Dialogue and Compromise
Experimentation with Ceramics in Glassblowing Process

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Abstract

This thesis project investigates the methods of implementing ceramics in glassblowing processes. Many practitioners regard ceramics and glass as incompatible materials in glassblowing process, due to difficulties in bringing them together. Main reason behind this incompatibility is the difference in expansion and contraction rates of ceramics and glass, along with thermal shock resistance and durability requirements of this process. In order to overcome this challenge, this project implemented empirical material research methods in ceramics and developed experimental production processes in glass, while following practice-led design research methodologies.

The material research in ceramics involved with testing and analysing existing clay bodies such as earthenware, porcelain or chamotte mixtures for creating reference data on how ceramics behave in glassblowing process. Utilizing this data, numerous specialized clay bodies developed and used in experimentations in glassblowing process. Two clay body types, which can withstand the effects of glassblowing process, developed as a result of this research.

Process in glass studio initiated with testing compatibility of materials, and thermal capabilities of the ceramics in glassblowing process. Following the development of suitable clay bodies, glass studio activities shifted their focus on design and production of prototypes and artworks with this material combination.

Objects designed and produced during this project aimed to combine ceramics and glass together in a juxtaposition. In my opinion, this combination starts a dialogue among materials, and through this dialogue, each material expresses their individual character in their form and textures, yet compromise various aspects of their materiality to accommodate the other.

This research is an attempt to bring a new perspective and approach to ceramics and glass design, through material research and process development. Outcomes of this research presents a method for developing clay bodies suitable for utilizing in glassblowing process, along with a collection of objects and artworks displaying the aesthetic and functional possibilities of this material combination.

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Introduction

Dialogue and Compromise: Experimentation with Ceramics in Glassblowing Process is a project utilizing practice-based material research and experimental design methodologies, in which I investigated the process of implementing ceramics in glassblowing processes over a year-long period.

The starting point of this research is one my personal interests. As a designer, I have long been interested in working on manufacturing processes, developing materials, experimental methods, techniques, or concepts for new ways of making. Moreover, in my recent projects, I have developed a fascination with ceramic and glass, bringing them together with various materials in order to create collections. During a material experiment in glass studio, I started using high-fired porcelain bowls as moulds for sandcasting. While the process broke all the porcelain pieces due to thermal shock, through this experiment, I discovered an interesting potential in terms of surface qualities with this combination. As a result, I decided to utilize ceramics in glass studio actively, as moulds for glassblowing and sandcasting as a starting point for my investigation. Following the initial tests, however, I decided that using ceramics just as disposable moulds for glassblowing is under utilizing the potential of ceramics, and a limited application of this material combination. Instead, focusing on developing ways of bringing these two materials together, and utilizing ceramics as an integral part of the final object design became the focal point of this project.

Ceramic and glass have a shared history of thousands of years, functioning side by side. Throughout this history, numerous methods of production have been developed and utilized to design and create objects from both of these materials such as tableware, accessories, lighting and cookware. In fact, Trentinella (2003) states that, baked clay (ceramics) is one the earliest and most common materials for making glassblowing moulds in Ancient Rome. Thus, there is an established connection between these two materials in production. However, while each material influenced the other in various ways, it is still quite uncommon to utilize these materials together in an integrated form. The main reason behind this situation is their well-known incompatibility in production. While both materials require high temperatures in their production and share a significant percentage of same compound, silica, in their formulation, there are quite significant differences in their physical and chemical characteristics. Due to differences in their thermal shock resistance and thermal expansion/contraction rates, most glassblowing in ceramic experiments result with cracking or breaking of either one of the materials. Therefore, this research project is focusing on developing a reliable and productive process for using ceramics in the glassblowing process.
In order to achieve this goal, I intended to address the issue on multiple levels:

- Material research in ceramics for developing the ceramic clay body suitable for glassblowing in terms of thermal shock resistance, thermal expansion and durability

- Experimentation in glass studio for developing an efficient glassblowing method with ceramics

- Design and production of objects and artwork demonstrating the potential of the materials and techniques developed in this research

One of the key reasons behind my interest in working with this complex and difficult process is that, in my opinion, when two different entities are brought together, it starts a dialogue between them. In this case, each material express their character, strengths and weaknesses individually and in relation with each other. This dialogue reveals new limitations and possibilities for new creations. As a designer and researcher, one of the most interesting and exciting aspects of working with material combinations is exploring through these attributes, discovering new possibilities and limitations in form, function and aesthetics emerging from these combinations. In this case, the first step in combining ceramics and glass is finding a compromise between these two materials to balance their strength, brittleness and thermal capabilities while maintaining their defining characteristics, which made them interesting and unique in the first place.
Background

During this thesis project, I delved into similar material research and experimental design projects in order to examine the methods implemented or research questions posited by previous designers and researchers. My aim with this examination is further developing my understanding of the research methods and techniques available, while also working on contextualizing my project in the contemporary design field.

In my preliminary research for similar projects, which combine ceramics and glass or utilize ceramics in the glassblowing process, I discovered a collaborative project by artist researcher Charles Stern, ceramicist Jonathan Keep and the design studio Unfold. In this project, titled The Transaction Project, this research group is working on developing 3D printed ceramic moulds for glass blowing processes. While both my research and their project have similarities in terms of material and processes, there are important differences in project objectives, methodology, techniques, and expected outcomes. During my research process, I had productive discussions and material-based collaborations with this group.
Glass works of Pieke Bergmans are inspiring projects I discovered during my research, with some similarities in approach to my research project. In her practice, Bergmans combines glass with various objects and materials as a production method, and present these combinations together as installations. Vitra Virus (2007) depicted in Fig.3-4 is a project, in collaboration with world renown furniture company Vitra. In this experimentation, designer examines and juxtaposes the relationship between the iconic design pieces and her glassblowing based interventions.

Strange Symphony by Philipp Weber is another intriguing experimental design project, in which designer develops a tool, a modified unique glassblowing pipe, allowing glassblower to blow through three valves instead of one. His playful approach of intervening with the process is an inspiration and a valuable example of creating artistic value through experimental methods in glassmaking processes. Objects in Fig.5 demonstrates the unique outcomes of the process, through the three inner cavities in glass, achieved with the specialised blowing pipe developed for this project. Fig.6 displays a detail from production process, focussing on how the cavities are formed in glass.
Formafantasma is a design studio who create visually bold objects with compelling concepts by utilizing raw materials in both traditional and experimental methods. While many of their projects are sources of inspiration, *De Natura Fossilium* is a good example to discuss further into among their catalogue. In this project, designers employ local materials for creating an experimental collection. For example, in order to create the unique volcanic glass material in their artwork, designers utilized volcanic ash from Mount Etna, which depicted in Fig. 7. Completing the collection are unique furniture pieces in Fig. 8, which produced with basalt rocks collected from Sicily.
Another project example, which was researching into similar aesthetics is a thesis project named Compiled by Aalto University alumni Sebastian Jansson. While in this project designer focuses on, stacking as the method of bringing together elements made from different materials; his aesthetic and functional inquiry in terms of material combinations have similarities with my research project. In Fig.11, two objects in display are made by stacking same elements in different composition to create objects with different functions and forms.

Stacking Vessels by Pia Wüstenberg is another example similar to previously mentioned project, Compiled. In this project, designer created a stacking vessel system in which three separate containers made out of three different materials such as wood, glass and ceramics piled on top of each other. Each element is designed in a shape, which enables creating an archetypical vase form, when all three elements stacked on top of each other. Main similarities between my project and this example can be observed in the form language, since both projects utilize traditional shapes, which are natural for the production methods, and inquire about the relationship between materials and form connections. Fig.10 displays three vessels created by stacking ceramics, glass and wooden elements on top of each other.

Finally, towards the end of my thesis project, I discovered a doctoral thesis work by researcher Jessamy Kelly titled "The combination of Glass and Ceramics as a means of artistic expression in studio practice". This doctoral thesis work has strong resemblances to my research in terms of the starting point and the research questions. However, it follows a different approach and research process compared to my study, which results with different conclusions. Despite the differences, however, there are many valuable information and examples provided in this research. For example, as a part of her project, Kelly introduces and compiles artists who combines glass and ceramics in their artwork, which became a valuable resource for my research.
Context of the Research

Throughout this thesis work, the context of the research is a frequently mentioned topic. In my opinion, clarifying the position and extent of this research is a crucial information. This thesis work focuses on material research and experimentation in ceramics and glass in the contemporary studio production. Thus, the material tests and experiments were conducted by utilizing equipment and tools available in typical studio environment of a designer or an artist. As a result, advanced testing methods from material sciences, highly detailed temperature controls, or microscopic level observations are outside of the scope of this project. Instead, materials and techniques were assessed by following empirical methods and with a goal-oriented attitude.

In addition, it is also important to point out that during this project, I acted as a reflective practitioner, actively participating in the process filling various roles: as a designer, a researcher, and a craftsman. The knowledge and experience generated by my hands-on involvement in the process is one of the key sources of information in this project. One distinction to this position has taken place in the glassblowing process. Throughout this project, glassblowers with various experience levels have undertaken glassblowing, and my role in the process was acting as a studio assistant. While this position is limiting my ability to first-hand experience the effect of glassblowing inside ceramics, it also has the advantage of observing the process from outside and reflecting on it. The first-hand impressions and experience of the process is gathered during and after production processes, through discussions with glassblowers, who shared their reflections and opinions regarding various aspect of the project.
Research Methodology

This thesis project, utilizes methodologies from practice-led design research, empirical research, material research and experimental design. As a result, it is important to provide a short description about these fields, their relationship and meaning in the context of this project.

Practice-led design research is one the most popular and well-discussed methodologies in design research, especially among researchers with practical backgrounds. Practice-led research has strong connections with practice-based research and other practice related research methodologies to a point where many resources employ these terms interchangeably.

According to Mäkelä (2007), practice-led research focuses on issues, concerns and interests, which can be explored and demonstrated through the production of objects and artefacts. (p. 159). Thus, practice-led research is a study undertaken in order to gain new knowledge through the practice, and from the outcomes of the practice. In this context, practice is organically related to actual production process of the design, or the artwork; however, it is also strongly connected with concepts, theories and reflection. In practice-based design research, creation of knowledge is dependent upon the first-hand experience gained by the practitioners, and their reflections throughout the process. This process yields explicit outcomes in terms of physical objects, samples and research data; along with intangible outcomes such as the implicit knowledge gained by the practitioner through tacit learning.

Documentation methods are also one of the key elements in practice-based design research in terms of capturing and communicating all aspects of the process. However, in my opinion along with typical documentation tools such as working diaries, photography and videos, the artwork itself is the realization of the study, and a method of documentation in itself. According to Mäkelä(2007), artefacts aside from being the outcomes of artistic process, function as means of realising a thing which has to be perceived, recognized and conceived or understood (p. 159).

In this thesis project, practice-based design research became the fundamental research methodology, which connected and structured techniques and approaches from other disciplines.
Empirical research is methodology, based on experiments and observations to test a hypothesis. According to Heitink (1999, p. 233), Dutch psychologist A.D. de Groot created a cyclical model for analysing the empirical research:

- **Observation**: The observation of a phenomenon and its causes.
- **Induction**: The formulation of hypotheses and devising explanations about the phenomenon.
- **Deduction**: The formulation of experiments to test the hypotheses.
- **Testing**: The procedures for testing the hypotheses and data collection.
- **Evaluation**: The interpretation of the results and the formulation of a theory, based on the outcomes of tests.

This empirical cycle is one of the key elements of this design research project. In both ceramic material research and glassblowing process development, research followed this cyclical route.

For example, at one point of the project some of the relatively successful ceramic clay bodies observed and analysed. Some of the key attributes among them determined. According to this analysis, it is hypothesized that “if the clay body is consisted of components with different particle sizes, objects have a higher chance of surviving the glassblowing process.” This hypothesis examined by developing new clay bodies with various particle sizes, which put into the glassblowing tests. If the tests point out that, this clay body type have a higher success rate than results of more uniform clay bodies, the ideas are validated and became a new data point in the project. This research cycle continues by focussing on observations, which came out during the previous step of the process and repeats the steps in succession until satisfactory results achieved.
In contemporary design field, there are different perspectives on the meaning of experimental design. Some designers employ this term to describe their innovative and novel concepts, which can be considered outside of the current design paradigm. For some others, experimental design is the process of creating artworks and designs, which are results of a series of trials with materials or methods. In this project, a third explanation of this term is employed, which is related with the second alternative; however apply a more scientific approach in experimentation. In the context of this research, experimental design is deemed as a methodology, in which designer/researcher changes a single variable of the process at a time in order to observe differences caused by the change. If this process is undertaken rigorously, it can yield objective and reliable conclusions, similar to typical scientific experiments. In this approach it is important to work within series, to be able to create a rigorous and controlled study.

In the context of this research, experimental design approach is applied in different levels. For example, ceramic clay body formulas have numerous variables that can affect the characteristics of the material and its applications. Thus, in recipe creation and testing process, only one variable is changed and tested at a time, in order to observe the specific change; whether it is caused by percentage amount of a component, firing temperature, or shaping method. Similarly, in glassblowing process in order to improve the success rate and efficiency of the production, many of the parameters such as blowing temperature, timing, surface coatings, or glass bubble type are tested with the same method.

Material research is another research field related to this thesis project. According to Cambridge Dictionary, a material is a physical substance that things can be made from. Material research focusses on creating and manipulating these substances to obtain materials with certain properties and characteristics. Materials research is a vast field involving with all types of materials from metals, semiconductors, ceramics and polymers to more advanced materials such as nanomaterials and biomaterials. Main relationship between materials research and this thesis work is the inherent motivation. This research had aimed toward developing a reliable ceramics material suitable for utilizing in glassblowing processes.

Material research in the context of this project is similar to the studies by contemporary artists and designers, who develop materials for their works and experiments, rather than the approach of a material scientist.
Handmade

“The maker and the object made reacted upon the other. Until modern times, apart from the esoteric knowledge of the priests, philosophers and astronomers the greater part of human thought and imagination flowed through the hands.” Lewis Mumford

In this practice-led design research, my individual experience throughout the process became the integral source of knowledge created in this project. Following a hands-on approach, I was involved in solving both theoretical and practical problems, under the guidance of workshop masters and project advisors. As detailed in other chapters, this research process had many interconnected steps, which required skills and experience in both ceramics and glassmaking areas, as well as knowledge in research methods.

In this project, making things by hand became a central theme. The material research in the ceramics lab, the production in the ceramics studio and the experimentation in glassblowing are all made by hand. As discussed in glassblowing experiments chapter however, the glassblowing is handled by glassblowers instead of myself. The act of glassblowing is a quite complicated and detailed process. The glassblower controls many variables while working on gathering, controlling and shaping the hot glass. Variables, such as temperature and thickness of the glass or blowing strength, are crucial information regarding the process. This information requires first-hand experience of the glassblowing and it is almost impossible to perceive by an observer without it. This situation creates a fundamental difference between the process in glass studio and ceramics studio by adding the important layer of teamwork, dialogue, and communication to the research formula. While the production is still handmade, communicating with the maker’s hand through various methods became one of the crucial points of the process.

Handmade production is also one of the key points, where this research project linked with crafts, as well as art and design. In a discussion about craft, skill has long been one of the most important topics. For this project, skill positioned in a unique situation. For an extended portion of the process, skill as an ability to create refined, elegant or masterful artworks did not have an important role. Rather, skill became a tool of consistency: being able to produce standardized test pieces, controlling the variables and following a methodical approach in the glass experiments to ensure the validity of the outcomes. Only after the development of reliable ceramic clay bodies and figuring out the efficient method of glassblowing inside ceramics, the skill became a tool for producing aesthetically pleasing and creative results.
CERAMICS

Clay - A Brief Introduction

Clay is the most fundamental component of ceramics. It is the physical medium and the material of this field. All creative processes and production with ceramics is conceived through clay. Thus, for the creative people working in this field, learning more about clay, understanding its potential, capabilities, and limitations is a significant asset.

Clay is a material based on aluminium silicates in a hydrated and plastic state (Lawrence & West, 1982). In production, workability and responsiveness are two of the most important aspects of the clay, and these aspects are in strong correlation with the hydration and plasticity of the clay. When wet/damp, clay is a quite soft and workable material that can be shaped in various ways repeatedly. However, when it gets dry, clay starts to set in a form. Thus, losing its plasticity and gaining solid strength with firing.

There are significant differences between different clay types in terms of physical qualities, chemical composition, crystal structure, and workability among many others. Due to these different qualities, selection of clay type and production technique is a crucial decision in terms of achieving the desired outcomes. For example, china porcelain is preferred for its whiteness, translucency and, durability even in thin wall thickness, yet it is also a material with difficult workability on potter’s wheel, which may not be ideal for a beginner level potter to work with. Fortunately, clay is material with many possibilities. With a thorough research in clay materials, minerals, and their effects in clay body mixtures, it is possible to develop many different clay body recipes with qualities matching with the requirements of the project.

There are innumerable clay body formulations available in the market. They can be purchased from material suppliers in ready-made form, or it is also possible to mix clay bodies from raw ingredients utilizing recipes found in ceramics books or online resources. Initially, these recipes developed to imitate naturally occurring clays, or produce workable clay bodies with similar qualities to idealized minerals such as Kaolinite, which lacks plasticity (Hamer, 1991, p. 183). However, as the knowledge of materials developed in the ceramics field, many specialized ceramic clay body formulations were developed with unique qualities, which are suitable to work in extreme physical and chemical conditions.

Throughout this project, numerous clay body recipes developed, and utilized in experiments and production. Methods and techniques employed for developing these clay bodies are articulated with detail in Appendix-A: Method for Clay Body Calculation.
Initial Tests with Porcelain, Earthenware and Stoneware

Porcelain, earthenware and stoneware are three of the most well-known clay body types in ceramics field. This diverse group covers the entire range of materiality provided by ceramics. At the initial stages of this research, clay samples from these ceramic types tested together as group, in order to create reference points for the project.

As a small and comparative introduction to these materials, according to Hamer (1991), all pottery can be simply categorized in two segments in terms of their porosity. If the porosity of fired clay body is less than 5%, it can be categorized as stoneware and if the fired porosity is higher than 5%, it can be categorized as earthenware (p.115, 311). Porcelain is a subcategory of stoneware, which has a completely vitrified surface, a naturally white body, and possibility of translucency. Aside from the porosity, there are many other differences among these groups due to their chemical compositions and formulations. For example, while objects made from earthenware mature at lower temperatures of 1100-1200°C range, for stoneware and porcelain maturation starts at 1200°C. This difference can be explained with the higher percentage of iron oxide in an earthenware clay body, which starts melting at lower temperatures compared to other components.
Considering innumerable clay body formulations with different physical and chemical capabilities, it is difficult to determine the starting point and reference data for this type of research. Thus, I decided to start my research in ceramic clay bodies, with samples from existing clays in the studio due to practicality. Among existing clays, Arabia Porcelain (40% Kaolin, 30% Feldspar, and 30% Quartz) is utilized for slip casting, while Finnish earthenware and stoneware plastic clays selected for working on the potter’s wheel. My motivation behind initiating the research process with these materials was the familiarity, ease of access and ease of use with these clays, hence producing initial test pieces in a fast and efficient way. These initial test pieces were created for observing how glass and ceramics are behaving together, analysing the existing problems and theorize potential characteristics of the required clay body.

These test pieces were fired to bisque and high fire temperatures. For porcelain slip, test pieces fired to 900°C for bisque, and 1240°C for high firing. Earthenware and stoneware clays were also fired to 900°C for bisque, however due to information on technical data sheet from manufacturer high firing temperature was limited to 1200°C.

Many samples produced from these clay bodies were utilized in the glassblowing processes for the initial tests of this project. Among numerous samples, only several bisque fired pieces made from all three clay types and two high-fired earthenware pieces survived the blowing process.

When results were examined, chance of bisque fired pieces surviving the blowing process came out more probable than to high-fired pieces. At the first glance, this result can be unexpected. In general, bisque fired ceramics considered to be unfinished products, since they are structurally weak, fragile and not vitrified; thus, dysfunctional in regards to expectations from a ceramic object. Only after high firing, ceramics become stronger, durable and vitrified; thus start to function as a ceramic object supposed to. For glassblowing process however, the structural strength and rigidity provided by high firing appears to be counter-productive. As the ceramic material sets into a physical condition and get rigid, it also becomes brittle. If the structural strength of the ceramic is high enough to endure the thermal shock and the pressure from the glassblowing process, this integrity is an important benefit. However, this strength was inadequate in porcelain, earthenware and stoneware samples from these initial tests. Thus, immediately after contacting with hot glass, these high-fired ceramics crack and get broken due to lack of plasticity in their structure. These materials were able to withstand the process in bisque fired state due to relatively plastic and less rigid structure of the clay when fired to only 900°C.
Outcomes of the initial tests identify several different approaches to follow in further steps of the process. First, the ceramic material needs to be either quite resistant to thermal shock and durable; or relatively softer, and tolerant to the effects of glassblowing. Bisque fired pieces demonstrate potential, as disposable mould making materials for glassblowing and can be an intriguing topic to study further. However, at this state due to their fragility after the production, they are not suitable for this research. Since my aim is to bring the ceramic and glass parts together in the final product, fragility is a considerable shortcoming of bisque fired ceramics.

The following step of the research became delving into ceramics, which are well-known for their thermal shock resistance and durability. While searching for these materials, I discovered various components utilized in thermal resistant industrial ceramics, and Zirconium became my first focus among the others.
Zirconium Based Clay Bodies

Zirconium is a highly refractory metal oxide with chemical formula of ZrO₂. According to Hamer (1991), ceramic industry adopted Zirconium as a potential replacement for the more expensive opacifier, tin oxide. Since then, it became a popular component for its many capabilities and functions. For example, Zirconium adds opacity and a strong white tint to clear glazed objects, contrasting to the soft whiteness of tin oxide glazes. Zirconium silicate, a compound of ZrO₂ with silicate, is a mineral with the chemical formula of O₄SiZr. It is a hard and highly refractory mineral with a melting point of 2550°C, which ceramic industry utilizes for producing kiln shelves and other kiln tools (Hamer, 1991, p.350-351). Due these functions and refractory capabilities of this compound, I started working on developing a Zirconium silicate based clay body.

In the initial tests, my aim was observing the behaviour of the zirconium silicate in the purest possible state. Thus, while developing the first formula, purity of ZrO₂ was the main consideration. The first batch of clay body had 96% Zirconium silicate and 4% Bentonite, which is included to add plasticity to the mixture. This mixture is utilized for preparing a casting slip and a plastic clay for working on the wheel. Preparation of these clay bodies required an unusually high amount of water (+40%) in order to create a workable clay body.

96% Zr casting slip had a similar behaviour to porcelain in production stage. However, their difference became quite apparent, especially when working on potter’s wheel. 96% Zr clay body had a short character and it was difficult to work with on the wheel. Water ratio in the body is difficult to manage, which causes cracks, weaknesses, and collapses throughout the production.

Since workability of the clay is as important as its technical capabilities, I started adding ball clay to the formula in order to increase the plasticity. Second Zirconium based formula had 75% Zirconium, 23% Ball Clay and 2% Bentonite in its mixture. This formula required a lower water percentage in mixture (37%), thus providing easier control on the potter’s wheel and a smoother surface result.
Test pieces made from 96% and 75% Zirconium were fired to bisque and high fire temperatures of 900°C and 1240°C degrees. After the firing, first thermal shock tests applied to Zirconium-based clay bodies in order to observe their behaviour. While some of the pieces tested with a flame torch, some of the pieces tested in glassblowing process. Both 96% and 75% Zirconium silicate clay bodies failed in these tests, by immediately cracking with the thermal shock. Due to results of these tests, I changed my approach and started researching for a clay body, where zirconium is an additive, instead of the base material to create a heat resistant formula.

In this research for clay bodies, which zirconium integrated as a supportive component, I came across a formula developed by Pussepitiya and Adikary (2013), for producing heat resistant ceramic cookware products. I decided to put their formula to test in glassblowing process, for comparing the results with the previous Zirconium based samples. Using their formula, 45% ball clay, 15% alumina, 15% talc and 25% zirconium, I prepared a casting slip for producing test pieces. The casting slip developed from this formula was easier to work with compared to previous Zirconium based clay bodies, due to high percentage of ball clay. However, experiments in glass studio displayed that thermal shock resistance provided from this formula was not adequate for glassblowing processes, because all ceramic test pieces cracked immediately in the blowing session.

Result of the final Zirconium based clay body test impelled me to search for another main ingredient, which could provide the required thermal and structural capabilities to the clay formula. Thus, I started focusing on the second main ingredient in the clay body recipe by Pussepitiya and Adikary, which is aluminium oxide.
Aluminium Oxide Based Clay Bodies

According to The Potter’s Dictionary of Materials and Techniques by Hamer (1991), aluminium oxide is the second most important oxide in ceramics, after silica. When combined with silica, aluminium oxide creates the clay crystals and the presence of alumina is giving plasticity to the clay. In ceramics, alumina has a wide variety of roles in glazes, or in clay bodies. However, it is rarely utilized as the pure aluminium in the oxide crystal form. Instead, it is introduced in compound minerals such as china clay and feldspar. Pure aluminium oxide powder is employed for reducing shrinkage rate and making the clay body more durable in higher temperatures (Hamer, 1991, p.6, 7).

In advanced ceramics industry extremely high percentage, up to 99%, aluminium oxide clay bodies utilized due to their high electrical insulation, mechanical strength, and chemical resistance. However, achieving this level of purity while still having a workable clay body is a significant technical challenge in studio environment.

In this project, I developed two aluminium oxide based clay bodies. First tests were made with 75% Aluminium oxide, 22% Ball Clay 3% Bentonite formula. This formula devised with the purpose of containing Aluminium oxide in high purity, combined with ball clay and bentonite, both of which were providing plasticity and workability to the mixture. However, production tests displayed that, this clay body was still quite rough and short, which makes it difficult to work with on potter’s wheel or in slip casting. Thus, the second formula is devised to ease the problems of working with this material: 60% Aluminium oxide, 37% Ball Clay and 3% Bentonite. The increase of ball clay percentage provided a smoother and more plastic clay body, compared to the first Al₂O₃ based formula.

Using both Aluminium oxide based clay bodies, numerous test pieces created through slip casting and throwing on potter’s wheel. All test pieces fired to bisque and high fire temperatures of 900°C and 1250°C degrees.

Following the firing step, these pieces utilized in glassblowing sessions to observe their compatibility with glass, and their thermal capabilities. During these experiments, only a few pieces made from 60% Aluminium oxide formula survived the glass blowing session.

As a result, while Aluminium oxide based clay bodies showed some potential; high degree of difficulty in shaping the material, combined with the high percentage of failure in production required further research in clay materials.
A brief analysis of progress

At this point of research, I analysed the outcomes of glassblowing tests, in order to identify some of the potential characteristics required from the ceramic pieces.

Among all test pieces, a few of bisque fired stoneware, low-fired earthenware and 60% Aluminium oxide pieces displayed limited success. Some of the key aspects of these objects were:

-non-rigid character of bisque fired and low fired pieces
-small area of contact with the glass, for aluminium oxide pieces due to the shape of test pieces
-high porosity

After identifying some potential characteristics, I researched for readymade clays in the market with similar qualities in order to make new experiments. During this research, I discovered about clay bodies with high chamotte content, which display similar characteristics.
Chamotte Clay Bodies

Chamotte, also known as grog in some resources, is a raw ceramic material with high aluminium and silica content. Chamotte is produced by firing ceramic clays to high temperatures and then breaking and grinding them, in order to prepare small size particles. Chamotte is mostly utilized as a type of opener in refractory ceramics, resulting with porous and low-density structure (Tichane, 1990, p.47). Chamotte has a widespread application in ceramics, and it is a frequent ingredient especially in pottery and sculpture clays. While there are numerous types of chamotte clay bodies available, during this research one earthenware and one stoneware based samples utilized in experiments.

First chamotte clay body can be described as a red clay mixture developed for brick making. This clay body had Finnish earthenware as the main clay, which was mixed with rough quartz sand and approximately 30% chamotte, made from Finnish earthenware. This clay has a red colouring, due to high iron oxide ratio in Finnish earthenware. Main reason behind my interest in working with this specific clay was, testing my theory regarding the correlation between thermal shock resistance, structural porosity, and direct contact area of hot glass and ceramics. Considerable difference in particle size in components creating this clay body, results with a porous structure. Additionally, when this clay was shaped on potter’s wheel, large chamotte particles created an uneven inner surface and rough texture. Due to this rough and uneven texture, in the glassblowing process, hot glass surface only gets into contact with a relatively small surface area, mostly composed of bigger chamotte particles.

Second chamotte clay body is named, TerraNigra 3520 and provided by German manufacturer Sibelco. This mixture has been utilized for producing of artworks, especially with hand-building techniques. This stoneware based clay body also included 35% Black chamotte with up to 2.0mm sizes in its mixture. Despite the difference in chamotte percentage, both clay bodies resulted with similarly uneven and rough surfaces. Due to particle size difference in components, larger chamotte particles became quite visible, which also added a strong tactility to the test pieces.

Both chamotte clay bodies were shaped on potter’s wheel, while producing the test pieces. Due to variance in particle size, preparing a casting slip is quite challenging with these clay bodies. In liquid state, clay is unable to keep large chamotte particles afloat, hence all big chamotte particles in the mixture sinks at the bottom of clay container.

Additionally, production process demonstrated the limitations and difficulty of shaping these clays on potter’s wheel. While rather short structure of the clay, limits the size and shapes of the objects produced on potter’s wheel; it is also a painful procedure due to high friction applied to maker’s hands by large chamotte particles during the throwing process.

Test pieces produced from chamotte clay bodies were fired to 900°C for bisque firing and 1200°C for high firing, according to the recommendation of material suppliers.
After the firing, production in glass studio started with test pieces made out of the red brick clay. In this step, several small test pieces survived the glassblowing process, while all larger test pieces got broken immediately with the thermal shock.

In glassblowing tests, the TerraNigra 3520 behaved quite similarly to the red brick clay, for most of the process. However, one significant difference between two clay bodies observed during the blowing process of relatively larger objects. In these tests, objects appeared to be getting closer to cracking during the blowing. However, after the annealing ceramics did not display any visible cracks.

The results of experimentation with chamotte clay body supported some of the theories regarding the required clay body characteristics, especially the potential significance of particle size difference, and porosity. However, since chamotte clays displayed susceptibility for cracking in production, the process required researching for clay bodies with stronger structures.

At this point of research, I contacted with the design studio Unfold through a series of emails, and discussed about a project they have participated named, The Transaction Project. During our discussion, they described the type of clay employed in their Ceramic 3D printing process, as “similar to traditional raku clays”. Considering the similarities between characteristics of the raku clay and the requirements identified in my analysis, next step for this research became studying raku clay bodies.
Raku Clay Bodies

Raku is a type of traditional Japanese pottery, known for the types of specialized clays and its unique production methods. Almost every clay can be made to work as a raku clay body, with the addition of openers such as grog, fireclay or sand in correct ratio. While this ratio depends on the clay type, and decided upon the desired effect, generally openers in the clay body are about 30-40% of the dry weight (Hamer, 1991, p. 260-261). Thus raku ware, a common name for the objects made with this technique, are generally quite porous. Traditionally, raku ware pieces are taken out of the firing kiln while in red hot state, and cooled down to room temperature immediately; in order to create unique aesthetics of this method, such as metallic finishes and carbon effects from reduction. Considering the amount of thermal shock caused by this sudden change, raku clay bodies requires significant tolerance to thermal shock. According to Hamer (1991), thermal shock resistance of these clay bodies can be improved with four adjustments:

1- Adding coarse materials will open the body
2- Adding materials, which burn out will open the body
3- Adding materials of low thermal contraction will decrease the overall contraction of the body
4- Adding materials of slow vitrification will improve sintering of the clay particles during biscuit firing and thus improving the strength of the body (Hamer, 1991, p.320-321).

Hamer’s analysis points out that, controlling the thermal expansion rate and opening the clay body, while maintaining its strength is essential for a strong raku clay body. This analysis confirms my previous hypothesis regarding to the relative success of bisque fired test pieces, and potential benefits of clay bodies prepared by mixing ingredients with different particle sizes.
At this stage of the research, a ready-made white raku clay body, with 30% 0.8mm chamotte opener, is utilized for creating test pieces. Several ring-shaped test pieces produced on the potter’s wheel for glassblowing experiments. Similar to chamotte clay bodies, due to big variance in particle size, producing a casting slip is almost impossible with the raku clay composition, which limits the potential production methods.

All test pieces produced from raku clay body fired to 1240°C for high firing temperature; however, the traditional shock inducing cooling technique did not apply to the test pieces, in order to keep structural strength of the objects as high as possible.

Pieces produced with raku clay, displayed valuable potential for working in glassblowing processes. During glassblowing sessions, almost all of objects survived the initial blowing and combination with basic glass bubbles rather safely. Because of the relative success of the raku clay body in this experiment, next step in glassblowing process started with inclusion of more complex forms and further steps of shaping the glass after the combination. In these lengthy shaping steps, glass and ceramics reheated inside the glory hole or by applying the burner. Most of the raku objects started to display signs of cracking as the process of glass shaping continued. Results of this experiment demonstrated the potential of raku based clay bodies in glassblowing processes, especially under limited exposure to thermal changes; further proving some of outcomes of The Transaction Project.

As a conclusion, working with raku clay provided valuable insights regarding to required characteristics of the ideal ceramic clay body for the glassblowing process. However, inability of slip casting and painful process of shaping on the potter’s wheel demonstrated significant flaws in workability. Moreover, tendency of breaking in longer blowing sessions displayed potential improvement areas such as structural strength and thermal shock resistance capabilities. In order to improve upon the shortcomings of raku clay body, my research focused on other thermal resistant and refractory clay types employed in industry, and cordierite displayed the most promising potential.
Cordierite-like Clay Bodies

Cordierite is a magnesium-iron-aluminium cyclosilicate, with the ideal chemical formula of 2MgO·Al₂O₃·5SiO₂, which has iron as a common impurity (Lawrence & West, 1982). While cordierite crystals and gems are found in mineral depositories around the world, in many industries cordierite is utilized in its synthetically produced form.

Commercial synthetic cordierite is first developed by Felix Singer in 1926 and many ceramists have been trying to produce commercial cordierite clay bodies since then (Hamer, 1991, p. 132). Cordierite has widespread application in industries due to its thermal shock resistance, low thermal conductivity and low thermal expansion. In ceramics industry, cordierite is being utilized as structural components for kiln furniture, along with other areas where rapid temperature changes occur regularly. Due to these characteristics, developing a synthetic cordierite based formula became the next step in this project.

Original recipes for new, synthetic cordierite clay calculated by applying the process detailed in Appendix - A: Method for Recipe Calculation. The reference data for the theoretical values of cordierite acquired from online resources. According to an article taken from a 2001 issue of Ceramic Industry Magazine, and corroborating information in technical specifications from Reade Chemicals International, theoretical weight distribution of the components in a synthetic cordierite clay body is 13.8% MgO, 34.8% Al₂O₃ and 51.4% SiO₂. This reference point became one of the guidelines for calculating component percentages in the clay body recipes, along with the basic formulation of cordierite: 2MgO·Al₂O₃·5SiO₂. For the first tests of cordierite clay body, chemical data for four materials, Andalusite, Olivine, Ball clay, and Kaolin were utilized in recipe calculations. While Kaolin and Ball clay were already frequently employed throughout the process, both Andalusite and Olivine became new additions. Selection of these two minerals were based on their chemical and physical capabilities, along with their availability in the ceramics lab during these experiments.

As a brief introduction, Andalusite is a hard and refractory mineral occurring in metamorphic rocks. It is an aluminosilicate, with the chemical formula of Al₂SiO₅. Due to its low thermal expansion, Andalusite is utilized in various industries with refractory applications such as producing refractory bricks, moulds, and mould coatings (Hamer, 1991, p. 298). Olivine is a magnesium silicate found in igneous rocks, with typically green colour. It is employed in metal industry for producing refractory bricks, and utilized as a type of casting sand (Singer, 1963). Due to its high magnesium content and refractory capabilities, olivine became an integral component in cordierite research.

In the first cordierite body, Andalusite and Olivine were the most important components for creating the cordierite structure. Ball clay and kaolin were utilized for improving the workability of the clay body, while balancing the chemical formula. Utilizing these materials, I managed to calculate two clay recipes, which are accurate in terms of chemical composition and weight distribution of components. These two recipes applied for creating both slips for casting, and plastic clays for throwing on potter’s wheel.
All test pieces were fired to a temperature range of 900°C, 1000°C, and 1250°C in order to observe differences in strength, porosity and visual changes in the clay. Andalusite-Olivine (AO) mixture had a drastic colour change in all firing temperatures. Due to variety in particle size and types of compounds in the mixture, it had a distinctive texture and highly porous structure. While test pieces made with slip casting demonstrated this character, the effect amplified when test pieces produced on potter’s wheel. This clay body had a short but plastic character making it easy and painless, yet limited clay body to work with on the potter’s wheel. Therefore, while producing small sized test pieces with basic geometric and organic forms was a simple process, it is quite challenging to make large and refined forms with this clay body. Test pieces created on the wheel had rough and sandy textures, resulting with a distinctive appearance and character.
In the following step, several objects produced from this clay body utilized in the glassblowing experiments and combined with glass bubbles. Glassblowing tests with this mixture became an immediate success and changed the course of this research project. Until this point in the research, damaging ceramic pieces in glassblowing stage was the most common problem in the process. Starting from the first glassblowing session, pieces made from cordierite-like clay survived the glassblowing, due to their thermal shock resistance and thermal expansion rate. Even in longer blowing sessions, in which ceramic piece went into glory hole several times; material withstood the constant thermal shock effect, unlike the previous clay bodies. Success of the AO mixture, allowed the production of bigger, more detailed and refined prototypes for the first time in this project.

Fig. 27
Since, basic requirements expected from clay body were achieved with AO mixture, the research started to focus on improving the formula and controlling the characteristics of the material. Numerous adjustments applied to enhance the working recipe. Some experiments involved with changing parameters of existing of component such as particle sizes, water and deflocculant ratio, while other experiments involved with employing new materials in the mixture. For example, another highly refractory compound Magnesium oxide was introduced to the formula in a quite small particle size, in order to control the porosity of the ceramic structure. However, this addition did not result with the desired effect. Even with the addition of powder size Magnesium oxide, AO mixture kept its high porosity level. Further tests and improvements on AO mixture was obstructed by a supply problem with one the key ingredients in this formula. Andalusite stones utilized in this project were acquired with the courtesy of a donation to the Aalto University ceramic studio, and were limited to approximately 20 kilograms. Due to this limited supply, I researched for suitable material suppliers around the world for weeks without success.

Material supply problem with Andalusite and Olivine mixture, brought forth the necessity to develop new clay body formulas based on synthetic cordierite by introducing new materials. While working on new formulas and Andalusite replacements, I found the solution in Raw Materials for Glass and Ceramics book by Christopher Sinton. According to Sinton (2006), Kyanite has the same nominal composition to Andalusite, with a different crystal structure and physical properties (p.196). In addition to Kyanite, a secondary ingredient is identified through researching online resources for cordierite body components. According to supplier website, Sierralite is a talc with low thermal expansion, which can strengthen refractory clay bodies and reduce structural porosity. Since both Kyanite and Sierralite were available in Finland, a new cordierite formula was developed by replacing Andalusite with these two components.

In the new formula of cordierite clay body, Kyanite, Sierralite and Olivine are utilized for creating cordierite crystals, while Kaolin and Ball clay have been taking a complementary role by providing workable clay qualities to the recipe. Kyanite, Sierralite and Olivine (KSO) based recipe is utilized for producing both slips for casting and plastic clay for throwing on the potter’s wheel.

In the production stage, KSO mixture behaved quite similarly to the AO mixture, in terms of physical characteristic and workability. In plastic clay state, it is a short clay body with painless, yet limited production capabilities in wheel throwing. Objects created by throwing KSO mixture had a distinctive and rough texture. As a casting slip, KSO mixture can produce objects in various sizes with smooth outer surface quality, with relative ease. However, due to variance in particle size, fine-tuning the amount of water in the formula remains a challenge.

Tests pieces produced with this recipe, fired to bisque (900°C) and high firing temperatures (1250°C), along with other temperatures in the middle (1000°C, 1100°C) to observe characteristics of the material in a wider firing range.
While the KSO mixture behaved similarly to AO mixture in production stage, after firing sessions their differences became apparent. First of all, instead of the mostly monochrome colour palette of AO mixture (pink tones in bisque, brown tones in high firing temperatures), KSO have a quite heterogeneous surface and texture. Similar to noise graphics, high fired KSO objects have a white base covered with black and golden particles all over. This unique appearance is consistent in all test pieces made with various production techniques and can be achieved with both rough, and smooth finishes. In different firing temperatures, only visible change is in the colour of the particles, which transform from red tones to black as the firing temperature rise to 1250°C. As observed in AO mixture, this clay body also has a porous structure due to variety in particle size and types of compounds employed.

In the following stage, numerous test pieces produced with KSO mixture utilized in glassblowing process and combined with glass bubbles successfully, demonstrating their thermal shock resistance capabilities and durability. Following the experiments with basic bubbles, capabilities of the material were tested in more extensive glassblowing processes, under stress of thermal shock in several steps. Almost all of the test pieces made from KSO mixture survived the glassblowing processes without breaking or getting visibly cracked. Due to success of numerous test pieces in these production processes, I have concluded that, both AO and KSO mixtures are suitable materials for complex and lengthy glassblowing processes.

Even if the KSO mixture replicates the success of AO formula; it was unable to overcome some of the functionality limitations of its predecessor, most importantly porosity. Since addition of Sierralite did not reduce the porosity, I started working on alternative solutions for this problem. First experiments were conducted by adjusting the firing program by changing the high firing temperature and the soaking time of test pieces. Through this adjustment, obtaining various levels of surface vitrification on the objects would reduce porosity of the structure drastically. For this experiment, test pieces were fired to 1280°C with 1 hour soaking time and 1300°C degrees with 2 hour soaking time; in order to observe the changes in clay body in higher temperatures and under exposure of prolonged soaking times.

Results of new firing temperatures changed the appearance of the objects in terms of colour and texture. Instead of black and gold on white colour palette, new objects had black spots on brown surfaces, combined with slightly melted and vitrified sections in green tones. However, these changes were limited to the appearance and aesthetics of the objects. Further experimentations in glass studio demonstrated that vitrified objects behaved similarly under thermal shock, and remained quite porous. Due to limitations of the electric kilns available in ceramic studio, high firing temperatures were limited to 1300°C. According to Lawrence and West (1982), cordierite crystals starts forming at 1300°C, however, in some formulations percentage of crystals increases as the firing temperatures get closer to 1400°C. Since satisfactory results, in terms of glassblowing compatibility, achieved with the both AO and KSO mixtures, further developing the firing programme did not become a priority for this project. However, potential of these clay bodies under different firing conditions is another research topic for future studies.

Aside from experiments with firing programme, additional minerals introduced to the clay body formula to reduce porosity in high-fired pieces. Most notable of these material tests involved with petalite. Petalite is a Lithium Aluminosilicate, utilized in ceramic glazes and glass ceramic clay bodies for Corning Ware cooking pots (Sinton, 2006, p.192). While addition of Petalite, did not affect the cordierite formulas significantly in terms of porosity, it also did not change the clay body in terms of aesthetics, or weaken the structural strength in glassblowing tests. During these examinations, researching further into Lithium based clay bodies bring forth the final type of clay body to examine in the context of this research.
Lithium Based Clay Bodies

Lithium based clay bodies are the final clay body type researched, in the context of this thesis project. A lithium based component, petalite, initially introduced to this project as an addition to cordierite based formulas, in an attempt to reduce the structural porosity. In cordierite-based mixtures, petalite did not solve the porosity problem of high-fired pieces. However, due to its low thermal expansion and contraction rate, petalite is already an established component in ceramics, utilized in clay bodies and glazes to help reduce thermal shock problems (Hamer, 1991, p. 198-199). Considering its fine particle size and thermal qualities, petalite based clay bodies appeared have significant capabilities in the context of this research and beyond.

Petalite (LiAlSi₄O₁₀) is a lithium feldspar with a high silica content. While creating a petalite-based clay body, my intent was utilizing petalite as the feldspar replacement in a porcelain clay body, thus develop a thermal shock resistant porcelain formula. In order to observe the compatibility of kaolin (fine china clay) and petalite, first clay body tests conducted with two combinations of these materials: %60 Petalite + %40 Kaolin and %55 Petalite + %45 Kaolin.

Clay body mixtures created with these formulas prepared as casting slips. However, both formulas had problems regarding the amount of water and deflocculant (Dispex) required for achieving the base level of plasticity required for a successful cast.

Using these slips, several test pieces created and high fired to 1250°C and 1280°C. After the firing, tests pieces displayed deformation and warping in their shape.

Additionally, some of the test pieces from 1280°C firing had stuck to the kiln shelves during the firing, due to a strong vitrification and melting on the outer surface of the material.

In glass studio, several samples from these test pieces combined with glass bubbles for examining their capabilities in this context. Almost all of the pieces survived the glassblowing successfully, demonstrating the thermal shock resistance of the material. Furthermore, leakage tests pointed out non-porous structure of petalite-kaolin mixture, which kept liquids inside without any leakage, due to its small particle size and vitrified surface. These results should have concluded that, this material composition is the ideal mixture. However, workability is the biggest limitation of this formula, and lithium based clay bodies in general. In addition to my empirical research data, research into various resources, online articles to forum discussions among experienced ceramicist, pointed out the same problems with workability. Flameproof lithium based clay body formulas have extremely low plasticity and they are almost impossible to shape as uniform objects in studio ceramics environment. They require industrial production tools, and firing programmes with detailed temperature control.

As a result, in the context of this research, I had to conclude my study in Lithium based clays as a future research topic with high potential, which requires an extensive study. Because, while the material displays significant promise in terms of physical and chemical capabilities; technical requirements of the material in production, limited conditions in ceramics studio and project schedule positions this material outside of the scope of this research.
Notes on Ceramics Tests

Researching and producing clay bodies is an intensive and complex process with many variables. Throughout this research in ceramics, guidance of ceramic studio master Tomi Pelkonen had been a substantial contributor to the project, with his extensive knowledge of materials and techniques.

I have chosen to present this project by focusing on each material type separately, in order to create a better understanding about the differences among them, and display the results of each step clearly. However, it is also important to point out that, these steps were interconnected in some level and knowledge created in these actions influenced the outcomes of following steps in multiple areas.

Initial tests made with existing materials in studio displayed the shortcomings of these clays, and identified some of the requirements for ceramics material suitable for glassblowing process. In addition, during that point of the process, I figured out problems with the shapes of test pieces, such as their size, proportions and wall thicknesses.

Second material type, zirconium based clay bodies, became the first tests for observing how this refractory material behaves in glassblowing process, under these different thermal conditions. At the same time, during that process I learned how to create a clay body based on a non-traditional material in studio environment, and develop it as a workable material through various adjustments.

During the experimentation with Aluminium oxide clay bodies, I observed how this industrially proven material behaves in ceramic studio level production, along with its behaviour in glassblowing processes, especially when the material is utilized in high purity. At the same time, results of these experiments supported some of my theories regarding to required characteristics of the ideal clay body for the glassblowing process.

Experiments with chamotte and raku clay bodies were informative material test, resulted with limited success and apparent problems. Moreover, outcomes of these experiments settled some of the most important requirements of the project for both qualities of ceramic materials, and steps of glassblowing process.

Experimentation with cordierite-based mixtures is the longest and most significant section of this research, which can be regarded as the core of this project. All previous steps supported the successful development of this clay formula, and its applications. Being able to work with a clay, which could withstand the glassblowing process, enabled theexpans of my experiments in glass studio. As a result, the project took a step further, and started focusing on possibilities with the ceramic and glass combination in terms of functional and aesthetic potential of these materials such as textures, combinations, details, and finishes.

Final tests made with Lithium based clay body became a valuable contribution to this research on two levels. On the one hand, samples created with this material performed successfully in glassblowing tests and proved its potential under these thermal conditions. On the other hand, these experiments also pointed out how workability problems can limit the potential of an otherwise fascinating material.

Recipe calculation process is the initial signifier of the dialogue between three stages of this research. Clay body recipes developed in ceramics lab aims to provide a suitable and effective ceramic material for producing thermal shock resistant ceramic wares, which were designed for glassblowing processes. All empirical testing and production made in ceramic studio and glass studio provides feedback to the results in ceramics lab, helping to adjust and refine the clay body recipes for the project, creating a circular pattern of feedback and improvements.

All these steps of the research project demonstrate that, experiments can yield some ancillary outcomes outside of the main objectives of the research. Thus, it is crucial to analyse the actions and the consequences of each step of the research process, in order to identify this explicit knowledge, which can remain unnoticed otherwise.
Glass

Glass is the second focal point of this thesis project. In this chapter, glass is discussed on multiple levels such as material qualities, production techniques and aesthetics in the context of contemporary glass design field and this research project.

Due to difference in their nature and working conditions, ceramics and glass demanded different approaches in terms of researching process and documentation. The process in ceramics followed a material research route: developing for new material formulations, preparing clay batches, producing test pieces and samples. All these actions experienced individually through a hands on a process, thus documented and analysed as individual practices and experiences.

The research process in glass followed a different route. Since in the glassblowing sessions, I have always worked with a glassblower, my role shifted to a participator in the process, instead of the sole practitioner. Moreover, the research in glass focused on adapting the existing traditional glassblowing practices to a new process, involving with ceramics, and results with a new material combination. As a result, in the glass chapter, existing practices, methods, tools, and knowledge in the glass field is presented and reflected upon, along with the experimentations, observations and possible contributions made during this project.

It is important to underline that, discussions regarding to glassmaking techniques, material capabilities, equipment and work environment are based on glassmaking by glassblowing professionals in studio environment. As explained in Context of the Research chapter, automated production methods are outside the scope of this research project.
A General Perspective on Glass

Glass is a material with numerous applications and a well-established place in our daily lives. A glass object is present in almost every space: tableware, windows, mirrors, mobile phone screens, laboratory equipment, art objects to name but a few. What gives glass its appeal and wide usage area is its unique characteristics as a material. While glass is well known for its abilities such as containing and remaining unaffected by most liquids or being heat resistant, initially glass came to prominence due to its relationship with light, most importantly its transparency. Light can pass through clear glass without distortion; but we can also manipulate light by using special glasses. Light beams can be bent by a lens of a microscope, or scatter and diffuse to light up a room through a light bulb. Because of these characteristics, glass established a wide usage in most parts of the world for almost 5000 years.

During this near five-millennium period, glass has been researched extensively, and produced in numerous ways. Our understanding of the glass as a material and our capabilities of utilizing it for various functions are in constant development. Aside from transparency, or the physical and chemical capabilities, there are many other aspects of the glass, which makes it an intriguing material.

Glassmaking process is regarded as fascinating as the material itself for many people, if not more. The public interest in glassmaking had a recent emergence, due to peaked interest in craftsmanship in contemporary design field. For a craft enthusiast, glassmaking process is an awe-inspiring sight to see. It is a quite performative process, requiring skill, experience, coordination and impeccable timing from the glass artist or the technician. Furthermore, it requires specialized working environment and machinery due to extreme working temperatures. These requirements raise the participation threshold of glassmaking process for the craft and design enthusiasts. Thus, due to these extensive requirements, working with hot glass is a rare and fascinating skill for the public. These intriguing aspects of production process and rarity of people working with the material, further supports the interest in glass, as a curious and fascinating material. In the following section, material qualities of glass are explained briefly, in order to create a better understanding of this curious material for the reader.
Material Qualities and Types of Glass

According to Cummings (2002), glass is a material that can be defined as a melted silica based solution (p.38). While it is possible to find naturally occurring glass types such as volcanic obsidian glass, the glass material most people are familiar with is the synthetically developed substance. It is possible to produce glass by combining many different materials; however, silica remains the main component of the most glass types we know. Through mixing silica with other minerals, numerous glass types have been synthesized and produced: soda lime glass, borosilicate glass, lead glass, aluminium silicate glass to name a few. In the context of this research, only soda-lime glass is utilized in production and thus it is the most relevant glass type among others.

Soda-lime glass is a mixture of silica, sodium oxide, calcium oxide, magnesium oxide, aluminium oxide, and boron oxide. According to Littleton (1971), in soda lime glass, sodium oxide provided by soda ash modifies silica and this mixture is stabilized with the addition of calcium oxide. Other compounds such as magnesium oxide, aluminium oxide and boron oxide can be added to provide chemical stability or adjusting working range of the glass (p.53). Soda-lime is a transparent glass type, which accounts for the mass majority of glass production in the world. It is utilized in the production of window glasses, incandescent light bulbs, and tableware and glass artworks. In production of these various types of goods, chemical composition of the soda-lime glass is changed according to functional and technical requirements of the object. Details regarding the chemical formulation of soda-lime glass is outside of the scope of this research, since experimentations with glass formulas are in the field of material sciences and rarely practiced in studio glass context. Instead, various physical characteristics of this glass type, and their impact on glassmaking is more relevant for this research.

Viscosity in molten state is one of the most significant characteristics of glass. Glass types can be categorized as short glass and long glass based on their viscosity levels. Working range of the glass can be defined as, the range of temperatures between where glass begins to soften, and the point where glass is too soft to control and shape. This range is directly connected with the viscosity of the glass.
Short glass can be described as low viscosity, and quick-setting glass, which has a working temperature falling between two narrowly spaced margins. Short glass is the ideal choice for fast production and mass manufacturing.

Long glass, conversely, is a highly viscose glass and remains workable in a wide temperature range. Due to its slow setting, long glass is ideal for complex production processes, thus in art glass production and in studio environment long glass is preferred over short glasses.

In the context of this research, viscosity of the glass is determined in comparison with other glass types, instead of numeric values. For example, in the early stages of this research project, Glasma 48C was the type of glass utilized in Aalto University glass studio, however after 2 months it is replaced with Cristalica Studio Glass 100. Cristalica has a longer character compared to Glasma, thus remain workable in wider temperature range.

This change in workability range had a significant importance in this project. In the previous tests, timing window for the blowing process was quite narrow. If the glassblower or the assistant was late only for a few seconds, glass could have been too hot or too cold to blow inside the ceramic. The cooling effect applied by the ceramic onto the glass surface on contact points, made the timing even more important. The longer character of Cristalica glass allowed a wider working temperature range, thus provided a more forgiving glassblowing process and working environment.

Changing the glass type reflected positively upon the results of production process. After the change, the amount of glass pieces got broken during the annealing process reduced significantly. Additionally, since Cristalica remains workable in a wider temperature range, the number of times glassblower needs to reheat the glass decreased, which in turn resulted with faster production processes. Impact of viscosity difference can also be observed on the objects created from both materials. According to glass artist, lecturer and project advisor Kazushi Nakada, due to longer and softer character of Cristalica, it is easier to create glass objects with lighter structures and finer wall thicknesses, especially by using bench-blowing techniques.

Differences between these two soda-lime glasses from two different manufacturers are not limited to the viscosity. Although, both Glasma and Cristalica are clear and transparent glasses, due to the difference in their mineral composition, each have their unique colour tint. While objects made out of Glasma have a cooler tint in blue tones, objects made out of Cristalica had a warmer tint in more earthy tones. The difference in tint among these glasses are in nuance levels and are only apparent when two the materials are examined side by side.
Glassmaking

Glassmaking has over 5000 years of heritage, and during this period, numerous techniques and methods developed for it. Traditionally, glass production is categorized under two distinct segments: hot working and cold working. According to Cummings (2002), “Historically, there has always existed a natural organic division between hot and cold glass processes.” He states that cold work technologies apply reductive processes, which shapes glass through abrasion. Most of these technologies were initially developed for shaping other materials, such as stone and metal, have been adapted and repurposed for glassmaking. In this sense, cold working in glass have historical connections with sculpture, jewellery and lapidary (Cummings, 2002 p.1).

Hot glass processes are more reflective of the unique material characteristic of the glass compared to cold working. Scientifically glass is categorized as a “non-crystalline amorphous solid”, which has a mobile character and behaves similar to liquids. Precise viscosity of the glass can be triggered and controlled by heat. Hot glass production methods utilize the changes in glass structure under the effects of heat, in order to create forms and volumes. This approach is unique for glass, compared to production techniques of other materials.

Hot glass production techniques are glassblowing, casting, static pressing, mobile pressing, stretching, centrifugal forging, lamp working, core forming, fusing and bending

Cold working techniques: grinding, engraving, polishing, sandblasting, cutting

An attempt to discuss about all these techniques and methods in detail would be a substantial challenge and out of place for this research. Instead, at this point it is more practical to narrow the scope of this research and focus on glassblowing, which is the most significant and important technique for this project.
Glassblowing Techniques

Glassblowing is a production process, which is generally carried out by a group under direction of a gaffer (lead glassblower). This process utilizes the fact that it is possible to inflate hot glass with air to create a bubble, which is controlled and shaped by rotation and application of heat. Tools and machinery utilized during the glassblowing process are explained in Appendix - B: Glass Studio Tools and Machinery.

Glassblowing methods separated to two groups based on shaping methods: freeblowing and mouldblowing. These two methods are explained in detail in following sections.
Freeblowing

Freeblowing is a glassblowing method, in which glassblowers give shape to the object with through their hands, and hand tools. In freeblowing, entire production process depends on skill, knowledge and experience of the glassblower, or the team working on the object. As a result, freeblowing emphasizes and demonstrates the handmade quality, and craftsmanship in glassmaking. It is a time-consuming production method, which is mostly allocated for artistic objects or prestige products. However, freeblowing techniques also frequently utilized for form and material explorations, experiments, prototype making among other areas.

Skill and experience of the glassblower is emphasized in the freeblowing techniques, since, the only guidance for giving shape to glass is the tacit knowledge and experience of the craftsman. Depending on the design of the object, freeblowing process can be quite complex and involve many steps. Glassblower plans the process systematically, managing every action required in the production. While making the object, glassblower employs various hand tools for shaping and controlling the glass bubble. These tools are as jack, shears, wet papers, blocks, puffer to name a few.

Freeblown glass objects have softer forms and more organic aesthetics compared to mouldblown objects. This softness is related with the tools and techniques utilized in the freeblowing production. This can be observed in drinking cups produced with freeblowing in comparison to mouldblown examples. Traditionally, if the rim of a glass object is handmade, through punty process and cutting, a very soft and organic rim is acquired. Historically, these soft rims were desirable especially for drinking cups. However, in mouldblowing, rim is acquired by flame cutting, which results with a very sharp and geometric finish.

In the context of this research project, freeblowing methods mostly utilized during the later stages of the process. Details of the application will be explained in the Steps of Production section.
Mouldblowing

In mouldblowing, final shape of the glass object is given by inflating the hot glass bubble inside a mould. As discussed in previous sections, hot glass is quite soft in high temperatures, and sets into a form when cooled down. The cooling down effect is quite rapid in mouldblowing due to the temperature difference between glass and the mould. Thus, through blowing and rotating the hot glass inside the mould, glassblower replicates the inner shape of the mould with hot glass, which sets into form while cooling down. Moulds enable replicating the same form repeatedly; thus allow standardized and serial production in glass studio. Additionally, compared to freeblowing, mouldblowing require less skill in production, and it is a more time-efficient process.

Mouldblowing has different technical requirements compared to freeblowing. While glassblowing skills are still quite valuable in mouldblowing, mouldmaking capabilities also have great significance. Because, quality of the mould is quite important in determining the quality of the outcomes. Thus, designing and producing high quality moulds is an important skill, and a necessity for the success of mouldblowing process.

One of the key differences between mouldblowing and freeblowing is the types of shapes that can be produced with each technique. While some forms and textures are unique for mouldblowing techniques, there are certain forms, which require freeblowing techniques exclusively. For example, for a long time aesthetics of glass objects were determined by the centrifugal force of freeblowing, which resulted with cylindrical or spherical forms for all glass ware. Through adoption glassblowing moulds, glassblowers started producing forms that are more geometric, and with sharper edges. (Cummings, 2002, p. 79-80)

Mouldblowing processes can be categorized based on the blowing technique and mould type as turn-around and still-blown methods.

In turn-around technique, the glass bubble is inflated and rotated inside the mould, which fully replicates mould’s inner form. This technique and mould type is ideal for producing symmetrical objects. The surface of the mould creates high quality, polished and smooth glass surface.

Shapes produced by still-blown technique does not allow turning the glass inside of the mould, whether because of the form or the texture desired to be created. Instead, glass bubble is only inflated inside the mould and taken out. If it is possible to take out the blown piece out of the mould by pulling out, a single piece still-blown mould is preferred. However, if pulling out is not possible due to form or the texture of the object, a multi-piece mould is utilized for the production.

In this research project, mouldblowing techniques had a quite significant role throughout the process. From initial material tests to final exhibition pieces, mouldblowing bubbles were prepared and blown into ceramic pieces, which were acting similarly to moulds. In most cases, these mouldblowings can be categorized as still-blown pieces. Still-blowing technique is utilized due to irregularities in ceramics pieces. Since most of the ceramics pieces have strong textures, asymmetrical shapes or closing forms, rotating the glass bubble is either impossible or unnecessary in this process.

While mouldblowing methods were crucial for the production process, without freeblowing methods they were limited for this project. One the key aspects of the process was bringing together elements from both methodologies, and creating artworks with the hybrid method.
Hybrid method

In the context of this research, techniques from both mouldblowing and freeblowing are incorporated to develop a “hybrid” glassblowing method. In hybrid method, while top half of the glass is shaped with freeblowing methods, bottom part of the glass is shaped by the ceramic piece, which is acting as a mould.

This result is achieved by, first, creating a glass bubble with freeblowing technique and shaping the top part of the glass in the form of final design. At the same time, by using blocks and wet newspaper, shaping bottom half of the glass to a size that can fit inside the ceramic piece. This glass form, then dipped and blown into the ceramic piece. As the bottom part of the glass expands, it replicates the inner form of the ceramic piece, and creates a connection between two materials. Objects created with this hybrid method, relies on knowledge and experience in both glassblowing methods, along with ability to improvise and adapt based on requirements of each object.

Principals of hybrid method, which briefly described in this section, are articulated with detail in the following chapter about the steps of production.
Glassblowing Experiments

Steps of production

The glassblowing process utilized in this project is described as the “hybrid method” in previous chapter. The hybrid method brings together techniques from both freeblowing and mouldblowing in various steps of the production. As described in glassblowing techniques chapter, mouldblowing and freeblowing methods have many similarities and nuances in their production steps. Thus, in most cases, it is not possible to identify in which step freeblowing ends and mouldblowing starts. Both techniques are interconnected during the making process.

Production steps of glassblowing method evolved and changed throughout the project, as the research into materials, their behaviour and relationship observed more thoroughly. In each iteration new steps added, existing steps altered or eliminated to create a more efficient and reliable production method. These changes in process occurred incrementally; however, it is possible to group them as five iterations of glassblowing processes employed throughout this project.
The first iteration of the glassblowing process is applied at the initial stage of glassblowing tests. This process had the following list of actions:

- Ceramic piece preheated in the annealer to 500°C, 2 hours before blowing session.
- The glassblower prepares a small glass bubble.
- The glassblower shapes bottom part of the bubble in a form and size, which can fit to the opening of the ceramic piece.
- When the glass bubble is ready, assistant takes the ceramic piece out of the kiln with a hand tool, and holds it slightly above a graphite block.
- Glass is blown inside the ceramic and two pieces are joined together.
- Ceramic-glass combination goes into annealer for a controlled cool down.

This initial process devised to act as a fast and efficient method for testing the compatibility of the ceramic clay body with the hot glass. It was utilized during the tests with porcelain, earthenware, stoneware and Zirconium oxide clay bodies. Preheating to 500°C is applied in order to reduce the amount of thermal shock to ceramics.

This first iteration of process had numerous problems. First of all, it required a 2-hour waiting period before the glassblowing session due to preheating, thus limited the ability of improvisations in studio. Handholding the ceramics was not an efficient and precise method during the glassblowing, which made it difficult for glassblower to aim the opening of ceramic piece to blow into. Due to unsuccessful results, this process altered in several aspects, which resulted with the second iteration of glassblowing processes.
Second iteration followed this list of actions:

- Ceramic piece pre-heated in electric kiln to 800°C, 3 hours before blowing session.
- The glassblower prepares a small glass bubble.
- The glassblower shapes bottom part of the bubble in a form and size, which can fit to the opening of the ceramic piece.
- Either a hotplate or a burner is positioned to keep a graphite block hot during the production process.
- When the glass bubble is ready, assistant takes the ceramic piece out of the kiln with a hand tool, and places it onto the graphite block, under the burner flame.
- Glass is blown inside the ceramic piece, and two pieces joined together.
- Ceramic-glass combination goes into annealer for a controlled cool down.

This second iteration of glassblowing process resulted with some of the earlier successful blowing sessions. It is utilized in experimentations with Aluminium oxide, Chamotte, Raku and Andalusite-Olivine based clay bodies. This glassblowing method is also the start of fusing connection type between ceramic and glass, which detailed in form analysis chapter. In short, when the ceramic and glass are joined together above 800°C, they start to create a type of physical connection in which both materials start to melt towards and stick to each other. While fusing is a unique method of combining ceramics and glass with high potential, this process also had many downsides. The percentage of failure was still quite high; in many cases, ceramic and glass pieces showed signs of cracking or breaking after the annealing. Heating up the ceramics to 800°C prolonged to production process for 3 hours due to pre-heating time. As a result, second iteration of glassblowing process became the glassblowing method specialized for fusing connections, and applied when the design required this type of connection. However, due to its shortcomings other glassblowing processes developed with different settings and actions.
Third iteration of glassblowing process is strongly related with the developments in ceramic clay body. As the success rate of clay bodies improved with the fusing method, I started to modify the glassblowing process in order to achieve a faster and more efficient production process. The advancement reached to a point where preheating in the kiln became unnecessary, and thus replaced with a quick pre-heating with the burner. Additionally, as the ceramics started to withstand the thermal shock, it became possible to work on more complex glass designs, and increasing the size and scale of the objects produced.

Following list is the steps of third glassblowing process:

- Ceramic piece placed on a graphite block and pre-heated just before blowing session.
- The glassblower prepares a glass bubble, matching the size of ceramic piece.
- The glassblower shapes the top part of the glass piece with freeblowing methods, based on the design of the object.
- The glassblower shapes bottom part of the bubble in a form and size, which can fit to the opening of the ceramic piece.
- After the shaping, glass bubble is blown inside the ceramic piece.
- If the ceramic part has a narrow opening, ceramic-glass combination bonds with a form connection and goes into annealer together for a controlled cool down.
- If ceramic part has a wide opening, ceramic-glass combination develops a perfect fit, and joins with fitting combination. In this case, glass is taken out of the ceramic and placed into annealer by itself, for a controlled cool down, while ceramic piece cools down in room temperature separately.

Third iteration of glassblowing process mostly employed for Cordierite-like clay bodies, and resulted with many successful test pieces and artworks. Both form connection and fitting connection methods had developed while working with the third iteration of glassblowing process. During these tests, a reliable durability and tolerance demonstrated by cordierite clay bodies, thus for the fourth iteration of the process, entire preheating stage is abandoned. In addition, further production steps implemented to examine possibilities and limitations of the process.
Fourth iteration followed this list of actions:

- Ceramic piece placed on a graphite block in room temperature.
- The glassblower prepares a glass bubble.
- The glassblower shapes top part of the glass piece with freeblowing methods, based on the design of the object.
- The glassblower shapes bottom part of the bubble in a form and size, which can fit to the opening of the ceramic piece. However, in this process bottom part of the glass is kept thicker than previous methods.
- Studio assistant prepares a punty.
- When the glass piece is ready, it is blown inside the ceramics.
- The glassblower reheats the glass ceramic combination in glory hole.
- Glass ceramic combination piece has transferred onto the punty.
- The glassblower opens up the form and inflates it with a puffer. Then shapes the top half the glass by using various hand tools and freeblowing methods. During this process, both materials are reheated numerous times.
- After the shaping, the ceramic glass combination goes into annealer together for the controlled cool down.

The fourth glassblowing process emphasizes freeblowing techniques, which allows design and production of complex forms. It is a valuable method for exploring craft oriented approaches to glass design. It is the most time-consuming method of production per piece, and requires at least a team of two glassblowers participating in production. During experimentations with this method, cordierite clay bodies yielded reliable results. They withstood the thermal shock caused by the contact of hot glass, and reheating inside the glory hole. However, as the length of the process increase, the risk of damaging either glass or the ceramic part also increased due to accumulative tension.
Fifth and final iteration of glassblowing process is the streamlined approach of fourth iteration, and introduced the colouring elements. Based on the colorant this process have different two versions:

1. Colour Bar

- If the source of glass colour is a bar, first, a small colour disc is cut from the bar with the diamond saw.
- Colour disc is preheated in annealer for 30 minutes to reach 500°C.
- Ceramic piece is placed on a graphite block.
- The glassblower picks up the colour disc, and prepares a glass bubble.
- The glassblower shapes the top part of the glass piece with freeblowing methods, based on the design of the object.
- The glassblower shapes the bottom part of the bubble in a form and size, which can fit to the opening of the ceramic piece.
- When the glass piece is ready, it is blown inside the ceramics to create the fitting connection, or the form connection.
- Resulting object is annealed according to the connection type between ceramic and glass.
2. Colour Powder

- If the source of glass colour is a powder, the powder application deck gets prepared in blowing area. Application deck includes a sieve for applying the powder, a tray for gathering the powder and the ventilation system for collecting the loose powder.
- Ceramic piece is placed on a graphite block.
- The glassblower prepares a glass bubble.
- Depending on the powder type, glass bubble is coated with colour powder with 1 to 5 layers. After the application of each layer, the colour on the surface is melted in glory hole to achieve a smoother surface.
- The glassblower shapes top part of the glass piece with freeblowing methods, based on the design of the object.
- The glassblower shapes bottom part of the bubble in a form and size, which can fit to the opening of the ceramic piece.
- When the glass piece is ready, it is blown inside the ceramics to create the fitting connection, or the form connection.
- If the applied colour is an iridescent type, hand burner flame is applied on the glass surface for the reduction process.
- Resulting object is annealed according to the connection type between ceramic and glass.

Final iteration of the glassblowing process, resulted with the most successful and consistent results of the project. Most of the final works displayed from this project produced by utilizing fifth version of the process. It is important to note that, while this method does not allow production of fusing connections or punty processes, it is a versatile and reliable method for combining ceramics and glass together.
Glassblowing as the Testing Mechanism for Thermal Shock Resistance

In chemistry and material science, there are well-established methods for testing thermal shock resistance of ceramic materials. Among these practices, indentation-quench method is one of the most frequently utilized and reliable methods for measuring thermal shock capabilities of advanced ceramics. In her doctoral thesis work researcher Permilla Petterson experiments with indentation-quench method for thermal shock testing sialons and alumina composite ceramic materials. According to Petterson (2001, p.3):

“To evaluate thermal-shock properties, an indentation quench method was used, in which Vickers cracks are made in the material and their lengths are measured. The sample is then thermally equilibrated in a furnace at a preset temperature and subsequently quenched in a water bath. The crack growth is measured and the test repeated at a higher temperature. Experimental parameters such as sample thickness, initial crack length and water bath temperature were evaluated… The best resolution was found for a sample thickness of 4mm, an initial crack length of 100 micromillimeter and a water bath temperature close to boiling point.”

As described in this quote from the researcher, in chemistry and material science, thermal shock resistance tests devised to result with quantitative scientific data. Material samples in these experiments compared and evaluated through numeric values. While, outcomes of this methodology is quite valuable for material science, numeric data provided by these methods are outside of the scope of this thesis project. As a result, instead of using scientific methodology in thermal shock resistance tests, material samples examined in their intended usage area, which is under effects of glassblowing process.

Thermal shock resistance tests constitute an important portion of experimental research stage of the glassblowing process. In developmental stages of ceramic clay bodies, glassblowing sessions focused on testing the thermal shock resistances and compatibility of materials efficiently. Therefore, in these blowing sessions, rather than focusing on details of a specific glass form, glassblowing tests made with simple bubble shapes fitting to the openings of the ceramic pieces. First three versions of glassblowing processes actively utilized for this purpose, as the project evolved.

This experimental stage of the process designed to test the ceramic-glass interaction with a strong attention to the details. As explained in previous sections, there are many parameters and variables in glassblowing process, which can affect the outcome significantly: adding new steps to process, changing parameters, or slightly modifying production steps are just some of the ways for altering the results completely.

Considering this variety, in addition to the diversity of numerous clay bodies developed for this project, complexity of the material experimentation becomes apparent. Thus, experimental design methods were applied to this process, in order to control the level of complexity.

Considering the number of different parameters to control and modify, it is important to have consistent aspects in the process. If both sides of the parameters are changing, it is impossible to identify the reason behind successes or failures. In order to prevent this, a two-step approach is implemented. In the first step, skills and craftsmanship in glassblowing is utilized as a tool of consistency as described in ‘Handmade’ chapter. While conducting thermal shock tests, glassblowers delivered basic glass bubbles with consistent temperatures and shapes, while maintaining the blowing pressure and timing in a controlled margin.

This consistency provided the opportunity to make alterations in clay formulations and shapes of test pieces in a controlled method, which enabled maintaining the experimental design approach throughout these experiments. All clay body types tested in same glassblowing process, until consistently successful results achieved with the development of Cordierite-like clay bodies.

This development facilitated the implementation of second stage, in which these reliable clay bodies and test pieces provided the required stability for more complex experiments with glassblowing. As clay started to take over the role of anchor for the project, it became possible to change parameters of the glassblowing process. These changes included producing different forms, connections, coatings, and blowing with different temperatures or strengths. Second stage allowed further testing the thermal shock capabilities and limitations of successful materials, while working on various designs and artworks created with the material combination.

Thermal shock resistance tests made with glassblowing yielded valid and valuable theoretical information, along with material outcomes for this project. Results of this study did not generate a holistic knowledge about how these materials behave in every thermal shock situation and the conclusions are context dependent. However, in terms of developing clay body formulas and identifying important characteristics for this production process, this approach proved to be functional and efficient.
Glass and Ceramic Combination

As stated in previous chapters, bringing together ceramics and glass in one object is an intriguing technical challenge due to their well-known incompatibility. In order to overcome the compatibility issue between ceramics and glass, I hypothesized about two main approaches to follow. First, one is finding or developing materials, which behave similarly to their counterpart: either a ceramic material with quite similar character to the glass or a glass material, which imitates ceramics. Conversely, the second approach would be keeping characteristics of these materials intact, while modifying them to be more accommodating for the combination.

First approach is followed in both ceramics and glass industries for a long time, and based on the principle suggesting that it is possible to, partially, convert high-fired porcelain into a glassy phase to create translucent effects. It is also known that, glass can be partially converted into a crystalline ceramic form through controlled crystallization processes. Thus, it is possible to create an approximation among these materials in both visual and crystal structure level. For example, until 18th century porcelain was deemed a quite rare and luxury material in Europe, while glass was in abundance. This led European scientist and craftsmen to develop glass materials and items copying fine china porcelain in terms of colour, tactility and aesthetics. According to Kelly (2009, p.34), in 17th century European glassmakers produced “milk glass” or “porcelain glass” to imitate Chinese porcelain. Conversely, for centuries people appreciated glass for its transparency and clarity. As a result, many ceramists developed materials and methods to replicate glass-like qualities in their work. The translucency of finest bone china porcelain is almost an attempt to recreate the visual qualities of a glass object. While this approach has many practical benefits, in some cases it results with one of the materials losing most of their characteristic attributes and imitate their counterparts.

Second approach is also being followed by industries, studio artists and designers. This method focusses on improving physical and chemical qualities of materials for making them workable in new settings without altering their characteristic material qualities. In the context of this research, following the second approach deemed more suitable, in terms of accomplishing the project goals and resulting with more visually interesting outcomes. Considering that in this project, final artworks designed for displaying two materials combined together, each material representing their unique character is a valuable asset. Trying to make glass more similar to ceramics or ceramics more similar to glass, can result with wasting the potential visual diversity and richness of this combination. Thus, for this research it means developing ceramic materials, which look, behave and produced similar to traditional ceramics, yet modified to be able to accommodate working together with glass. On the other side, it also means, not changing the glass material or production techniques radically, but adapting them to meet the requirements of the combination.

Even the ceramics and glass produced with traditional methods and tools, when brought together in this new way, they demonstrated new aesthetic and functional possibilities in object language. Moreover, they also became starting points for further research and experimentation in production techniques utilizing these materials and methods.
Objects

Throughout this research project, numerous objects were designed and produced with ceramic and glass combination. Functionally, most of the objects created during this process were vases and containers. Main reason behind this selection is the possibilities and limitations implemented onto the form language due to this material combination.

When ceramics and glass combined, resulting object represents various characters of these materials in juxtaposition. While it is possible to design and produce each of these materials to have more geometric or organic forms, some material characteristics are inherent. The transparency, coldness and uniformity of the glass have always displayed a stark contrast with rough, textured and tactile characteristic of ceramics developed in this project. The contrasting characteristics, in my opinion, added new aesthetic dimensions to the objects designed with this material combination.

Another factor to consider is the enabling effect of the material composition. On the one hand, traditionally, ceramics are known for their ability to contain liquids, since it is their one of the most frequently utilized functions. Ceramics have this ability due to their fine particle size, surface vitrification or the glazing. Glazing can be described as covering the ceramic surface with a glass-like substance, thus in most ceramic objects we come across every day, this material combination already takes place in one point of view. Additionally, some resources claim that invention of glass is a result of the work in ceramic glazes. According to Berlye (1983), archaeologic discoveries from 6000 years ago displays usage of glass as coatings and glazes for pottery (p. 1).
As discussed in ceramics chapter, however, ceramic materials utilized in glassblowing process are quite porous and difficult to glaze. Thus, these ceramics are unable to contain water. Therefore, glassblowing process acts as a way of glazing the surface of these porous ceramics, and making them impervious to liquids.

In addition to the possibilities, this material combination embody various limitations. For example, in most cases objects made with ceramic and glass combination are slightly heavier and bulkier than an object made out of only one of these materials. The additional weight changes the feel of the object at the hand, and results with an unusual tactile effect. Moreover, since the process demands significant amount of time and skill in production, it is more reasonable to create objects that can function as stand-alone items. Due to these distinct characteristics, producing objects such as tableware out this combination is challenging.

Vases and containers are stand-alone objects, which have common characteristics with sculpture along with their functional purposes. Main function of a vase is holding and displaying flowers, while remaining aesthetically pleasant even without them. Thus, as long as the shape is able to support flowers and keep the water inside, design of a vase can be considered as a study in form and aesthetics.

During form explorations, objects such as lighting appliances, service utensils (tray, wine carafe) are prototyped and will be explored in future design projects. However, in the extent of this thesis work, vases and containers remained as the main object typologies explored.
Fitting

Fitting is the most frequently applied connection technique in this project, due to its practicality. It is the fastest, most efficient and reliable method of producing prototypes and objects when combining ceramics and glass. Fitting connection is the result of 3rd, 4th and 5th versions of glassblowing processes, which were explained in detail in Steps of Production chapter.

In fitting connection, glass piece is blown into an open ceramic object kept in room temperature. With this blowing, bottom part of the hot glass takes the exact form and details of the inner part of ceramic piece, similar to mouldblowing techniques. Due to thermal difference, glass does not stick to ceramic surface and naturally separate from ceramic part immediately after the blowing. In this connection method, glass part is annealed separately from ceramic part. Two pieces joined after the annealing. Due to separate annealing, fitting connections are the most reliable method of production, since no further damage to glass part happens in annealing process. When the objects are produced with this method, glass and ceramic parts have a perfect fitting with each other; in most cases, ceramic part is in the bottom acting as a pedestal for the glass part of the object.

This production technique, which is mostly represented in the vase collection in final works, requires proficiency in freeblowing techniques, as well as experience with timing, and temperature control among other details of the blowing process.
Fusing

Fusing is the most complicated connection technique in this project, which has taken the most amount of effort to develop into efficiency. In fusing technique, glass piece is blown into a very hot (approximately 800°C) ceramic piece. Due to their thermal approximation, ceramic and glass pieces fuse and join to each other. This connection between two parts, bring forth both possibilities and risks in the production process. On the one hand, due to thermal shock resistant quality of the specialized ceramic clay body, glass part of the piece can be shaped after the connection, which allows production of artwork or objects with forms that are more complex. For example, second iteration of glassblowing processes is one of the possible application areas for this technique. On the other hand, fused pieces have relatively high percentage of failure. In almost all cases, this failure occurs in annealing oven, where glass part got cracked or broken. Traditionally, this problem is caused by the difference in thermal contraction rate between the ceramic and glass. However, the specialized ceramic clay bodies utilized in this project developed to accommodate the proper thermal contraction rate to the glass. Still, this type of physical connection increases the chances of error, especially in thermal condition of glass and timing of actions in production. As a result, while the ceramic clay bodies developed in this project are suitable for this type of production, general success of the making process is still tied to the practice of glassblower and assistants in the process.
Form connection

Form connection is a term coined up to describe a unique type of connection between ceramics and glass, developed during this project. In form connection, glass and ceramic parts are joined together by utilizing their geometric shapes and the effect of inflation. One way of achieving form connection is, creating a long and narrow glass bubble, which is blown through a ceramic shape open on both sides. Blowing expands the glass on both sides of the ceramic, locking the ceramic part between two halves of glass part. Another method of creating a form connection is achieved by creating a ceramic piece with a wide base with a narrow opening, and a narrow glass bubble that can fit into the opening. When the glass is dipped into the ceramic and blown, the part inside of the ceramic gets bigger and gets trapped inside the ceramic. Thus, this form based connection brings two materials together. For form connections, ceramic part of the object can be shaped as ring, a cylinder, or any other form provided that the openings allow the initial glass bubble to go through.

Form connection method can be applied to both room temperature and hot ceramic pieces, depending on the design of the object. If the middle ceramic part is designed to have a fixed position, fusing is the ideal approach. However, if moving parts is not an issue, fusing method can be replaced with form connection. Weight of the ceramic piece is an important aspect to consider in form connections. Since after the physical connection, both ceramic and glass parts are on the blowing pipe, thus it creates an unusual weight imbalance for the glassblower. Moreover, glass part of the object is carrying the weight of the ceramic part throughout this process. This weight-related imbalances could cause potential problems for the object, if the ceramic part is quite heavy. While empirical tests in this project demonstrated that, safe working weight margins of ceramics is relative to the size and thickness of the glass pieces; actual calculations of ideal values should be examined in a further study. As a general principal however, thicker glass pieces in lower temperature have less tendency to deform under the weight. During this project, working with lighter ceramic pieces displayed a lower amount of risk.

Since glass part is carrying the ceramic part in form connections, it is impossible to reshape the glass parts by reheating in the glory hole, as the weight of ceramic part would deform the glass part when it is hot and soft. In this soft state, glass part loses the locking form and cause ceramic part to get loosened and eventually separate.
Side Projects

Significant amount of time and effort put into material research and experimentation resulted with many side projects, along with developments in ceramics and glass combination. Some of these projects yield intriguing preliminary outcomes and will be explored further in future research, however they will not be a part of this thesis work. Nonetheless, some of the other interesting outcomes are developed further during this process as side projects. In this chapter, samples of these side projects are briefly described to demonstrate various characteristics and potential of the materials.
Moulds Made Out of Ceramic

Making glassblowing moulds out of ceramics is not a novel idea. According to Trentinella (2003), baked clay is one of the first materials utilized for glass mould making in Roman Period. The idea of these moulds, however, derived from the research on fitting connection technique. In fitting technique, inner surface of ceramic transfers onto the surface of glass, during the blowing process. This effect can be employed in numerous ways:

- designing patterns inside the mould,
- transferring handmade marks of thrown ceramics onto glass surfaces,
- one-time usage moulds for quite complex forms

While the initial outcomes bring forth these possibilities focusing on transferring the form and the eventual surface effect, as the project developed further possibilities emerged. For a long time, it was not possible to prevent a type of texture change on glass surface and the attempts were focused on controlling the type of effect caused by the process. After discovering the importance and effects of particle sizes in clay bodies, other possibilities emerged. Utilizing fine particle sizes in clay body, it is possible to develop thermal shock resistant clay bodies with smooth surfaces. This smooth ceramic surface type allows production of clear glass surfaces without texture, in the blowing inside ceramic process. Due to this development, a possibility of producing typical glassblowing moulds out of ceramics emerged.
Ceramic Accessories and Furniture

One of the interesting outcomes of the research on ceramic clay bodies were the physical qualities and capabilities of the specialized materials developed for this project. High firing outcomes from some of the clay bodies pointed out the effortless heat tolerance of these ceramic clays, and their ability to keep their form in extreme conditions. Due to relative ease of firing thicker ceramic pieces made out of cordierite-like clay bodies compared to traditional clays such as porcelain or earthenware, potential functions and usage areas for this material tested.

Initially, this process started with the design and creation of thick and geometric ceramic blocks to combine with glass. During this process, geometric blocks in various thicknesses and sizes produced. While working on the production and firing of these blocks, I started producing various functional objects such as candleholders, bookends and even tabletops by utilizing same techniques.

Results of this process are a collection of side tables and accessories, which displayed alongside the vases and containers, made from ceramic and glass combination in the exhibition of this project.
Exhibition

Outcomes of this year-long research in ceramics and glass displayed in a solo exhibition during Helsinki Design Week 2017, in Lobby Gallery of Aalto University Arabia Campus building. Exhibition title, Glitter & Noise, is a reference to the material qualities and visual aesthetic of the unique ceramic clay bodies developed for this project. Due to material composition of KSO-Cordierite, these ceramic pieces have a strong pattern of minuscular black and golden dots, resembling a mixture of noise and glitter.

The exhibition displayed the results of this process with a selection of vases and containers, emphasizing the aesthetic and functional possibilities of this material combination, along with a series of furniture and accessories reflecting the individual character and qualities of these unique materials.
Discussion and Conclusions

This research project is an attempt to bring a new perspective and approach to ceramics and glass design, through material research and process development.

Initially, this research did not aim to achieve any predetermined result, in terms of aesthetics or function. The information I had at the start of this project is that glass and ceramics are deemed as incompatible materials, and combining them in glassblowing process is a significant technical challenge. As a designer and researcher, I was intrigued by the potential for experimentation within this area, and possibilities emerging from this challenge. Achieving satisfactory results with the process could yield a new material, technique, or method, which can potentially lead to unique and novel outcomes. Even when the experimentation resulted with failure, I identified the value in the learning aspect of the process and expected to understand the characteristics and intricacies of these materials through this project. Thus, in this situation delving into the unknown did not have any significant disadvantages. In my opinion, this is one of the significant benefits of working with materials in a hands-on, experimental process.

After this longitudinal study, I managed to develop ceramic clay body formulations, which are compatible with glassblowing process and implement an effective and reliable glassblowing method for this combination. Outcomes of the research can be summarised with following ten points.

1. Glassblowing process require thermal shock resistant and durable ceramic clay bodies with open structures.

2. Openness of a clay body can be increased with the addition of suitable thermal shock resistant components, with different particle sizes, into the formula.

3. Particle size of the components is a quite important aspect in determining the structure, aesthetics and function of a clay body.

4. Clay body compositions made from purely thermal shock resistant components (Zirconium, Alumina) did not yield successful results in the context of this research.

5. Workability of a clay body is as important as the physical and chemical qualities of the material, especially in studio production.

6. Cordierite based clay bodies displayed most successful and consistent results in glassblowing tests, while maintaining a good workability in various production methods such as slip casting, throwing and hand building.

7. In the glassblowing inside ceramics process, both freeblowing and mouldblowing techniques have significant importance.

8. Communication, dialogue and teamwork are crucial in glassblowing process for productive sessions, especially in experimental processes such as this project.

9. Ceramics and glass can be combined with various connection methods. A permanent physical bond can be achieved with fusing; a form connection can be realized through inflating the glass bubble through ceramics; and a perfect fitting connection can be created by blowing part of the glass inside the ceramics.

10. Through material combinations, I believe it is possible to develop a new form language and aesthetic style by utilizing traditional materials.
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Appendix - A: Method for Clay Body Calculation

Clay body recipes can be formulated with both singular and complex components. Singular components are single raw ingredients such as silica (SiO$_2$), or Alumina (Al$_2$O$_3$). Through utilizing singular components, chemical formulations of clay bodies can be calculated with basic mathematical operations. Complex components however, include many raw ingredients in their formulation and have an existing crystal structure. In current practice, many of the ceramic material manufacturers produce these complex components with specialized formulations, and act as suppliers for ceramic artists and designers.

Complex components have chemical data sheets provided by their manufacturers, which have significant importance in recipe calculation. For example, a ball clay produced by IMERYS is a frequently utilized component in this research project. According to data sheet, material distribution for the IMERYS Hyplas64 Ball Clay is:

- Al$_2$O$_3$ 24%
- SiO$_2$ 63%
- K$_2$O 2.5%
- TiO$_2$ 1.6%
- Fe$_2$O$_3$ 1%
- Rest 1% <

Depending on the clay recipe, many complex components such as Hyplas 64 Ballclay are added to the mixture in various percentages, which increases the intricacy level of the process.

There are different practices and methods for recipe calculation among material scientists and craft practitioners. In this project, a software called Insight is selected among other alternatives due to its availability in Aalto University ceramic studio. Recipe calculation with Insight constitutes several steps, which can be explained with a practical example from this research project:

One of the most significant recipes developed for this project belongs to cordierite-like clay bodies. In development of this clay body, there were two important data points available: chemical formulation of cordierite and an ideal weight distribution of its components, provided by resources from ceramics industry datasheets and reports. The challenge was developing a clay body meeting with these two data points, by utilizing the materials available in the ceramic lab.

In order to achieve this purpose, first, chemical composition data for all related components are recorded into the Insight software database. In the Fig.61, mineral composition of Olivine (Oliiviini in Finnish) is depicted.
In second step, chemical formulation and ideal weight distribution data has entered into related fields on the software interface as reference points. For this example, reference points for calculation are the values of MgO, Al₂O₃ and SiO₂ in the mixture, since these compounds are the most important aspects of the cordierite formula. In Fig.62, these values are taken place on second column.

In third step of the process, materials in database were added to the recipe in various percentages. Then, these percentages were adjusted until a close approximation is found between the reference points and values from the recipe. In Fig.63, values of compounds such as MgO, Al₂O₃ and SiO₂ on the first column are being adjusted to match the reference values in second column. Other compounds such as CaO, K₂O, TiO₂ and Fe₂O₃ considered as impurities in this formula, which are introduced by the complex components in the mixture.

In the final step, the recipe is analysed for further characteristics such as workability and impurities. Based on the results of this analysis, recipe is refined and adjusted. For example, if the calculated clay body has a very low percentage of plastic clay such as Hyplas 64, it would be very hard to shape, which limits its workability and usefulness. This problem can be prevented by increasing plastic clay percentage and recalculating the recipe. Same recalculation can be necessary due to high percentage of impurities such as iron oxide (Fe₂O₃) in formulation. Since iron oxide weakens the clay body in higher temperatures, it is a damaging component, which needs to be limited in thermal shock resistant ceramics. As a result, if the analysis demonstrates a high amount of iron oxide, amount of components containing iron as impurity, such as Hyplas 64, needs to be reduced in formula. Thus, the recipe needs to be recalculated accordingly.

These two examples underline an important characteristic of recipe calculation, which is balancing the values and compromises. Material in this example, Hyplas 64 Ball Clay, on the one hand improves workability, and on the other hand weakens the strength of the clay body in higher temperatures. All mineral components present similar dualities; hence, the refinement of the recipe calculation is an intricate process. As a conclusion, while in theory clay recipes can be calculated with a software; making empirical tests for observing the effects of changes in the formulations, and relationships of the components is a fundamental necessity, in order to refine and adjust optimal clay body recipes.
Appendix - B: Glass Studio Tools and Machinery

In glass studio, tools and machinery have a significant importance due to unique working conditions of the material, in terms of temperature and production processes. While some of the tools are prerequisites and indispensable for every studio, some of these requirements may differ in various studios, based on the techniques utilized in production.

In glassblowing, even if the objects are classified as handmade, the glassblower is not in direct contact with the material. Instead, entire process requires various tools acting as proxies. The touch of maker is reflected on glass by a piece of wet paper, a squeeze of shears, or a tightening of jack. The air, which fills and inflates the glass bubble, is directed through the blowing pipe or the curved puffer. In following section, most of the glass studio tools used in the context of this research are briefly introduced in alphabetical order. In these descriptions, along with my personal experience with these tools, information from An introduction to glassblowing by Elisabeth Flygt (2005, p. 126-133) and descriptions in Glassblowing: Search for Form by Harvey Littleton (1971, p. 58-73) were valuable resources.

**Machinery**

**Annealer (Annealing Oven):** Annealer is a type of oven, utilized in glass studio for cooling down hot glass pieces to room temperature, with a controlled programme. Glass pieces produced in hot production methods, such as glassblowing or sandcasting, requires a controlled cooling down process in order to prevent structural stress. Shaping process results with substantial temperature differences in various sections of the glass piece, due to poor heat conductivity of the material.

For example, when a glass bubble is heated up inside glory hole, sections of the object, which are closer to pipe are much colder, compared to the bottom half of the glass bubble. Similarly, when the burner is applied to a section of the glass piece, it creates a considerable temperature difference between the effected and unaffected areas.

If a glass object cools down with these temperature differences, it results with structural stress, thus the object bear a significant risk of cracking or breaking in the future. Therefore, after the blowing process glass pieces are placed in annealing ovens. In this project, annealers were all programmed to cool glass pieces down from 500°C to room temperature in a 24-hour window.

In the context of this project, annealing process carried an additional level of complexity because of the material combination. The type of connection between the ceramic and glass parts of the artwork has effects on the annealing process. If the ceramic part has an open form, it is only utilized as a mould for the bottom half of the glass during the shaping, and two materials separated before annealing. Thus, the annealing process of the glass is not different from the typical annealing process. However, in many cases, ceramic and glass pieces are physically joined together during the blowing stage, hence required to be put into annealing kiln together. As detailed in Form Analysis of the Objects chapter, there are two different types of permanent physical combinations in this project: fusing and form connections. When ceramic and glass are joined together with fusing, annealing process have the highest risk, in terms of cracking the glass part. This problem causes the failure of many other ceramic and glass combination experiments due to material incompatibility, along with the initial tension occurring in materials during the blowing.

Compared to fusing, form connection is the more reliable and safer method of connection, according to numerous production tests during this project. Almost all objects created with form connection method survived the process without further stress or cracks occurring during the annealing.

**Electric kiln:** Electric kilns in glass studio are mostly utilized in kiln castings techniques, and for heating glass pieces. During this project, these kilns are employed for preheating ceramic pieces up to 800°C.

**Glass furnace (Pot):** Glass furnace, or the pot, is the heart of a glassmaking studio, where the glass is melted from raw materials into the liquid molten state. Historically heated up by wood fire, today pots can use electricity, oil, or gas as energy sources. A typical glass furnace for a small studio can contain 50-150 kilograms of glass.

**Glory hole:** Glory holes are important heating elements in the glass studio, used for reheating glass pieces during the production process. In this project, glory holes had also acted as a secondary testing element for thermal shock capabilities of the ceramic pieces. After glass and ceramic parts joined together with the blowing, the material combination is reheated in glory holes for further shaping the glass part. In addition, glory holes were a significant tool in controlling the reduction process, and heating of iridescent coloured glass pieces towards the end of the design process.
Pipe Turner: Pipe turner is an electric machine, which automatically turns the blowing pipe and keeps the glass piece centred without the glassblower. In this project, pipe turner is employed during powder coating and colouring step of the glassmaking.

Tools:

Air: Air is a unique and fundamental tool in glassblowing. As the name of the act suggests, air from the lungs of the glassblower, or a compressor, fills the hot glass bubble and gives it shape. It is also utilized for cooling the glass down, and controlling the temperature.

Blocks: Blocks are wooden tools in various sizes, which are utilized for shaping the glass bubble in various stages of the glass blowing process.

Blowing pipe: Blowing pipe is the main tool of a glassblower. It is an approximately 1-meter long pipe, which has two ends with specific functions. The nose is where the molten glass is gathered, and the mouthpiece is where glassblower blows air inside the glass for shaping the glass piece.

Burner (Torch): Burner is a handheld heating element utilized in glassmaking. Torches are versatile tools with various purposes. They provide focused and zonal heating on selected parts of the object. Additionally, they can also be applied for balancing the temperature changes especially in neck area of a glass object. In this project, torches are also used in the reduction process of iridescent coloured glass pieces.

Calipers: Caliper is a measuring tool utilized in glassmaking.

Colour bars and powders: There are two common ways of making coloured glasswork. First method is melting a pot full of coloured glass to produce coloured glass objects. Second method is adding colorants such as colour bars and powders to clear glass. Throughout this project both colour bars and powders employed as colorants.

Graphite blocks: Graphite blocks are used as pedestals for placing hot glass and other hot objects during glass production process. Graphite can withstand the temperature differences of the process, while also providing a clean and smooth surface to prevent impurities and other harmful effects.

Jacks: Jack is a hand tool similar to tweezers, which gives shape to the glass by squeezing.

Moulds: Moulds are fundamental glassblowing tools, which are utilized for giving the final shape to a hot glass bubble. Traditionally moulds are produced from materials such as wood, metal and graphite, while various materials such as plaster or concrete are also used with varying levels of success. Details of utilization of moulds in glassmaking is explained in Mouldblowing chapter.

Paddles: Paddle is a wooden hand tool, which is utilized for two separate functions. First, it is used for smoothing and flattening the bottom part of glass objects in blowing process. In its second function, assistant uses the paddle as heat shield to protect glassblower’s hand from the heat coming from hot glass during the shaping process, especially in freeblowing.

Punty: Punty is an iron rod utilized for controlling hot glass. In its general purpose, glassblower can pick up molten glass from the pot with a punty. Punty can be a transfer tool in glassblowing process. When an object is shaped on the blowing pipe, form giving is mostly focussed on bottom half of the object, where the glass is hottest. The glass object on the pipe can be transferred onto a punty for further shaping the other end of the piece. Punty is also utilized for picking up hot colour bars from the annealer, or the electric kiln.

Scissor Tong: Scissor tong is a specialised hand tool for picking up and handling hot objects such as colour melting pots in glass-making processes. In this project this tool is used for picking up and carrying ceramics pieces during production.

Shears: Shears are a group of hand tools, which works with scissor principle. Depending on their shape, shears have various functions in shaping and trimming hot glass.

Wet newspaper: Wet newspaper is a common tool of protection used by glassblowers to help them shape the glass by hand.
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