly and cost-effectively. Magnesium alloys and titanium are suitable materials in this process as it is difficult to form these materials at room temperature. In addition, high cost tool-based processes, like superplastic forming, -often handle titanium alloys. Local heating is used to improve the formability of materials that cannot, or can be formed difficultly at room temperature. The forming area is heated by a laser beam in front of the motion of the tool.

Single Point Incremental Forming is the most flexible and numerically controlled sheet metal forming process in the recent years. However, there are some drawbacks in the SPIF process, such as accuracy and formability from excess deformations of plastic. Correction algorithms for the toolpath have been used to get more precise sheet metals. Some research has been tested to reduce the limits in this process.

3.3 Research of laser assisted incremental forming

3.3.1 Force reduction

Duflou et al have demonstrated the effect of a area temperature increase on the process. A backing plate with diameter 180mm was used to support 1.25mm thick blank of size 225*225mm. The cone was formed from the plate with an original 1400mm outside diameter, 40° wall angle and 20mm depth. The step size was 0.5mm, and a tungsten carbide tool with 10mm diameter coated by a high-temperature resistant coating was applied in the experiment. (Duflou, Callebaut & Verbert, 2011) In their experiment, in order to improve absorption, they used a graphite 33 coating in the laser side of the blank and 8 and 12mm spot laser was chosen with a forward offset of 2.4mm. Feed rate were varied in the test.

Experimental results

We can see the results from Figure 10. The process forces dropped gradually, allowing a reduction of up to 50% with the rising of temperature. (Duflou, Callebaut & Verbert, 2011)

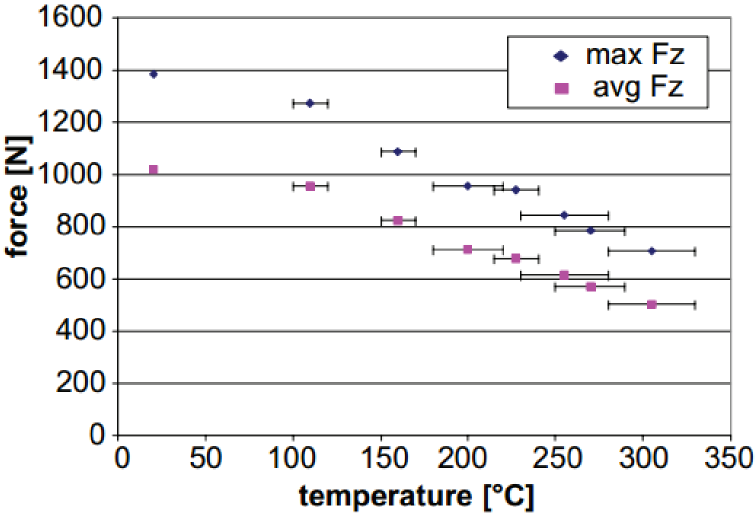


Figure 10, Maximum and average axial forces as a function of heating temperature (Duflou, Callebaut & Verbert, 2011.)

3.3.2 Improve accuracy

In order to reduce springback, reduction of unwanted plastic deformation will be beneficial from reducing process forces. Duflou et al used 65Cr2 0.5mm thickness blanks to compare the accuracy in a non-heated and a motional heated shaping test. A 160mm outer contour, 40mm depth and 50° slope angle conical shapes were formed by a tool with a diameter of 10mm which is made of tungsten carbide. A 180mm diameter backing plate was selected. The toolpath of a 0.5mm step down size was utilized. The feed rate of the robot was 1500mm per minute for the cold situation and 2000mm per minute for the laser assisted operation. CAD geometry generated the toolpath. (Duflou et al. 2011) The example of wall angle (symbol Φ) and backing plate can be seen in Figure 11.

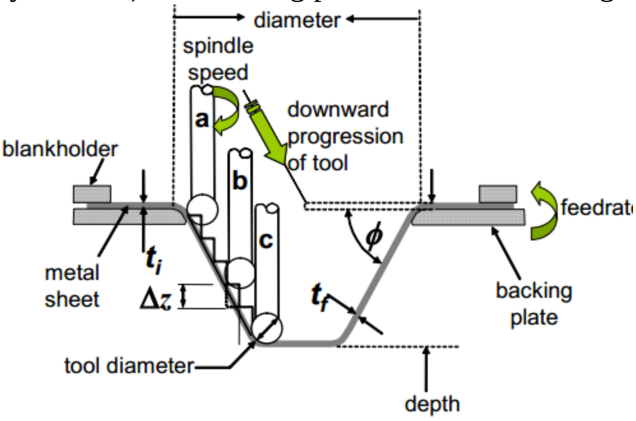


Figure 11 Example for Wall angle and backing plate (M. Ham & J. Jeswiet , n.d.)

Experiment results

The target CAD geometry used for toolpath generation and typical sections obtained when forming at room temperature and with laser supported heating are depicted in Figure 12. (Duflou et al. 2011)

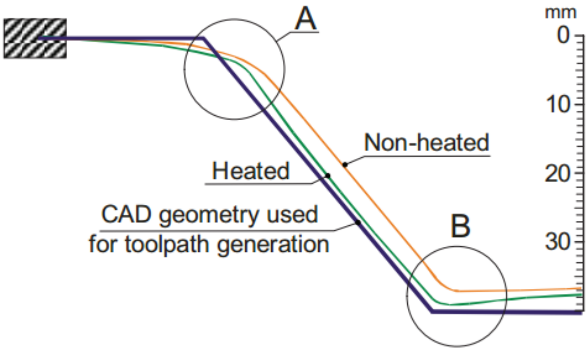


Figure 12 part geometry under heated and cold process.(Duflou, Callebaut & Verbert, 2011.)

3.3.3 increase formability

In order to compare the formability behaviour, Duflou et al used 0.6mm thickness TiAl6V4 sheets under dynamically heated conditions, and got test results at room temperature. A high temperature resistant coating 10mm tool was used to form the conical shape with an outer diameter of 140mm and increasing wall angle. A 180mm backing plate supported the workpieces. Many research teams have used a similar setup to determine the formability of different materials. In order to adapt the test with low wall angle in room temperature, maximum depth for the cones was limited to 30mm.incremental step of 0.5mm of toolpath was used. (Duflou et al, 2011) The original feed rate of the robot was 1000mm/min.

Experiment results

At room temperature (20°C), forming the cone with slope angles reaching 32° was impossible, however a higher wall angle in the experiment lead to cracks that showed before the depth of 30mm was achieved (see Figure 13). (Duflou et al. 2011)

Non-heated		**Heated**			
wall angle [°]	obtained result	wall angle [°]	spot size [mm]	energy input [J/mm²]	obtained result
30	OK	45	12.0	0.875	OK
35	failed	50	12.0	0.875	OK
32	OK	55	12.0	0.875	failed
34	failed	53	12.0	0.740	OK
33	failed	55	12.0	0.740	OK
		57	12.0	0.740	failed
		56	12.0	0.740	failed
		56	14.0	0.740	OK
		57	15.0	0.740	failed

Figure 13 Formability test results for 0.6mm TiAl6V4 (Duflou, Callebaut & Verbert, 2011.)

3.3.4 Residual stress reduction

Duflou et al test two TiAL6V4 specimens after unclamping. Part 1 a 30° cone was processed at room temperature. Part 2 a 50° cone was created by dynamic local heating support. The residual elastic stress levels are clearly reduced in Part 2. (Duflou et al. 2011)

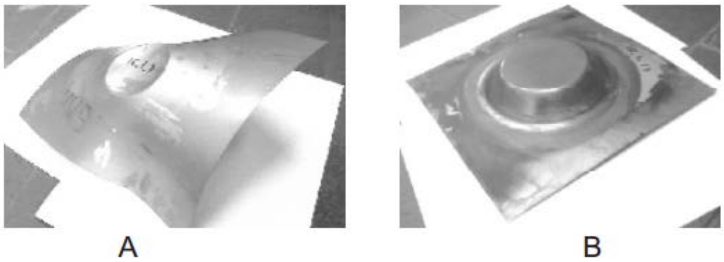


Figure 14 received shape of parts after heated and non-heated process. (Duflou, Callebaut & Verbert, 2011)

3.4 Type of laser

For laser assisted incremental forming, a high power laser has been chosen in the process due to the productivity demand. A Nd:YAG laser is the better choice for laser assisted incremental forming in terms of flexibility, as the laser can be propagated by a fiber beam. The M2-value of Nd:YAG laser is much higher so that the risk of localized melting will be reduced. The laser focusing is installed on an X-Y-Z table. The CO_2 and Diode laser is an option. But on the several aspects, the Nd:YAG laser is superior to the CO_2 laser. The characterizes of the Nd:YAG laser are shown in Figure 15.

	Nd:YAG
w_0	337 μm
M^2	88.7
K	0.0113
z_R	3.81 mm
BPP	29.9 mm mrad

Figure 15 characterizes of Nd:YAG laser (B Callebaut 2009)

3.5 Applications of laser assisted incremental forming

In order to avoid the disadvantages of heating the whole sheet, the laser is applied to heat area around the tool and workpiece. Locally heating the material reduces the probability of unwanted deformation. The laser is generally used in the SPIF process. A laser assisted incremental forming system created by Duflou is shown in Figure 16. The goal of the laser is to reduce the springback and increase the accuracy and formability in SPIF (Duflou et al. 2011.). A 500W Nd:YAG laser was used in the back of the sheet with a 3-axis X-Y-Z system. The laser was used to heat the CNC-controlled tool position, and a cooling system was used to ensure the materials stay at a low temperature.

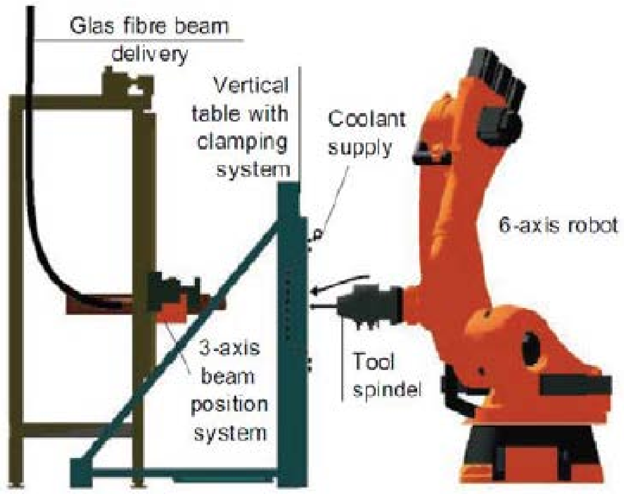


Figure 16 laser assisted incremental forming system created by Duflou (Duflou et al. 2011.)

In recent years, the main applications of laser assisted incremental forming were used to process materials in the aerospace industry, for example Ti alloys. An experimental set-up (Figure 17) created by Göttmann was used to test formability of Ti alloys. In this system, a variety of Ti alloys had been tested, and 1700W laser output was used. The distance between the tool and laser optic was 45mm. The dimension of the laser spot was 15mm*45mm. The position of laser spot was recorded (Figure 18). (Göttmann, 2011) The results are shown in Figure.16

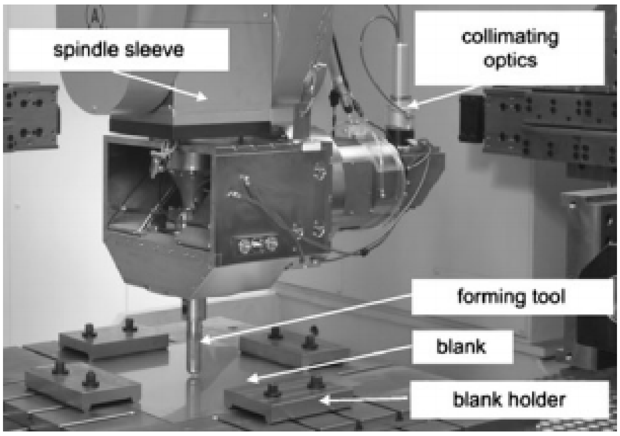


Figure 17 experimental setup created by Göttmann (Göttmann, 2011.)

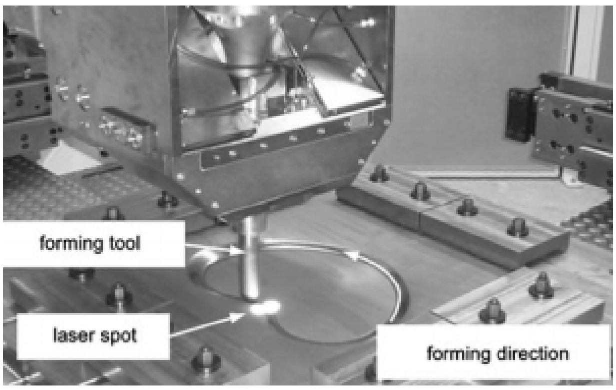


Figure 18 positions of laser spot (Göttmann, 2011.)

Material	Laser output (W)	Tool diameter (mm)	Maximum depth (mm)	Failure mode
Ti Grade 2	1,700	20	94	Thermal failure
Ti Grade 2	1,700	30	60	Thermal failure
Ti Grade 2	1,700	30	38	Thermal failure
Ti Grade 2	0	20	110	–
TiAl6V4	1,700	20	98	Thermal failure
TiAl6V4	1,700	30	50	Crack
TiAl6V4	1,700	30	50	Crack
TiAl6V4	0	20	16	Crack

Figure 19 experimental results (Göttmann, 2011.)

3.6 Material for the laser assisted incremental forming

Generally, the materials which are used in the LASPIF process are low- and high- carbon steel, titaniums and aluminums. The thicknesses are between 0.5 and 2.0 mm. Materials with low yield strength and low hardening coefficient are suitable for this process.

3.7 Influences of laser on incremental forming process.

The main influences of a laser on the incremental forming process are increased accuracy, a reduction in forces and the possibility to get a larger wall angle.
Mohammadi et al have experimented on how the LASPIF process affected the accuracy of the sloped metals. Compared to the SPIF, the test results illustrated that, in the outside offset case, the raised height had been reduced by 42.3％. By contrast, for the without and inside offset case, an increase of 9.79％ and 27.3％ in the raised height were shown respectively (see Figure 20). Furthermore, overforming of the taper wall processed in SPIF turn into an underforming in the laser assisted incremental forming process due to thermal stresses caused by laser heating. Moreover, because of improving robot’s dynamic rigidity, reducing shaping forces lead to production of more identical parts.

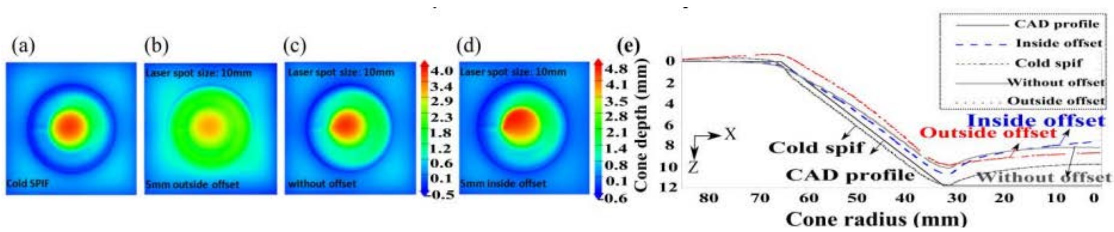


Figure 20 the effect of the laser location on the accuracy of geometric measurements (a) SPIF, (b) outer offset of 5mm, (c) offset without lateral, (d) interior offset of 5mm and e) comparison of accuracy. (Mohammadi, Vanhove, Bael and Duflou, KULeuven. N.d.)

With respect to hardness, it increased due to heating by laser and SPIF process. LASPIF carried compressive residual stresses on the heating area and no influence on the roughness. The grains of the materials would be elongated after the SPIF process due to initial radial extension. Laser heating did not cause recrystallizations in the microstructure.

3.8 Possible improvement of the LASPIF

- A monitor system

Now, no camera and feedback systems are used for the laser assisted incremental forming process. As high temperature which needs to be controlled is the main problem. There are two options for monitoring, a thermal camera or pyrometer. Although a thermal camera is more expensive than a pyrometer, but the camera has a wider monitor area which is more suitable for controlling the temperature and it is also more suitable for getting an idea about the actual spot size.

- Cooling system

Today, in the LASPIF process, pressurized air is used to clear the coolant. The area where no coolant is applied can only be adjusted roughly. By optimization of air flow, a smaller coolant film will remain on the surface of the sheet. The maximum achievable wall angle and accuracy will be beneficial from the optimization.

- Influence of the lateral offset

A lateral offset considering into the spot size and position could be beneficial to obtain a larger wall angle. The contact area between tool and sheet metals depends on the wall angle and tool size.

- Maximum wall angle

The investigation of influence of dynamic laser heating on the maximum wall angle should be taken for more materials in a particular industry and that are difficult to form at ambient temperatures. (Callebaut. B, 2009)

- More material research on the LASPIF process

After the material is heated by laser, the microstructure and properties of the material's change should be researched. The hardness of the material undergoing laser assisted incremental forming should be investigated.

- Behavior of material roughness

Roughness of some materials will increase and this increase is shown a lowering trend. More detailed investigation should be worked to confirm and explain these trends.

- Influence of the atmosphere around process

When a laser heats some temperature sensitive material, a chemical reaction will occur so that a series of possible problems of the function of the sheet metal or hazardous working circumstances can be caused. In order to address this problem, the use of protective gas jet which is combined with a gas-sucking service can be considered as an option.

4 EXPERIMENTAL SET-UP

The CNC drilling machine from Aalto University was used in the experiment. The face and end milling capacity was 63mm and 16mm respectively. The drilling capacity was 16mm. The maximum feeding speed was 500mm per minute. The length of spindle travel was 270mm, and the length of table travel was 300mm in vertical direction and 120mm in a horizontal direction. The rotating speed of spindle ranged from 100 to 5000 rpm. The tool path was controlled by CNC code. The work space of fixture is a square area with 150mm*150mm size.

Figure 21 CNC drilling machine in the experiment

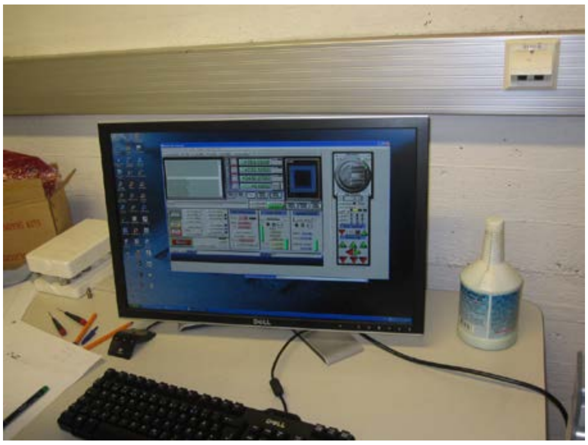


Figure 22 CNC control system

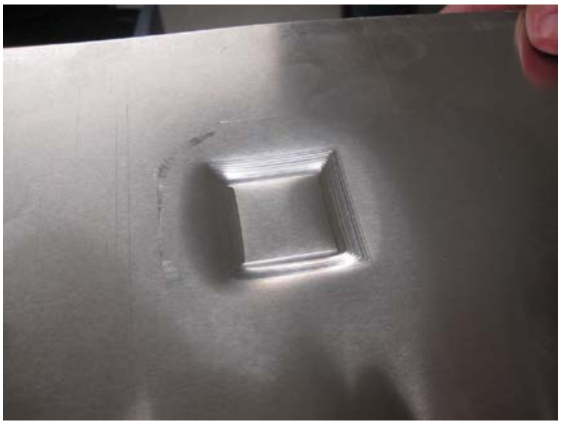


Figure 23 a example produced by Drilling machine

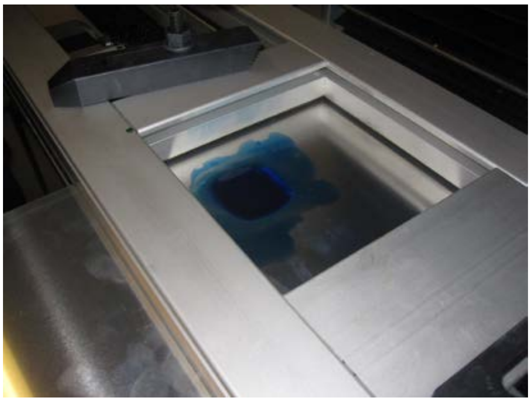


Figure 24 workspace

A 6-axis Fanuc robot was used to guide the laser head in the experiment. The reach and stroke of this robot was 951 and 622 mm respectively which was the best in class reach versus stroke ratio. Diverse installing positions such as inverted, vertical, wall or angle mounting without changes to the mechanical units make the robot more flexible. The laser would heat the metal in front of the location of tool of drilling machine. This robot had various motion range (degrees) and speed (degrees / sec) in the different joints. The robot could be applied into tiny openings in the workspace due to a thin size of wrist. The payload of robot was 6 kg.

Isometric

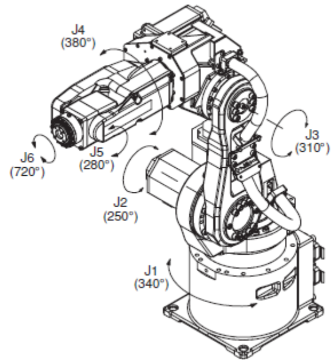


Figure 25 motion of 6 joint of robot.

Items		
Axes		6
Payload (kg)		6
Reach (mm)		951
Repeatability (mm)		±0.08
Interference radius (mm)		273
Motion range (degrees)	J1	340
	J2	250
	J3	310
	J4	380
	J5	280
	J6	720
Motion speed (degrees/sec.)	J1	200
	J2	200
	J3	260
	J4	400
	J5	400
	J6	720
Wrist moment (kgf•m)	J4	1.6
	J5	1.0
	J6	0.6
Wrist inertia (kgf•cm•s^2)	J4	6.4
	J5	2.2
	J6	0.62
Mechanical brakes		All axes
Mechanical weight (kg)		135
Mounting method (1)		Floor, ceiling, angle and wall
Installation environment		
Temperature °C		0 to 45
Humidity		Normally: 75% or less Short term (within a month): 95% or less No condensation
Vibration (m/s^2)		4.9 or less
Payload at axis 3 (kg)		12

Figure 26 specifications of robot

A 2kw Diode laser is used as a heating source. The focused spot diameter of this type of laser is 3mm and the power density is 0,023 MW/cm^2. The laser head is mounted on joint 6 of the robot. A laser is used to heat the materials between the fixture and work table, but the space between them is limited so a new part for fixing the laser head with robot is needed. The laser will heat the bottom surface of material when the drilling machine processes the material. The laser head is connected with an adapter which was mounted on joint 6 of robot by an aluminum plate (see Figure 25) which links them by holes and pins. The pressurized air will be used as cooling system for the material as high temperature would be issued by local heating.

5 CONCLUSION

In the thesis, two types of incremental forming processes: single point incremental forming and two point incremental forming were described. There were various incremental forming methods such as electrically hot incremental forming, laser-assisted incremental forming, dual robots assisted incremental forming and warm forming methods.

Laser assisted incremental forming could be used to form the materials with low yield strengths and low hardening coefficients. This process could be applied to the aerospace industry and alloy forming. Furthermore more research should be taken to minimize the drawbacks of laser assisted incremental forming such as high temperature during the process and shape inaccuracy.

For the experiment, a 2kw Diode laser in the laboratory was guided by the Fanuc 6-axis robot. A laser head was connected with the robot by an aluminium plate which was fixed by an adapter mounted on the robot. Through the experiment set-up, a feasible laser assisted incremental forming system has been discussed. However some problems, for instance high temperature on the material and ways of guiding laser, should be considered and optimized.

SOURCES

Bartolo.P, Innovative Developments in Virtual and Physical Prototyping: Proceedings, 2011. Accessed 29.4.2014

Brecher. C, Integrative Production Technology for High-Wage Countries. Accessed 29.4.2014

Callebaut.B, 2009. Accessed 29.4.2014
https://lirias.kuleuven.be/bitstream/123456789/233785/6/part+2.pdf

Duflou.J, Production Processes] Single Point Incremental Forming (SPIF). n.d. Web. 19 Apr. 2014. Accessed 29.4.2014
https://www.mech.kuleuven.be/pp/research/spif

Duflou.J, Callebaut.B, Verbert.J, Baerdemaeker. H, Laser Assisted Incremental Forming: Formability and Accuracy Improvement, Department of Mechanical Engineering, K.U.Leuven, Belgium, 2011, Accessed 29.4.2014
http://www.sciencedirect.com/science/article/pii/S0007850607000686

European Research Programme." Brief Introduction to Incremental Sheet Forming. N.p., n.d. Accessed 29.4.2014
http://cornet.efb.de/index.php?menuid=22

Göttmann.A, Laser-assisted asymmetric incremental sheet forming of titanium sheet metal parts, 2011. Accessed 29.4.2014
http://www.pdfdrive.com/laser-assisted-asymmetric-incremental-sheet-forming-of-titanium-e6859326.html

Hossmachine Homepage. N.p., n.d. Accessed 29.4.2014
http://www.hossmachine.info/

"Incremental Sheet Forming." Low Carbon Materials Processing. N.p., n.d. Accessed 29.4.2014
http://www.lcmp.eng.cam.ac.uk/welcome/equipment/incremental-sheet-forming

Jackson.K, Allwood.J , The mechanics of incremental sheet forming,journal of materials processing technology, 2009. Accessed 29.4.2014
http://www.elsevierscitech.com/lmfile/otherformat/jackson_allwood.pdf

Júri, João, Single Point Incremental Forming, Setembro de 2009, Accessed 29.4.2014
https://fenix.tecnico.ulisboa.pt/downloadFile/2589867766221/dissertacao.pdf

"MicroManufacturing" 4.2 DESCRIPTION OF THE PROCESS —. N.p., n.d. Accessed 29.4.2014
http://www.micromanufacturing.net/didactico/Desarollo/microforming/4-incremental-sheet-metal-forming/4-2-description-of-the-process

"Metal Forming Research Centre." Metal Forming Research Centre. N.p., n.d. Web. 19 Apr. 2014. Accessed 29.4.2014
http://centers.ulbsibiu.ro/cscdp/indexe.html

Mohammadi.A, Vanhove.H, Bael.A, Duflou.J, Influence of laser assisted single point incremental forming on the accuracy of shallow sloped parts. Accessed 29.4.2014
https://lirias.kuleuven.be/bitstream/123456789/424936/1/Influence+of+laser+assisted+single+point+incremental+forming+on+the+accuracy+of+shallow+sloped+parts.pdf

M. Ham & J. Jeswiet, Single Point Incremental Forming and the Forming Criteria for AA3003, n.d.Accessed 29.4.2014
http://me.queensu.ca/Courses/424/F04_Jeswiet.pdf

[Production Processes] Single Point Incremental Forming (SPIF). N.p., n.d. Accessed 29.4.2014
https://www.mech.kuleuven.be/pp/research/spif

APPENDIX

No appendix

Kokoonpantujen kappaleiden suunnitteluohjeet materiaalia lisäävää valmistusta varten

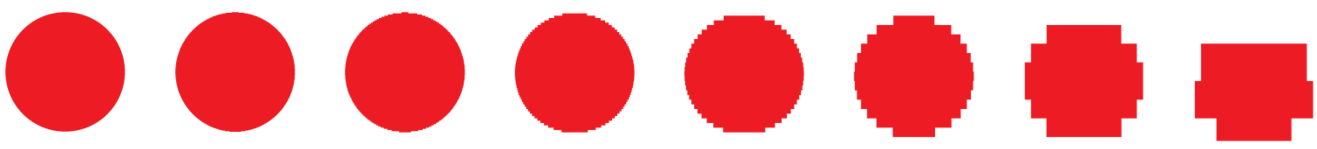
Aalto-yliopisto
3D Manufacturing –tutkimusryhmä
Sergei Chekurov
23.7.2014

1. Kappaleiden suunnitteluun vaikuttavat tekijät

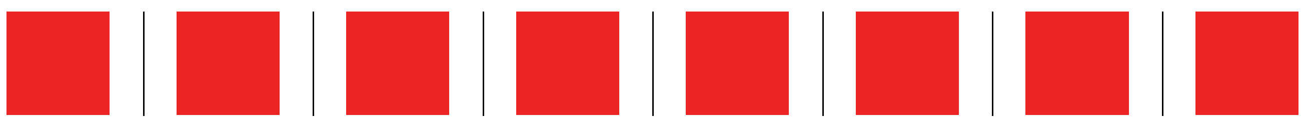
1.1 Kerrospaksuus ja porrasvaikutus

Kaikki yleisimmät materiaalia lisäävän valmistuksen menetelmät rakentavat kappaleet kerros kerrokselta. Näin ollen jokaisen valmistettavan kappaleen 3D-malli käsitellään ennen valmistusta jakamalla se kerroksiin.

Kerrospaksuuden arvolla on suuri merkitys kappaleen tarkkuuteen korkeussuunnassa, mikäli siinä on vinoja tai kaarevia pintoja. Kuvat 1 ja 2 ovat esimerkkeinä siitä, mitä erilaisten kappaleiden geometrioille käy, kun kerrospaksuutta lisätään.



Kuva 1. Ympyrämäinen geometria kerrospaksuudella pienimmästä suurimpaan.



Kuva 2. Neliömäinen geometria kerrospaksuudella pienimmästä suurimpaan.

Kuten kuvista huomaa, ympyrämäinen muoto alkaa menettää muotoaan hyvin nopeasti tietyn kerrospaksuuden jälkeen, mutta neliömäinen muoto pysyy samana. Sama ilmiö nähdään monimutkaisemmissa kappaleissa, joissa kuva 1 edustaa kaltevia pintoja ja kuva 2 edustaa suoria seinämiä. On huomionarvoista, että vaikka suorissa seinämissä ei näy leikkauksen jälkeisessä esikatselussa poikkeamaa nimellisgeometriasta, kerrospaksuus saattaa silti näkyä riippuen valmistusmenetelmästä. Ilmiötä, jossa kerrospaksuus vaikuttaa kappaleen geometriaan, kutsutaan porrasvaikutukseksi.

Kerrospaksuuden arvo riippuu valmistusmenetelmästä ja laitteesta. Suurimmassa osassa laitteita kerrospaksuutta voidaan säätää. Kerrospaksuutta pienentämällä saadaan pystysuunnassa tarkempia kappaleita, mutta koska kappaleen valmistusaika on melko suoraan riippuvainen kerrosten määrästä, se myös kasvattaa rakennusaikaa.

,

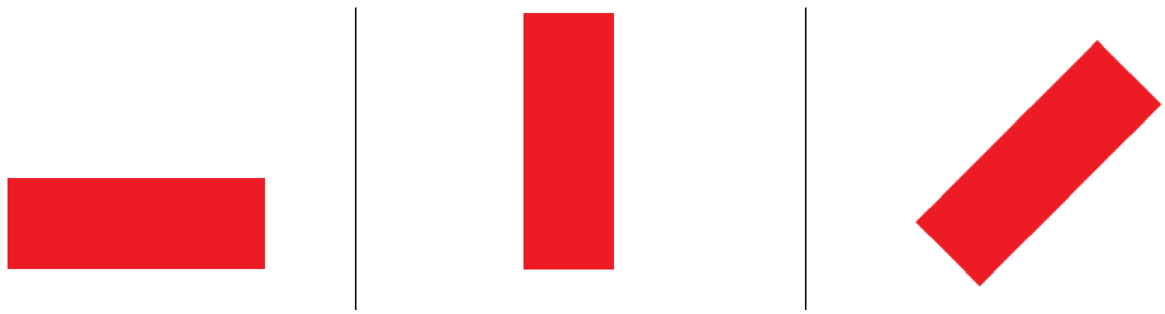
Aalto-yliopisto
3D Manufacturing –tutkimusryhmä
Sergei Chekurov
23.7.2014

1.2 X-Y-tarkkuus

Toinen kappaleen geometriaan vaikuttava tekijä on laitteen tarkkuus x-y-tasossa, joka vaikuttaa kappaleen geometriaan määrittelemällä kuinka tarkasti kappaleen mitat voidaan valmistaa. Kuvasta 1 nähdään, että vaikka kerrospaksuus muuttuessa x-y-tason tarkkuus voi pysyä samana.

1.3 Rakennusorientaatio

Koska materiaalia lisäävä valmistus pohjautuu kappaleen valmistamiseen kerros kerrokselta, myös kappaleen rakennusorientaatio vaikuttaa lopputulokseen. Rakennusorientaation vaikutukset näkyvät kappaleen geometriassa ja mekaanisissa ominaisuuksissa. Kuvassa 3 on esitetty kolme eri rakennusorientaatiota.



Kuva 3. Kolme eri rakennusorientaatiota.

Geometrialtaan kuvan ensimmäinen ja toinen palkki ovat menetelmästä riippuen melko samannäköisiä, mutta kolmannessa palkissa esiintyisi rakennettaessa porrasefektiä. Koska x-y-tason tarkkuus on usein parempi kuin pystysuunnan tarkkuus, kappale kannattaa rakentaa niin, että sen tarkat piirteet tulevat x-y-tasoon.

Mekaanisilta ominaisuuksiltaan ensimmäinen palkki on vahvin, sillä sen rakennuskerrosten pinta-ala on suurin. Toinen palkki on heikoin, sillä sen rakennuskerrosten pinta-ala on pienin. Kolmas palkki on keskimmäisiltä osin vahvempi kuin toinen palkki, mutta sen alimmat ja ylimmät kohdat ovat hyvin heikkoja.

1.4 Tukirakenteet

Tiettyjen teknologioiden kohdalla tarvitaan tukirakenteita, mikäli kappaletta ei voida rakentaa sellaisenaan. Esimerkkinä kuvassa 4 on rakenne, jossa pylväiden välissä on materiaalia, jonka alla on ilmaa.

Kuva 4. Esimerkki riippuvasta geometriasta.

Tukirakenteita tarvitaan, mikäli käytettävä valmistusteknologia on sellainen, jossa kappaleen alla ei rakennusvaiheessa ole materiaalia. Tämä johtuu siitä, että muuten materiaalia jouduttaisiin lisäämään ilmaan, jolloin se ei muodostaisi haluttua muotoa vaan roikkuisi tai tippuisi rakennusalustalle. Jyrkin kulma, joka voidaan saavuttaa suurimmassa osassa laitteista, on 45 astetta. Muovikappaleita valmistavat laitteet, jotka perustuvat jauhepetimenetelmiin, eivät tarvitse tukirakenteita, koska jauhe tukee kappaleita muutenkin. Metallikappaleita valmistavat jauhepetimenetelmälaitteet tarvitsevat tukirakenteita.

Tukirakenteet valmistetaan myös kerros kerrokselta samanaikaisesti kuin muukin kappale. Tukirakenteet voidaan valmistaa materiaalista, joka poikkeaa rakennusmateriaalista niin, että ne voidaan poistaa helpommin esimerkiksi liuottamalla tai painevedellä. Mikäli laite ei tue tukimateriaalia, voidaan tukirakenteet valmistaa samasta materiaalista kuin varsinainen kappale ja poistaa mekaanisesti.

Tilanteissa, joissa tukimateriaalin poisto on haastavaa tai muuten epätoivottua, voidaan tukirakenteet kiertää muuttamalla geometriaa. Esimerkiksi kuvan 4 geometriaan voisi lisätä viisteet, jotta siinä ei olisi alle 45 asteen kulmia. Tällainen ratkaisu on esitetty kuvassa 5.

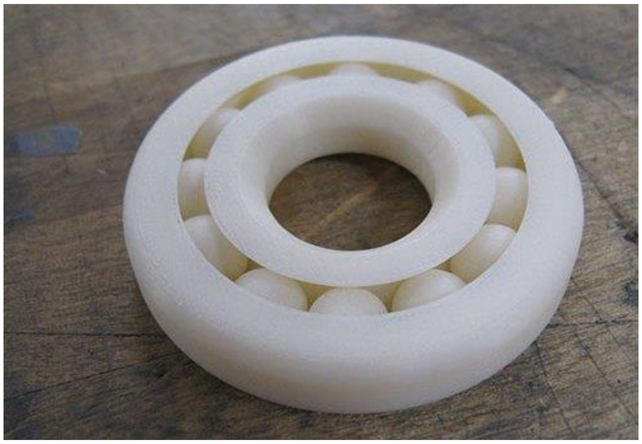
Kuva 5. Muutettu geometria tukirakenteiden tarpeen poistamiseksi.

Aalto-yliopisto
3D Manufacturing –tutkimusryhmä
Sergei Chekurov
23.7.2014

2. Kokoonpannut kappaleet

2.1 Mahdollisuudet

Materiaalia lisäävillä menetelmillä voi rakentaa kappaleita, jotka ovat valmistuessaan kokoonpanoja. Tämä tarkoittaa sitä, että kokoonpantavuus ei ole ongelma, ja että voidaan valmistaa kappaleita, joita ei käsin voisi kokoonpanna. Esimerkkinä tästä on kuvan 6 laakeri, jossa urat ovat liian kapeita kuulien sovittamiseen.



Kuva 6. Kokoonpantuna valmistettu laakeri. [http://www.mmsonline.com]

2.2 Rajoitukset

Kokoonpantujen kappaleiden rakentamisen rajoitukset ovat hyvin läheisesti tekemisissä porrasvaikutuksen, rakennusorientaation ja tukirakenteiden kanssa.

Akseleiden ja pallonivelten ollessa pyöreitä porrasvaikutus on hyvin tärkeä tekijä. Mitä pahempi porrasefekti on, sitä jäykemmin akseli pyörii ja pallonivel kääntyy. Akseleiden kohdalla rakennusorientaatio ratkaisee porrasvaikutuksen määrän. Porrasefekti on suurimmillaan kun akseli valmistetaan vaakasuunnassa ja pienimmillään kun se valmistetaan pystysuunnassa.

Tukirakenteiden poistaminen on suurin yksittäinen tekijä kokoonpantujen kappaleiden valmistuksessa. Parhaiten soveltuvissa valmistusmenetelmissä jauhemaiset tukirakenteet voi puhaltaa ulos. Painevedellä poistettavat tukirakenteet ovat myös hyviä, mutta ne tarvitsevat isompia poistumiskanavia ja niiden poistumiskyky rajoittuu paineveden tavoittamalle alueelle. Samasta materiaalista tehdyt tukirakenteet ovat haastavia ja joissain tapauksissa lähes mahdottomia poistaa.

2.3 Teknologioiden soveltuvuus

Teknologioiden soveltuvuus kokoonpantujen kappaleiden valmistukseen perustuu laajalti siihen kuinka helppo tukirakenteita on poistaa. Taulukossa 1 on lueteltu materiaalia lisäävän valmistuksen seitsemän teknologiaryhmää ja niiden tukirakenteiden poistamiseen yleisimmin käytetyt toimenpiteet.

Taulukko 1. Teknologioiden tukirakenteiden poistamismenetelmät

Teknologiaryhmä	**Yleisin tukirakenteiden poistamismenetelmä**
Binder Jetting	Paineilma
Directed Energy Deposition	Mekaaninen
Material Extrusion	Liuottaminen
Material Jetting	Painevesi
Powder Bed Fusion	Paineilma
Sheet Lamination	Mekaaninen
Vat Photopolymerization	Mekaaninen

Parhaiten teknologioista kokoonpantujen kappaleiden valmistamiseen taulukon perusteella soveltuvat binder jetting ja powder bed fusion. Binder jettingissä käytetään kuitenkin tällä hetkellä hyvin haurasta materiaalia, joten liikkuvien kappaleiden valmistaminen tällä teknologialla ei ole toteuttamiskelpoista. On huomionarvoista, että koska powder bed fusion-prosessissa käytetään lämpöä, mikä rajoittaa pienten välysten valmistusta suuresti.

Material jettingin tukirakenteet voi poistaa painevedellä, joten se on varteenotettava ehdokas tukirakenteiden poistamiseen. Material extrusionin liuottamismenetelmällä poistettavat tukirakenteet tekevät siitä myös hyvän teknologian tähän tarkoitukseen.

Directed energy deposition, sheet lamination ja vat photopolymerization vaativat tukirakenteiden mekaanista poistoa, minkä takia niiden käyttäminen kokoonpantujen kappaleiden valmistamiseen ei ole käyttökelpoista. Sheet laminationista on lisäksi tällä hetkellä kaupallisesti tarjolla vain paperia materiaalina käytettäviä laitteita.

3. Laitteen kyvykkyyden testaaminen

3.1 Testattavat ominaisuudet

Jotta saadaan selville tietyn laitteen kyvykkyys kokoonpantujen kappaleiden valmistuksessa, pitää valita oikeat ominaisuudet testattavaksi. Näitä ovat aksiaalinen minimivälys, radiaalinen minimivälys ja pienin rako.

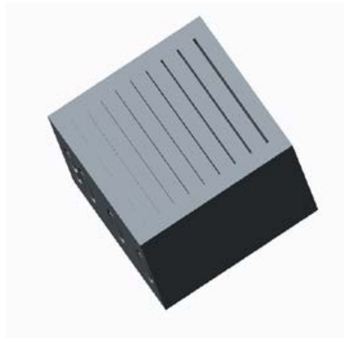
3.2 Testigeometriat

Testeissä käytetään yhtä 3D-mallia jokaiselle testattavalle ominaisuudelle ja ne ovat ladattavissa osoitteesta X.. Aksiaalinen minimivälys mitataan tapilla jonka ympärillä on renkaita tietyin välein. Radiaalinen minimivälys mitataan tapilla jonka ympärillä on renkaita vaihtelevalla etäisyydellä tapista. Pienin rako mitataan kappaleella, jossa on erikokoisia rakoja. Geometriat on esitetty kuvissa 7, 8 ja 9.

Kuva 7. Aksiaalisen minimivälyksen testausgeometria.

Kuva 8. Radiaalisen minimivälyksen testausgeometria.

Aalto-yliopisto
3D Manufacturing –tutkimusryhmä
Sergei Chekurov
23.7.2014



Kuva 9. Pienimmän raon testausgeometria

Geometrioiden välykset ovat pienimmästä suurimpaan seuraavat:

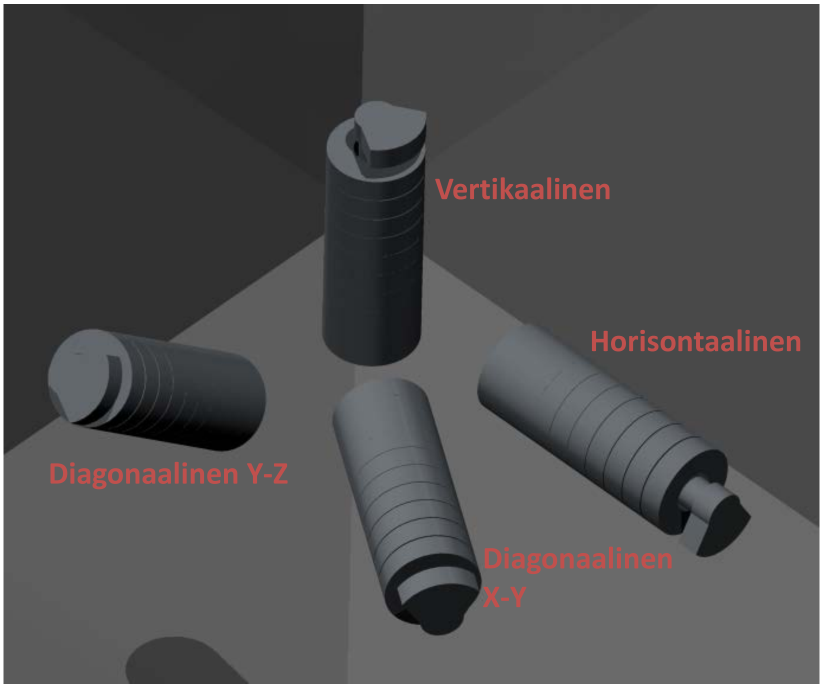
0,01 mm
0,02 mm
0,05 mm
0,09 mm
0,1 mm
0,15 mm
0,2 mm
0,2 mm
0,3 mm

3.3 Geometrioiden orientaatiot

Jokainen geometria asetetaan valmistettavaksi neljässä eri orientaatiossa: x-akselille, z-akselille, 45 asteen kulmassa x- ja z-akseleiden välille, sekä 45 asteen kulmassa x- ja y-akseleiden välille. 3D-mallien pohjassa on lukuja, jotka kertovat mihin asentoon kappale tulee. Tämä auttaa muistamaan, mikä kappale oli missäkin asennossa tukimateriaalin poistamisen jälkeen. Taulukossa 2 ja kuvassa 10 näytetään miten kappaleet tulee asetella.

Taulukko 2. Rakennussuuntien selitys

Numero	Akseli
Horisontaalinen	X
Diagonaalinen Y-Z	45 asteen kulmassa Y:n ja Z:n muodostamassa tasossa
Diagonaalinen X-Y	45 asteen kulmassa X:n ja Y:n muodostamassa tasossa
Vertikaalinen	Z



Kuva 10. Testikappaleiden asettelu

4. Esimerkkilaitteiden testitulokset

Tulosten analysoimiseen käytetään binäärijärjestelmää eli rengas joko pyörii tapin ympärillä tai ei, sekä rako on selkeä tai ei. Tässä projektissa suoritettiin testit Objet 30- ja uPrint SE+-laitteille. Testien tulokset löytyvät taulukoista 3-8.

4.1 Radiaalinen minimivälys

Taulukko 3. Objet 30:n radiaalisen välyksen testitulokset

Objet 30 Kerrospaksuus 0,16 mm	Välys (mm)								
Rakennussuunta	0,01	0,02	0,05	0,09	0,1	0,15	0,2	0,25	0,3
Horisontaalinen	0	0	0	0	0	1	1	1	1
Vertikaalinen	0	0	0	0	0	1	1	1	1
Diagonaalinen Y-Z	0	0	0	0	0	0	1	1	1
Diagonaalinen X-Y	0	0	0	0	0	0	1	1	1

Taulukko 4. uPrint SE+:n radiaalisen välyksen testitulokset

uPrint SE+ Kerrospaksuus 0,254 mm	Välys (mm)								
Rakennussuunta	0,01	0,02	0,05	0,09	0,1	0,15	0,2	0,25	0,3
Horisontaalinen	0	0	0	0	0	0	0	1	1
Vertikaalinen	0	0	0	0	0	0	0	0	1
Diagonaalinen Y-Z	0	0	0	0	0	0	0	1	1
Diagonaalinen X-Y	0	0	0	0	0	0	0	1	1

4.2 Aksiaalinen minimivälys

Taulukko 5. Objet 30:n aksiaalisen välyksen testitulokset

Objet 30 Kerrospaksuus 0,16 mm	**Välys (mm)**								
Rakennussuunta	0,01	0,02	0,05	0,09	0,1	0,15	0,2	0,25	0,3
Horisontaalinen	0	0	1	1	1	1	1	1	1
Vertikaalinen	0	0	0	0	0	1	1	1	1
Diagonaalinen Y-Z	0	0	0	0	0	1	1	1	1
Diagonaalinen X-Y	0	0	0	0	0	0	1	1	1

Taulukko 6. uPrint SE+:n aksiaalisen välyksen testitulokset

uPrint SE+ Kerrospaksuus 0,254 mm	**Välys (mm)**								
Rakennussuunta	0,01	0,02	0,05	0,09	0,1	0,15	0,2	0,25	0,3
Horisontaalinen	0	0	0	0	0	0	0	1	1
Vertikaalinen	0	0	1	1	1	1	1	1	1
Diagonaalinen Y-Z	0	0	0	0	0	0	0	1	1
Diagonaalinen X-Y	0	0	0	0	0	0	0	0	1

4.3 Pienin rako

Taulukko 7. Objet 30:n rakotestin testitulokset

Objet 30 Kerrospaksuus 0,16 mm	Välys (mm)								
Rakennussuunta	0,01	0,02	0,05	0,09	0,1	0,15	0,2	0,25	0,3
Horisontaalinen	0	0	0	0	0	1	1	1	1
Vertikaalinen	0	0	0	0	0	1	1	1	1
Diagonaalinen Y-Z	0	0	0	0	0	0	0	0	0
Diagonaalinen X-Y	0	0	0	0	0	0	1	1	1

Taulukko 8. uPrint SE+:n rakotestin testitulokset

uPrint SE+ Kerrospaksuus 0,254 mm	Välys (mm)								
Rakennussuunta	0,01	0,02	0,05	0,09	0,1	0,15	0,2	0,25	0,3
Horisontaalinen	0	0	0	0	0	1	1	1	1
Vertikaalinen	0	0	0	0	0	0	0	0	0
Diagonaalinen Y-Z	0	0	0	0	0	0	0	0	0
Diagonaalinen X-Y	0	0	0	0	0	1	1	1	1

4.4 Yhteenveto

Tuloksista voidaan luoda laitteille kokoonpantujen kappaleiden suunnitteluohjeet. Objet 30:n ja uPrint SE+:n suunnitteluohjeet on esitetty taulukoissa 9 ja 10.

Taulukko 9. Objet 30:n kokoonpantujen kappaleiden suunnitteluohjeet

	Piirre		
Rakennussuunta	**Radiaalinen välys (mm)**	**Aksiaalinen välys (mm)**	**Pienin rako (mm)**
Horisontaalinen	0,15	0,05	0,15
Vertikaalinen	0,15	0,15	0,15
Diagonaali Y-Z	0,2	0,15	-
Diagonaali X-Y	0,2	0,2	0,2

Taulukko 10. uPrint SE+:n kokoonpantujen kappaleiden suunnitteluohjeet

	Piirre		
Rakennussuunta	**Radiaalinen välys (mm)**	**Aksiaalinen välys (mm)**	**Pienin rako (mm)**
Horisontaalinen	0,25	0,25	0,15
Vertikaalinen	0,3	0,05	-
Diagonaali Y-Z	0,25	0,25	-
Diagonaali X-Y	0,25	0,3	0,15

Aalto-yliopisto
3D Manufacturing –tutkimusryhmä
Sergei Chekurov
23.7.2014