The rapidly growing public concern and awareness on issues related to climate change, has forced a fast shift across several industries toward more sustainable practices and products, namely the transportation sector. In the referred work, a variant of an alternative dissimilar material joining technology has been investigated. Designated as Friction Riveting, this process allows multi-material overlapping joints to be performed in a fast and relatively simple manner. One variant of this process is designated as force-controlled. The work studied how the parameters, influenced the amount of energy applied to the materials being joined. Statistical analytical models were established, allowing the production of fine-tuned joint formation and resulting mechanical performance. The knowledge gathered in this investigation has further demonstrated the potential of friction riveting for dissimilar material joining and allows the process to be considered for a wide range of industrial applications.
Energy Efficiency Based Analysis and Optimization of Friction Riveting

Goncalo Pina Cipriano

A doctoral dissertation completed for the degree of Doctor of Science (Technology) to be defended, with the permission of the Aalto University School of Engineering, at a public examination held at the lecture hall K1/213a of the school on the 18th of October 2019 at 13 o'clock.

Aalto University
School of Engineering
Department of Mechanical Engineering
Supervising professor
Professor Pedro Vilaça, Aalto University, Finland

Thesis advisor
Professor Sergio Amancio, Graz University of Technology, Austria

Preliminary examiners
Professor Dulce Rodrigues, University of Coimbra, Portugal
Professor Jean Pierre Bergmann, Ilmenau University of Technology, Germany

Opponent
Professor Dulce Rodrigues, University of Coimbra, Portugal
**Author**
Goncalo Pina Cipriano

**Name of the doctoral dissertation**
Energy Efficiency Based Analysis and Optimization of Friction Riveting

**Publisher** School of Engineering

**Unit** Department of Mechanical Engineering

**Series** Aalto University publication series DOCTORAL DISSERTATIONS 184/2019

**Field of research** Engineering Materials

**Permission for public defence granted (date)** 2 September 2019

**Abstract**
The rapidly growing public concern and awareness on issues related to climate change, has forced a fast shift across several industries toward more sustainable practices and products. Industries which have been some of the most challenged on this regard are those in the transportation sector. Here, designs and engineering solutions have been forced to be adapted at a far greater pace than usual. With this push for change, ways to integrate alternative materials and less conventional technologies, which can benefit the overall designs, are becoming a necessity rather than an option. Examples of new designs which embrace the use of dissimilar material combinations are becoming common. In order to effectively increase the use of less conventional materials, e.g. in automotive or aeronautic applications, new technologies are being developed in order to overcome the restrictions imposed by conventional methods, such as mechanical fastening and adhesive bonding. In this work a variant of an alternative dissimilar material joining technology has been investigated. Designated as Friction Riveting, this process allows multi-material overlapping joints to be performed in a fast and relatively simple manner. One variant of this process is designated as force-controlled. The present work studied how this process variant parameters influenced the amount of energy applied to the materials being joined. Design-of-experiments and response surface methodologies were applied in this investigation to maximize the knowledge gained on the fundamentals of the process, the performance of the joints produced and also on their energy efficiency. Statistical analytical models were established, allowing the production of fine-tuned joint formation and resulting mechanical performance. Optimizations on process control, energy efficiency and process parameter flexibility were achieved. Based on mechanical performance, an energy efficiency threshold was established. After this energy level, excessive rivet plastic deformation inside the polymeric plate was observed and did not contribute to an improvement in mechanical performance of the joints. The feasibility of an even more specific process approach, designated as single-phase friction riveting, was successfully and systematically demonstrated. Here, it was possible to achieve sound joints while greatly reducing the forces used during the process. This can lead to a wider range of applications for this technology, requiring less robust equipment and thus, more flexible to be integrated into production designs. The knowledge gathered in this investigation has further demonstrated the potential of the friction riveting for dissimilar material joining.

**Keywords** Friction, dissimilar, joining, riveting, energy, optimization, design-of-experiments, response surface methodology, hybrid structures


**ISBN (pdf)** 978-952-60-8755-9

**ISSN (printed)** 1799-4934

**ISSN (pdf)** 1799-4942

**Location of publisher** Helsinki

**Location of printing** Helsinki

**Year** 2019

**Pages** 120

The doctoral thesis work started on November 2015 at Aalto University and was performed in external research sites, in close cooperation with Aalto University. Namely, from the start until November 2017 at the research center Helmholtz-Zentrum Geesthacht (HZG), Germany, and since February 2017 until the end, at the Graz University of Technology in Austria. The present doctoral work aims to fill the knowledge gap related to the generation and impact of the frictional energy in the friction riveting process. The friction riveting process was invented recently at the Helmholtz-Zentrum Geesthacht and is a fast and reliable solution to manufacture dissimilar joints, between metallic rivets and polymers/composites.

I wish to acknowledge the institutional support to this thesis work via funding and high quality experimental and computational conditions made available to me, by the Helmholtz-Zentrum Geesthacht, Germany, and the Graz University of Technology in Austria.

I am grateful to the Associate Professor Pedro Vilaça, who has given me the opportunity to pursue this doctoral thesis at Aalto University. Having provided me his supervision, trust and commitment, which have helped me in achieving the work presented in this document.

I wish to express a deep gratitude towards my thesis advisor and supervisor at all the external institutions: Univ.-Prof. Dr.-Ing. Sergio Amancio. Firstly, for being responsible for the invention of the impacting Friction Riveting process and giving me the opportunity to join his research team. Secondly, for all his endless support, encouragement and teachings. It is due to his supervision, help and friendship, that I have successfully arrived at this point.

I would like to thank Prof. Dr. Jorge dos Santos, for the guidance and support, and without whom I would not have had the opportunity to start working at the Helmholtz-Zentrum Geesthacht by 2013, on the scope of my master thesis.

Also, to thank everyone who have at some point been involved in my research.

Finally, I want to express the gratitude that I have toward all those friends that have, across these years, shared this journey with me and without whom it would have been a much harder path.

To my family, for everything, goes my deepest gratitude.

Aalto, May 6th, 2019

Gonçalo Filipe Pina Cipriano
Contents

Preface .......................................................................................................................... 1

Contents ...................................................................................................................... 3

List of Abbreviations and Symbols ........................................................................... 5

List of Publications .................................................................................................. 8

Author’s Contribution .............................................................................................. 9

Original Features ........................................................................................................ 11

1. Introduction ........................................................................................................... 13

1.1 Background and Motivation ............................................................................... 13

1.2 Friction Riveting ............................................................................................... 16

2. Materials and Methods ....................................................................................... 23

2.1 Materials ............................................................................................................ 23

2.2 Joining Procedure ............................................................................................. 24

2.3 Non-destructive Testing of Joint Formation .................................................... 26

2.4 Mechanical Performance Testing ...................................................................... 27

2.5 Process Mechanical Energy Input ..................................................................... 27

2.6 Statistical Analysis of Evaluated Responses ..................................................... 28

3. Summary of Publications ..................................................................................... 29

3.1 Publication I ....................................................................................................... 29

3.2 Publication II ...................................................................................................... 31

3.3 Publication III ................................................................................................... 33

4. Ongoing Work ....................................................................................................... 37

5. Conclusions and Outlook ..................................................................................... 39

References .................................................................................................................. 41

Publication I ............................................................................................................... 45

Publication II .............................................................................................................. 69

Publication III .......................................................................................................... 89
## List of Abbreviations and Symbols

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>°C</td>
<td>Degrees celsius</td>
</tr>
<tr>
<td>AA</td>
<td>Aluminium alloy</td>
</tr>
<tr>
<td>Al</td>
<td>Aluminium</td>
</tr>
<tr>
<td>B</td>
<td>Height of the deformed rivet tip</td>
</tr>
<tr>
<td>CFRP</td>
<td>Carbon-fibre-reinforced-polymer</td>
</tr>
<tr>
<td>Cr</td>
<td>Chromium</td>
</tr>
<tr>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
</tr>
<tr>
<td>DoE</td>
<td>Design-of-experiments</td>
</tr>
<tr>
<td>Dp</td>
<td>Anchoring depth</td>
</tr>
<tr>
<td>E</td>
<td>Young modulus</td>
</tr>
<tr>
<td>Ed</td>
<td>Translation deformational energy</td>
</tr>
<tr>
<td>Ef</td>
<td>Frictional energy input</td>
</tr>
<tr>
<td>EM</td>
<td>Total mechanical energy input</td>
</tr>
<tr>
<td>EPR</td>
<td>Energy performance ratio</td>
</tr>
<tr>
<td>F</td>
<td>Axial force</td>
</tr>
<tr>
<td>Fe</td>
<td>Iron</td>
</tr>
<tr>
<td>FEM</td>
<td>Finite element method</td>
</tr>
<tr>
<td>FF</td>
<td>Friction force</td>
</tr>
<tr>
<td>F-ICJ</td>
<td>Friction-based injection clinching joining</td>
</tr>
<tr>
<td>FoF</td>
<td>Forging force</td>
</tr>
<tr>
<td>FoT</td>
<td>Forging time</td>
</tr>
<tr>
<td>FT</td>
<td>Friction time</td>
</tr>
<tr>
<td>H</td>
<td>Rivet penetration depth</td>
</tr>
</tbody>
</table>
h Height of the molten polymer layer
ICJ Injection clinching joining
J Joule
K Kelvin
k Kilo
Lo Grip distance
m Metre
M Torque
Mg Magnesium
mm millimetre
Mn Manganese
N Newton
PEEK Polyether ether ketone
PEI Polyetherimide
Qtotal Total heat input
Ro.2 Yield strength
R² Coefficient of determination
Rm Ultimate tensile strength
rpm Rotation per minute
RS Rotational speed
Si Silicon
SI International system of units
Tg Glass transition temperature
Ti Titanium
U Displacement
UTF Ultimate tensile force
Vmax Maximum velocity
VR Volumetric ratio
W Watt
W Maximum width of the deformed rivet tip
wt.% Weight percentage
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>Zink</td>
</tr>
<tr>
<td>η</td>
<td>Viscosity</td>
</tr>
<tr>
<td>θ</td>
<td>Deformation rate</td>
</tr>
<tr>
<td>μ</td>
<td>Solid friction coefficient</td>
</tr>
<tr>
<td>π</td>
<td>Pi</td>
</tr>
<tr>
<td>ω</td>
<td>Rotational speed</td>
</tr>
</tbody>
</table>
This doctoral dissertation consists of an initial summary and of the following publications which are referred to in the text by their numerals.


Author’s Contribution

**Publication I:** “Fundamentals of Force-Controlled Friction Riveting: Part I – Joint Formation and Heat Development”

The author designed, performed the experiments and analyzed all collected data; L. A. Blaga, P. Vilaça and J. F. dos Santos contributed with discussions on the experimental results; S. T. Amancio-Filho determined the structure of the manuscript; all authors contributed to the preparation and revision of the manuscript.

**Publication II:** “Fundamentals of Force-Controlled Friction Riveting: Part II – Joint Global Mechanical Performance and Energy Efficiency”

The author designed, performed the experiments and analyzed all collected data; L. A. Blaga, P. Vilaça and J. F. dos Santos contributed with discussions on the experimental results; S. T. Amancio-Filho determined the structure of the manuscript; all authors contributed to the preparation and revision of the manuscript.

**Publication III:** “Single-phase friction riveting: Metallic Rivet Deformation, Temperature Evolution and Joint Mechanical Performance”

The author designed, performed the experiments and analyzed all collected data, with the assistance of A. Ahiya, a master degree student working under the author’s supervision; L. A. Blaga, P. Vilaça and J. F. dos Santos contributed with discussions on the experimental results; S. T. Amancio-Filho determined the structure of the manuscript; all authors contributed to the preparation and revision of the manuscript.
Original Features

This work investigates multi-physical aspects of the application of friction riveting to join metallic rivets made of aluminium alloy (AA2024-T351), to polymeric plates made of polyetherimide (PEI). A force-controlled time-limited process variant was used to produce the specimens object of the study. The friction riveting process is a new solution of great scientific and industrial impact. Due to its novel and disruptive character, the process demands research on governing physical fundaments and engineering performance to successfully transfer its benefits into industrial applications. A design-of-experiments approach was used to develop technological conditions and parameters with which the dissimilar joints were performed. The influence of the process parameters on the joint formation mechanisms and main geometrical features, with focus on the plastic deformation of the rivet tip inserted into the polymer, were systematically investigated and determined. Through statistical analysis, following response surface methodology, the correlations between parameters, mechanical energy input and process temperature were established. This information in turn allows for a better understanding of the process variant used, regarding the mechanical performance of the produced joints. The knowledge gathered and established experimentally, is ready to serve as basis and validation for ongoing computational finite element analysis, simulating the rivet plastic deformation. The following features are considered to be original:

1. The influence and relative contributions of the process parameters on joint formation, i.e. rivet penetration depth, maximum width of the deformed rivet tip and anchoring depth, were determined via statistical analysis.

2. Joint performance was correlated with mechanical energy input, establishing an energy efficiency threshold beyond which excessive deformation was found to occur.

3. An updated calculation method for the volumetric ratio was successfully demonstrated to better estimate the mechanical performance of the connection based on joint geometry.

4. Response surface methodology was used to determine joint performance optimization based on process parameters. A simple linear equation has
been established, which allows the production of friction riveted, for the material combination investigated, in a manner that minimizes mechanical energy input while maximizing performance.

5. The analytical regression models for joint formation and global mechanical performance determined with this work, allow the production of tailor-made joints without the need for experimentally search application-specific process parameters.

6. The feasibility of single-phase force-controlled friction riveting was proven for the material combination investigated. Where successful and sound joints were performed without the need for a process forging phase.

7. Statistical analysis on the joints produced with single-phase friction riveting, established the influence of parameters and their relative contributions to the rivet plastic deformation during the process.

Ongoing process computational simulations yielded a good correlation between experimental and simulated rivet plastic deformation, based on analytically determined external heat flux and experimental process parameters used. The computational simulation envisages to complement the knowledge on fundamentals of the process, such as, the thermomechanical conditions that triggers the visco-plastic deformation of the metal rivet and energy analysis.
1. Introduction

The present document consists of an overview on three publications regarding the analysis of friction riveting. The main scientific findings of this work are detailed in those publications. This short overview document is meant to introduce the carried-out research and outline the main findings of the published work.

This study focusses on joints (or connections) performed between dissimilar materials, by friction riveting process. The investigation into process variants and how the parameters used affect the material responses, aims at further understanding how the performance of these joints are affected. Having in mind a novel energetic efficient approach, enabling a fast tailoring of the technological conditions to real application design requirements.

1.1 Background and Motivation

The environmental impact of the transportation sector is nowadays a major driving factor for research on solutions which can curb energy consumption and reduce CO2 emissions. Increasing public concern and awareness over climate change and the need for ecological sustainability, is fuelling new policy initiatives across the world. The European Commission regulation on vehicle emissions limit [1] is an example of incentives and restrictions being implemented in order to direct research and manufacturing towards more environment-friendly practices. A good example in the more specific case of the automotive industry, is that the EU fleet-wide average emission target for new cars will be 95 g CO2/km in 2021 [2].

Two basic engineering approaches to reduce greenhouse gas emissions, direct or indirect, resulting from mobility of people and goods, are more efficient and sustainable power generation and weight reduction. The latter is generally achieved through the usage of lightweight materials and less conventional material combinations. According to Timmis et al. [3], a global fleet of high-composite-usage aircraft, such as Boeing Dreamliner 787 and Airbus A350, could reduce carbon emissions by up to 15%, taking into account a comprehensive life cycle assessment. In the automotive industry, there is also a drive to increase the role of composites and engineering plastics, namely carbon-fibre-reinforced polymer (CFRP), on the design of mass-produced popular and even entry-level vehicles. Until not long ago, these materials were almost exclusive to high-end
sports and luxury cars. With recent events that led to public distrust on automotive industry reported emission reductions by conventional internal combustion engines, automotive manufacturers have been forced to accelerate the push towards more efficient electric or hybrid powered solutions for mobility. Other concerns regarding the use of composite materials is the recyclability of such materials. Boeing has recently announced the company plans to recycle remnant CFRP material from the production of their 777X model. A new approach developed in partnership with ELG Carbon Fibre, allows for this material to be recycled into automotive applications [4]. This is one example of developments which can further promote the use of these types of composites across diverse industries.

The technologies mainly used to join dissimilar materials are adhesive bonding and mechanical fastening [5]. On specific applications, inserts are also used to connect parts which are (co)ured [6]. When performing connections between thermoplastics, welding is also an alternative [7]. The local melting of the plastic materials and clamping them together, promotes the formation of multipolymer matrices [8]. The same is not valid for thermoset polymers and elastomers. This has to do with the fact that these are processed by an irreversible crosslinking reaction, so, they cannot be reshaped by heating [5]. Likewise, issues arise if friction-based processes are used, as these may originate a matrix degradation of a composite material through fibre shredding and misalignment.

As adhesive bonding is based on the creation of intermolecular forces between the materials to be joined and a polymeric adhesive, it does not require material melting, thus not altering their mechanical properties and avoiding thermal-induced stresses. This technique can also give a positive contribution to the overall assembly, due to the fact that larger bonding areas allow a more even distribution of stresses, usually leading to better fatigue properties [8]. However, there are several negative aspects to adhesive bonded joints, such as: extensive surface pre-preparation; long curing cycles (which lead to longer production time); and the permanent nature of the bonded joint/structure, preventing it from being disassembled without damaging the joined materials [8]. Moreover, these joints are susceptible to environmental-induced degradation, resulting from temperature and moister adverse conditions [9].

There are several methods to mechanically fasten dissimilar materials. The most common joint configurations rely on additional clamping components such as bolts and rivets, widely applied in the aerospace industry. These are not only robust, but also allow visual inspections for damage to be carried-out. Limitations regarding the state-of-the-art of mechanical fastening methods are related to the need of pre-features on the materials to be joined. The holes or profiles created for the fasteners become stress concentration points, having a negative effect on fatigue properties and can generate issues related to corrosion [8]. Furthermore, the use of a large number of additional fastening components works against the purposes of weight and cost reductions. Also a source of additional weight on a mechanically fastened connections involving composite materials, is the fact that these may need to be locally reinforced, by increasing the thickness for example, to compensate the susceptibility of these materials to
notch effects, given the presence of the mechanical fastener and that the potential damage to material is not easily detectible.

Joining either polymers or polymeric composites to metals with conventional technologies presents several restrictions on the design of lightweight structures. In order to mitigate these challenges and facilitate the usage of design solutions where dissimilar connections would bring considerable advantages in comparison to the use of conventional materials, several alternative joining technologies have been developed and investigated. The most selected alternative techniques are laser [10, 11], ultrasonic [12], resistance [13] and induction joining [14], used on several material combinations [5]. That being said, these techniques present several drawbacks such as material and energy consumption and cost and limitations associated with the necessary equipment. In order to tackle these limitations, research and development continues to push for novel joining solutions.

One example of an innovative solid-state joining technique is Friction Spot Joining. This process was developed at Helmholtz-Zentrum Geesthacht, Germany [15] and is meant to perform dissimilar metal-polymer/composite joints. In this process the heat is generated by friction on the metallic component, having relatively small effect on the polymer/composite. Hence, the damage to fibre matrix and/or polymeric degradation are also comparatively small and locally confined [16]. Other advantages of this process are the relatively flexible equipment and the short joining cycles, for several material combinations [17, 18].

Another recently developed alternative technique that allows this type of hybrid connections to be made, is Friction-Based Injection Clinching Joining (F-ICJ). This is a variation of Injection Clinching Joining (ICJ), developed and patented by Helmholtz-Zentrum Geesthacht [19]. Based on staking technology, F-ICJ uses friction to generate heat, by pressing a rotating non-consumable cylindrical tool against a polymeric stud, melting it and deforming it in a forging-like manner. The new joining technique is faster and shows similar mechanical performance to that of other state-of-the-art polymer staking technologies [20]. Typically, the sound dissimilar joints, e.g. in metal-polymer structures, are only as strong as the polymeric part, considering that the fastener (stake) is formed out of the original polymeric stud material [21]. Moreover, the production of long/woven-fibre reinforced stakes is very complex as the stud is added during the manufacturing process of the polymeric component. Therefore, F-ICJ is more adequate for short-fibre reinforced composites and unreinforced polymers, which can be cost-effectively produced by injection moulding.

The above-mentioned drive for the development and application of engineering plastics and composite materials in several industries, mainly transport-related, has led to an increased use of multi-material structures. In order to accommodate these design solutions and overcome the shortcomings of established manufacturing techniques, new approaches to join dissimilar materials must be accomplished.
The present doctoral work aims to fill the knowledge gap related to the heat generation and impact of energy efficiency in the friction riveting process. A systematic study was necessary to broaden the understanding regarding heat generation mechanisms and their influence on material flow and consequent joint formation on force-controlled friction riveting. This is crucial towards further developing the technology and scaling-up this process to industrial applicability. As interest from industry in friction riveting has already been demonstrated by several projects and collaborations on previous works [18, 22]. Where several dissimilar material combinations have been successfully joined. The deeper understanding of the process will further widen the range of possible industrial applications. As such, in order to investigate how energy is delivered to the materials being joined by force-controlled friction riveting, which until this work was yet to be addressed, joint formation, process temperature, energy efficiency and global mechanical performance where studied when joining a structural AA2024-T351 to polyetherimide (PEI). The influence of the process parameters on the investigated responses was determined, consolidating knowledge on this process variant and optimizing it towards possible specific application-driven demands and constraints. Hence, allowing for a lean design approach on dissimilar material joint solutions.

1.2 Friction Riveting

The Friction Riveting process has been developed and patented at Helmholtz-Zentrum Geesthacht, Germany [23]. This alternative hybrid joining technology is meant as an alternative solution to perform overlap spot connections between metallic and polymeric materials [17]. This process allows for these connections to be produced with a wide range of materials and material set-ups, using distinct process-control methods as well and configurations [17, 18, 24, 25]. Although the technology itself draws its basis from both friction welding and metallic-insert, it presents several distinct advantages.

Initially developed by Amancio et al. [17], Friction Riveting was proposed as substitute for conventional solutions such as mechanical fastening and adhesive bonding, which are the most used in industry for performing dissimilar non-weldable multi-material connections [26]. In order to tackle some limitations of these more conventional joining methods, such as the additional weight of the structure, due to the use of additional connection components, most evident in mechanical fastening, or the relatively long curing cycles in adhesive bonding, friction riveting takes advantage of the materials and the hybrid nature of the intended joints. In its simplest configuration, a featureless metallic rod (rivet) is normally pressed, while rotating, against the surface of polymeric plate. Initially, solid friction occurs between the two bodies, which leads to an increase in temperature and subsequent softening or melting of the polymer, depending on its respective thermoplastic or thermoset nature. At this point, the rivet begins to be inserted into the plate and heat starts being generated by viscous dissipation – given internal shearing of polymeric chains in molten state – and/or by
solid friction, when in the presence of a reinforcement (fibre-reinforced plastic). The heat being generated promotes a local increase in temperature in both the base material and in the rivet tip. This also further accentuated by the low thermal conductivity of the polymeric material, that concentrates the heat in the zone being processed, i.e. at the tip of the metallic rivet. Despite the considerably short joining cycles involved in friction riveting – dependent on the materials being joined and on the intended joint performance, these can lower than a couple of seconds – the continuous heating of the rivet tip and applied axial pressures lead to a localized plastic deformation of the metal. Using adequate process parameters, the rivet tip plastic deformation takes place well inside the polymer, promoting the mechanical interlocking between these two dissimilar components. Hence, creating a hybrid connection without need for (significant) pre- or post-processing operations.

The process base configuration of friction riveting consists of two element types, the joining and the joined ones, being the first a cylindrical metallic rivet and the later polymer/composite or metallic alloys, assuming several possible configurations, such as sheets, plates, rods. The rivet element can also vary, having a profiled or a flat outer surface, which can induce tailored changes on the joint’s characteristics. The simplistic configuration of a joint, metallic-insert joint is comprised of one polymeric plate as joined element and a non-profiled metallic rivet.

The basic configuration of the joining process (metallic-insert type joint), illustrated in Figure 1, consists of three phases: friction; forging; and consolidation. On the first phase, the rotating rivet is pressed against the polymeric plate, generating heat by friction, causing a local increase in temperature, causing the polymer to melt as the temperature reaches its softening point. The softening point corresponding to the glass transition temperature for amorphous polymers or the melting point for semi-crystalline ones. The continuous feed of the rivet into the plate causes the molten thin layer of polymer to flow outwards as flash material. At the end of this friction phase, the heat generation is significantly greater than the heat outflow on the vicinity of the rivet, due to the low thermal conductivity of the polymeric part. The tip of the rivet plasticizes as the process temperature achieves values of up 95 % of the melting point of the metal. At this point, the rivet’s rotational speed is decreased to full stop and the forging phase begins. The axial force being applied is increased resulting on the plastic deformation of the originally cylindrical metal, into an anchor, or bell-shaped axisymmetric geometries. This deformation is originated by the opposing resistance offered by the colder solid polymer, which becomes in contact with the rivet after the pressure-induced removal of the polymer’s molten thin layer. In the end, during consolidation phase, the reminiscent molten polymer in contact with the rivet cools down activating some adhesive joining mechanism with the metal, and the metallic-insert joint consolidates under pressure. The process user-defined joining parameters are rotational speed (RS); friction time (FT); friction force (FF); forging time (FoT); and forging force (FoF).
From initial investigations, friction riveting has evolved, not only on the combinations of materials which have been successfully joined, but also regarding possible joining process configurations, controlling approaches, and process variants. Most of the investigations on friction riveting made use of two distinct process phases, friction and forging. The friction phase is characterized by occurring while the rivet is rotating, promoting high energy generation. Subsequent to this phase, the rotational speed can be brought to a halt and the axial force being applied to the rivet increased, which can lead to higher rivet plastic deformations. Hence, the designation of forging phase. Typically, the rotational speed of the rivet is kept constant throughout the friction phase. Several process-controlling approaches have been used and detailed in works available in literature. Two of the most investigated are the force- and displacement-controlled variants, both limited by time. This directly correlates to how the material responds during the process, i.e. the rivet insertion and its eventual plastic deformation. In the case of force-control, the forces involved during the process are kept constant, and the total amount of energy being delivered to the system is limited by pre-set time intervals, corresponding to both friction and forging phases. In the case of displacement-control the insertion rate of the rivet is predetermined, being the resulting axial force applied a driven parameter.

The process possible configurations are explored in the awarded patent on friction riveting. These configurations can integrate not only polymeric materials, but also metallic base plates, e.g. a sandwich set up. In this complex case, a variant of the process designated as direct-friction riveting, can be used to join overlapping layers of polymeric plates in-between metallic sheets. Here, the rotating rivet would go through the upper metallic layer and through any number of subsequent polymeric layers plastically deforming only at the last one and entering in contact with the bottom metallic sheet, where an actual weld would take place between the rivet and set sheet. The exposed rivet body – not inserted into the plates being joined – could have features tailored at promoting an external constraint against the upper metallic sheet, and, if possible, by the type of materials used, also forming another weld between the top plate and the rivet.

Initial works on friction riveting focused on proving the feasibility of the process and on understanding the influence of process parameters both on joint formation – the final rivet plastic deformation state – and possible degradation.
of the polymeric component. Amancio et al. [27] conducted initial investigations into thermal degradation of unreinforced polyetherimide after friction riveted with AA2024-T351. The influence of the rotational speed process parameter on this degradation was assessed and found to be low. The overall degradation was mainly attributed to polymeric chain scission and considered to be relatively small, with a loss of about 10% in molecular weight, localized in a thin layer surrounding the inserted rivet tip, following its shape contour. Further investigations by Amancio et al. [17] with the same material combination studied the process temperature, characterized the microstructure of the inserted rivet tip and tested the produced joints both for local and global performance. In their work the metallic rivets used were threaded. Distinct microstructural zones were identified, resulting from thermal history of the process and the effects of plastic deformation. These heat-affected and thermo-mechanically affected zones were mainly characterized by annealing phenomena and dynamic recrystallization, respectively. Microhardness testing yielded drops in the values measured when compared to the base material, further evidence of the transformations underwent by the metal. When quasi-statically tested on T-Pull configuration, the joints produced experienced failure through the rivet, achieving over 90% of the metal rivet base material testing performance. After these initial works on the friction riveting, the joinability of other combinations of materials started to be explored. Blaga et al. [22] established with their work the feasibility of the process for titanium grade 2 (Ti gr2) and glass-fibre-reinforced polyetherimide. Mechanical performance, rivet plastic deformation and process temperature were correlated with rotational speed. An increase in this parameter led to an increase in heat input, which promoted further rivet plastic deformation and increased quasi-static mechanical performance. The temperatures measured during the process reached about 30% of the base material Ti gr2 melting point. The relatively low plastic deformation of the rivet observed in their work could be explained by this relatively low process temperatures. The heat input and forces involved produced only a small increase in the rivet diameter. A volumetric ratio was proposed by the authors as to quantify the volume of base plate material above the plastically deformed rivet tip, which offers resistance to a pullout mechanical solicitation. Altemeyer et al. [18] explored the joinability of titanium grade 3 and short-carbon-fibre-reinforced polyether ether ketone composite (30% fibre content by weight). The authors sought to understand how the process parameters would influence the rivet plastic deformation within the semi-crystalline fibre-reinforced thermoplastic. A design-of-experiments (DoE) was used to set the joining parameter matrix and maximize the information which would be used for statistical analysis of the joint formation and mechanical performance responses. Failure through the rivet as observed for some conditions, proving the soundness of the friction riveting process also for this combination of materials. The energy input delivered to the materials, by increasing rotational speed and friction time, led to higher rivet plastic deformation, resulting in also higher mechanical performance. The authors observed that an increase in the axial pressure applied to the rivet was counterproductive for these responses. Also, this process parameter did not
have a significant effect on the mechanical energy input. Altmeyer et al. [16] reported, for the same material combination as in the previous mentioned work (Ti gr.3 and short-fibre-reinforced PEEK), on how the process affected both the metallic rivet and composite material. In the composite surrounding the inserted rivet, the authors observed three distinct areas. These designated as stirred, plastic thermo-mechanically affected and plastic heat affected zones, allowed for an assessment on if and how the composite material integrity had been affected by the process parameters. By analysing the short fibre orientation around the rivet, it was observed that the flash material flow – flow of polymeric based plate material being expelled as the rivet is inserted – was greatly affected by the rotational speed of the rivet. The correlations between friction riveting joint formation, its mechanical performance and failure types when tested under quasi-static T-pull tensile testing, were also investigated by Rodrigues et al. [24] following a similar DoE approach. In their work, a combination of AA2024-T351 featureless rivets and polycarbonate amorphous thermoplastic plates were successfully joined. They also observed well distinguishable process-affected microstructural zones in the rivet. Grain refinement and partial dynamic recrystallisation were observed. Local drops in microhardness values were measured when comparing to the rivet base material. The parameter sets used also yielded two different types of joint failure, namely failure through the rivet and full rivet pullout. These were direct consequences of the process resulting joint formation, or plastic deformation of the rivet tip. Higher plastic deformation, characterized by a higher increase in the rivet diameter, led to a stronger mechanical interlocking. A relatively good correlation between the joint formation and mechanical performance was studied via a volumetric ratio proposed in previous work. Borba et al. [28] proved the feasibility of friction riveting for Ti6Al4V and glass-fibre-reinforced polyester with 50 % volume in fibre content. With their work the viability of the process for joining thermoset polymeric plates was demonstrated. The fibre matrix local destruction was observed in the vicinity of the rivet. The authors also investigated the degradation of the material matrix, which was found to be severe. Evidence of this were the volumetric flaws in the composite material surrounding the inserted rivet. The authors also identified inclusions of metallic splinters on the composite material. These are thought to result from ruptures at the outer surface of the metallic rivet while it underwent considerable plastic deformation and with peak process temperatures reaching the maximum service temperature of the alloy. The same authors reported in a later work [29], for the same material combination, that the rotational speed parameter had considerable influence on the mechanical performance of the joints. An increase in rotational speed was found to promote the increase in volumetric defects, surrounding the rivet, which lower the performance of the connection. Proença et al. [30] used a force-controlled displacement limited process variant to joint AA6056-T6 and glass-fibre-reinforced polyamide 6 with 30 wt.% of short fibres. They observed failure through the rivet for the joints produced with higher energy input. They also reported the low influence of the forging force parameter on the rivet plastic deformation and subsequent global performance, for the parameter ranges used. Using thermogravimetric analysis,
they observed no significant thermomechanical degradation of the composite material in the vicinity of the inserted deformed rivet tip. In another by the same authors [31], the same aluminium alloy and unreinforced polyamide 6 were joined. Where again the authors observed the same joint failure type for the higher energy conditions. This energy was greatly influenced by the rotational speed parameter. Amancio et al. [32] proposed an analytical model to determine the heat input in friction riveting process. The calculations, which had as theoretical basis both friction and spin welding principles, were done based on experimental data from AA2024-T351 and PEI friction riveted joints. One of the conclusions from the determined heat input was that the axial forces applied to the rivet (friction and forging process parameters) were found to be negligible (contribution of less than 10 % of the total heat input), when compared to those from viscous dissipation. This establishes that for amorphous thermoplastics the internal shear within the molten polymer is the major heat generator during friction riveting. In 2017, Borba et al. [25] reported on joining Ti6Al4V to glass-fibre-reinforced polyester (50 wt.% of nominal fibre content). A metallic sheet gusset of AA2198 was then assembled to the friction riveted joint, in order to mimic a mechanical fastened conventional connection of these materials. Lap shear testing was carried out assessing the performance of the joint. Complex microstructural changes were observed on the metallic rivet. Equiaxial alfa-grains with beta-phase precipitate in their boundaries were present in the metal heat affected zone. Refined alfa’ martensite, Widmanstätten structures and beta-fleck domains were present in the metal thermomechanical affected zone, due to the plastic deformation of the alloy, resulting in increased microhardness. The same authors also worked with Ti6Al4V now friction riveted to carbon-fibre-reinforced PEEK (58 wt.% nominal fibre content). In this work a process variant designated as direct-friction riveting was used. In this variant, the rivet goes through a first plate/sheet of material stacked on top of the material where the deformation and anchoring of the rivet is intended to take place. No feature on this top plate/sheet is required. In their work, also the top plate was on the same material (CFR-PEEK). The authors reported that a good connection was achieved with the rivet being plastically deformed on the bottom plate as intended. The connections were tested via quasi-static lap shear testing. In order to keep the upper plate/sheet in place while the rotating rivet goes through it, a clamping system was used. The influence the clamping pressure applied by the system on joining process was investigated by Borba et al. [33]. Joining the same material combination of the previous mentioned work by the same authors (Ti6Al4V – CFR-PEEK), the authors reported on how the pressure influenced the outflow of material expelled as flash, or squeezed out, in-between the top and bottom composite plates being joined. The squeezed flow was as expected greatly diminished by the increase in clamping pressure. It was also observed by the authors that an excessive use of such clamping pressure coupled with also high process axial force applied to the rivet, led to delamination of the composite during joining.
2. Materials and Methods

In this chapter the investigated materials and main experimental approaches and methodologies used are described. Further detailed information and discussion can be found in the Publications I – III.

2.1 Materials

The investigations carried-out during this work fussed on friction riveted joints of AA2024-T351 rivets and Polyetherimide (PEI). The polymer used is a high-performance engineering amorphous thermoplastic developed by Wirth et al. [34]. The chemical composition of this materials consists of aromatic imide, propyldiene and ether groups. It is characterized by a high mechanical strength, elevated glass transition temperature \( T_g \) [35], high mechanical performance, dimensional stability and flexural modulus. It also displays good flame resistance, good chemical stability, electrical properties and elevated softening point [36, 37]. Hence, meeting specific flame resistance and low smoke evolution requirements, which make this material suitable for both automotive and aircraft interior applications [36]. Table 1 shows some of the properties, which characterize this engineering material. The polymeric specimens used for experimental investigation were obtained from 13.4 mm in nominal thickness extruded plates (Quadrant Engineering Plastic Products, Switzerland). The joining plate specimens were cut into 70 x 70 mm.

Table 1. Selected Polyetherimide (PEI) properties [38].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0.2 (MPa)</td>
<td>129</td>
</tr>
<tr>
<td>E (MPa)</td>
<td>3500</td>
</tr>
<tr>
<td>Glass Transition Temp. [°C]</td>
<td>215</td>
</tr>
<tr>
<td>Thermal Conductivity [W/(m*K)]</td>
<td>0.24</td>
</tr>
</tbody>
</table>

The metallic rivets used to perform the investigated joints were produced from extruded AA2024-T351. The rivets had a nominal diameter of 5 mm and a length of 60 mm. The used metal is a solution heat treated and cold worked aluminium alloy, which is naturally aged to a substantially stable temper condition. Its chemical composition is presented in Table 2. This alloy is characterized
by medium-to-high mechanical strength and it is widely used in aircraft applications, such as primary structures, fuselage and mechanical connections. This makes it highly suitable for friction rivet development. Properties of interest on this alloy can be found in Table 3.

### Table 2. Common nominal chemical composition of aluminium alloy AA2024-T351 [39].

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight [wt.%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>90.7-94.7</td>
</tr>
<tr>
<td>Cr</td>
<td>≤0.10</td>
</tr>
<tr>
<td>Cu</td>
<td>3.8-4.9</td>
</tr>
<tr>
<td>Fe</td>
<td>≤0.50</td>
</tr>
<tr>
<td>Mg</td>
<td>1.2-1.8</td>
</tr>
<tr>
<td>Mn</td>
<td>0.3-0.9</td>
</tr>
<tr>
<td>Si</td>
<td>≤0.5</td>
</tr>
<tr>
<td>Ti</td>
<td>≤0.15</td>
</tr>
<tr>
<td>Zn</td>
<td>≤0.25</td>
</tr>
</tbody>
</table>

### Table 3. Selected physical properties of aluminium alloy AA2024-T351 [40].

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>R0.2 [MPa]</td>
<td>310</td>
</tr>
<tr>
<td>Rm [MPa]</td>
<td>427</td>
</tr>
<tr>
<td>E [MPa]</td>
<td>72</td>
</tr>
<tr>
<td>Annealing Temp. [°C]</td>
<td>518-548</td>
</tr>
<tr>
<td>Melting Temp. Domain [°C]</td>
<td>256</td>
</tr>
</tbody>
</table>

### 2.2 Joining Procedure

The joints investigated in this work were produced using a customized lab-scale joining friction riveting equipment: RNA, H. Loitz-Robotik, Germany. This equipment is characterized by a high maximum rotational speed, of 21000 rpm, and a maximum axial load of 24 kN. Integrated sensors allow for live monitoring of forces and torque being applied to the materials. It also allows several process control methods, e.g. control by force and displacement. This equipment is shown in Figure 2.

![RNA custom friction riveting equipment](Photo: Helmholtz-Zentrum Geesthacht/Rasmus Lippels)

The process parameters used to produce the joints defined the rotation and forces applied to the rivet and the time intervals during the sequential phases of the process. The rotational speed (RS) was kept constant during friction phase, where friction force (FF) was also kept constant for the set friction time (FT). In the conventional friction riveting process, this friction phase is followed by an additional forging phase. In this phase the rotational speed is brought to zero and the axial force applied to the rivet is increased, designated as forging force.
(FoF) during a forging time period (FoT). In part of this study joints were produced without a forging phase, investigating the feasibility of such process variant: Single-phase friction riveting. The process parameter matrixes used to produce the joints are shown in Table 4 and Table 5, for the two phases and single-phase process, respectively. In both cases, DoE response surface methodology, was used in defining the parameter sets [41–43]. For the conventional process with a forging phase, a central composite design was selected. In the case of single-phase process, a Box-Behnken design was applied [41]. These statistical approaches are intended to minimize the amount of experiment work, in this case the number of joints produced, while maximizing the information extracted from correlations between the investigated process responses and the process parameters used.

Table 4. Friction riveting process joining parameter matrix used in Publication I.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Process Parameters</th>
<th>Joint</th>
<th>Process Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>18</td>
<td>1.6</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>1.6</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>18</td>
<td>1.6</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>1.6</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>18</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>18</td>
<td>1.6</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>20</td>
<td>1.6</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>18</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>20</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>18</td>
<td>1.6</td>
<td>2</td>
</tr>
<tr>
<td>14</td>
<td>20</td>
<td>1.6</td>
<td>2</td>
</tr>
<tr>
<td>15</td>
<td>18</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>16</td>
<td>20</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>17</td>
<td>19</td>
<td>1.8</td>
<td>1.5</td>
</tr>
<tr>
<td>18</td>
<td>19</td>
<td>1.8</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table 5. Friction riveting process joining parameter matrix used in Publication III.

<table>
<thead>
<tr>
<th>Joint</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RS [krpm]</td>
</tr>
<tr>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>19</td>
</tr>
<tr>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>9</td>
<td>19.5</td>
</tr>
<tr>
<td>10</td>
<td>19.5</td>
</tr>
</tbody>
</table>
2.3 Non-destructive Testing of Joint Formation

The plastic deformation of the inserted rivet tip, or joint formation, was non-destructively tested by X-ray tomography. This provided the projected geometry of the rivet inside the polymeric plate. Hence, some additional joint formation features were investigated, complementing the global mechanical performance and microstructural analysis based on destructive testing. An example of such X-ray tomography is shown in Figure 3. These tomographic measurements (Seifert Isovolt 320/13, Russia) were performed in accordance with DIN EN ISO 17636-1, with a tube current of 5.4 mA, at 80 kV and a focal spot of 1.5 x 1.5 mm at an 800 mm focus-to-film distance. The joint formation was characterized by the dimensions of the inserted rivet tip, where rivet penetration depth (H), maximum width of the deformed rivet tip (W), height of the deformed rivet tip (B) and anchoring depth (Dp) were measured.

![Figure 3. Example of X-ray tomography measurements for the joint formation analysis. Main geometric features of the joint: D – original rivet diameter; H – rivet penetration depth; W – maximum width of the deformed rivet tip; Dp – anchoring depth; and B – height of the deformed rivet tip [44].](image)

The process temperature was recorded by a thermographic camera (High-End Camera Series ImageIR, Infratech GmbH, Germany). The infrared thermometry assessed the temperature of the polymeric flash material being expelled as the rivet was inserted into the polymer base plate. The equipment was calibrated for temperatures ranging from 150 up to 700 °C. The distance and angle of the camera lens in relation to the joint being performed is further detailed in the publications. An example of the temperature measurements, by the equipment during the process, is shown in Figure 4.
2.4 Mechanical Performance Testing

The global mechanical performance of the joints produced for this work, quasi-static pullout tensile testing was performed on the specimens (adapted from ISO 6892 [19]). These tests were conducted on a Zwick/Roell 1478 universal testing machine equipped with a 100 kN load cell, at room temperature and rate of 1 mm/min, similarly to previous published works on friction riveting [18, 24]. Figure 5 represents the custom clamping adapter used, where grip distance ($L_0$) was 22 mm. The constraints on the polymeric plate were set at a minimum radial distance of 40 mm from the rivet axis.

2.5 Process Mechanical Energy Input

The heat generated in friction-based processes can be estimated by evaluating the mechanical energy input used. This is valid both for processes where metallic materials and thermoplastics are involved [46, 47]. The total mechanical energy input ($E_M$) used to produce the investigated joints was determined with Equation 1.

$$E_M = E_f + E_d = \int M. \omega. \, dt + \int F. \theta. \, dt \text{ [J]}$$  \hspace{1cm} (1)
In this equation, the first term represents mostly the frictional energy ($E_f$), which results from the applied torque ($M$) and rotational speed ($\omega$) of the metallic rivet. The second term determines the translation deformational energy ($E_d$), considering the axial force ($F$) and the deformation rate ($\vartheta$) used. The estimation of these energy contributions allows for important correlations. Namely, correlations with the mechanical performance of the joints, aiming at assessing their energy efficiency. Moreover, establishing optimized parameter sets which also promote more favourable plastically deformed rivet tip geometries and yield better mechanical properties, with the less energy being necessary.

2.6 Statistical Analysis of Evaluated Responses

The parameter sets used for the present work followed a response surface methodology [41]. These process parameters were considered as statistical input factors in order to assess their influence on the investigated responses [41]. The investigated responses being geometrical features defining the joint formation, and global mechanical performance. In part of the work, a central composite design was used. This integrates a factorial design, a set of centre points and another of axial points. A fractional factorial design of five parameters with two levels ($2^{5-1}$) was applied. The value of $\alpha$, which sets the distance between the centre and the axial design points, was chosen in a manner by which the design would have the properties of rotatability and orthogonality [41]. In another part of the work, a Box-Behnken design was used to minimize the number of samples necessary, while achieving a considerable amount of information on the responses. Here the statistically investigated process responses were joint formation (rivet penetration and rivet tip width), process temperature and mechanical energy input. The terms of all the statistical models in both designs were obtained via a stepwise backward elimination procedure. Here the linear, two-way interaction and quadratic terms were considered with an alpha-to-remove value of 0.05. Statistical predictive regression models were determined and experimentally validated.
3. Summary of Publications

The main scientific contributions of this thesis work are compiled in the three journal publications accompanying and supporting this report. Summaries of the publications are given in the following sub-sections.

3.1 Publication I

The investigation carried out in this work focussed on the effects that process parameters have on joint formation, in force-controlled time limited friction riveting of AA2024-T351 with PEI. A wide range of rivet plastic deformation was achieved with the selected parameter range, with the resulting rivet penetration (H), rivet maximum width (W) and anchoring depth (Dp) observed ranges being shown in Table 6. This wide range of conditions was intended to be generated in order to consolidate the knowledge which would allow the development of statistical analytical models capable of being used as tools when designing friction riveting connections.

Table 6. Joint formation geometry measurements of the plastically deformed rivet tip [45].

<table>
<thead>
<tr>
<th>Joint</th>
<th>Joint Formation Measurements</th>
<th>Joint</th>
<th>Joint Formation Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.7</td>
<td>3.7</td>
<td>6.2</td>
</tr>
<tr>
<td>2</td>
<td>6.8</td>
<td>5.0</td>
<td>7.3</td>
</tr>
<tr>
<td>3</td>
<td>6.8</td>
<td>6.4</td>
<td>7.4</td>
</tr>
<tr>
<td>4</td>
<td>7.5</td>
<td>7.0</td>
<td>9.3</td>
</tr>
<tr>
<td>5</td>
<td>4.9</td>
<td>4.4</td>
<td>6.2</td>
</tr>
<tr>
<td>6</td>
<td>5.5</td>
<td>5.0</td>
<td>7.0</td>
</tr>
<tr>
<td>7</td>
<td>6.9</td>
<td>6.4</td>
<td>7.8</td>
</tr>
<tr>
<td>8</td>
<td>7.5</td>
<td>7.1</td>
<td>8.4</td>
</tr>
<tr>
<td>9</td>
<td>6.2</td>
<td>5.7</td>
<td>8.2</td>
</tr>
<tr>
<td>10</td>
<td>6.6</td>
<td>5.3</td>
<td>10.0</td>
</tr>
<tr>
<td>11</td>
<td>7.6</td>
<td>5.7</td>
<td>10.0</td>
</tr>
<tr>
<td>12</td>
<td>8.4</td>
<td>5.4</td>
<td>11.3</td>
</tr>
<tr>
<td>13</td>
<td>5.7</td>
<td>5.0</td>
<td>9.2</td>
</tr>
<tr>
<td>14</td>
<td>6.7</td>
<td>5.5</td>
<td>9.6</td>
</tr>
<tr>
<td>15</td>
<td>7.5</td>
<td>5.4</td>
<td>9.9</td>
</tr>
<tr>
<td>16</td>
<td>8.7</td>
<td>6.1</td>
<td>11.9</td>
</tr>
<tr>
<td>17</td>
<td>6.4</td>
<td>5.6</td>
<td>7.5</td>
</tr>
</tbody>
</table>
These possible connections can be dimensionally constraint in specific applications. Hence, knowledge on how to fine tune the joint formation was necessary and had yet to be investigated. The range of rivet plastic deformations achieved is represented in Figure 6, with the measured values for anchoring depth (Dp) being displayed.

Figure 6. Friction force direct effect on Dp: a) Condition 33 (RS=19000 rpm; FT=1.8 s; FoT=1.5 s; FF=1500 N; FoF=4500 N); b) Condition 25 (RS=19000 rpm; FT=1.8 s; FoT=1.5 s; FF=2500 N; FoF=4500 N); and c) Condition 34 (RS=19000 rpm; FT=1.8 s; FoT=1.5 s; FF=3500 N; FoF=4500 N) [45].

From previously published works on friction riveting, a correlation between the volume of polymeric material present above the deformed rivet tip and the global performance of the joints have been established [18, 24]. As such, a rivet final geometry which maximizes the volume of material present above the rivet is desirable. This can be promoted by maximizing the value of anchoring depth (Dp). Hence avoid over-deformation of the metallic material. The mechanical energy input and the balance between its frictional and deformational components were found to play a crucial role in avoiding premature increase of rivet width, which leads to over-deformation. From the statistical analysis, the friction force (FF) parameter was found to have greater influence over this phenomenon, promoting considerable increase in the energy delivered to the material and thus, it must be carefully set. The determined values for the total energy input ranged from 24 to 208 J. As a result, also the measured process temperature also varied considerably, from 319 to 501 °C.

From the assessment on how the process parameters influence the responses and the relative contributions of two-way interactions and quadratic effects, the forging parameters were found to have considerably small contributions toward joint formation, for the investigated range of parameters. Therefore, for optimization purposes, these parameters can be set at their mid-range values. The rotational speed (RS) parameter displayed a linear increasing influence on the rivet penetration (H), rivet maximum width (W) and anchoring depth (Dp) responses. Hence, it was also maximized for optimization purposes.

One important deliverable from the study is a contour plot overlaying the effect that both friction force (FF) and friction time (FT) parameters have on the joint formation responses. This contour plot is depicted in Figure 7, and it allows for the determination of process parameters when aiming for a specific joint formation, without the need for process parameter investigations. Another relevant conclusion from this work was that by using higher values of FF and FT,
this would considerably decrease the anchoring depth (Dp), as over-defor-
mation takes place. Resulting in inefficient connections from an energetic per-
spective.

Figure 7. Influence of friction force (FF) and friction time (FT) on joint formation (H, W and Dp) across the parameter ranges. Values in millimetres. Regions of interest highlighted. The rotational (RS) was set at 21000rpm, forging time (FoT) at 1.5 s and forging force (FoF) at 4500 N [45].

3.2 Publication II

In this publication the mechanical performance and energy efficiency of the fric-
tion riveting joining process was systematically investigated for the force-con-
trolled process variant. Before this publication, there was no comprehensive
study on the correlation between mechanical energy input, joint formation and
resulting global mechanical performance. In addition, a volumetric ratio was
used to qualitatively estimate the performance of a friction riveted connection
based on measurements of geometrical joint features, following a similar ap-
proach to previous works [18, 24]. This volumetric ratio approximately calcu-
lates the volume of material above the plastically deformed rivet tip, considering
that this volume is responsible for the strength of the connection. However, in
this work a revised version of this volumetric ratio was prosed, introducing a
new formula with the anchoring depth (Dp) measurement (Equation 2).

\[ VR = \frac{(W^2 - D^2) \times D_p}{H \times W^2}, [0 - 1] \]  

The quasi-static mechanical testing of produced joints yielded a wide range of
performances, as expected from the range of rivet plastic deformation. The
loads on which the performed connections failed varied from 1096 to 9668 N.
Three types of joint failure modes were observed, full rivet pullout, rivet pullout
with back plug and rivet pullout. Examples of these failures can be seen in Fig-
ure 8. The failure mode which yielded the highest mechanical performances was
rivet pullout, where the plastic deformation of the rivet tip is both capable of
sustaining the mechanical solicitation and sufficient so to transfer the load to
the polymer above it. The joint formations of both the lowest (1096 N) and high-
est (9668 N) performing joints are shown in Figure 9. Here, the distinction between a very slight rivet plastic deformation and a considerable one, with high anchoring depth is clear.

Figure 8. Examples of friction riveting failure modes observed: a) full rivet pullout failure, corresponding to the worst mechanical performance; b) rivet pullout with back plug, corresponding to the intermediate mechanical performance; c) polymeric plate, rivet pullout failure, corresponding to the best mechanical performance; d) side view of rivet and detached polymer, rivet pullout failure [44].

Figure 9. Join formation assessment by X-ray tomography of: a) Condition 33 (RS=19000 rpm; FT=1.8 s; FoT=1.5 s; FF=1500 N; FoF=4500 N); and b) Condition 36 (RS=19000 rpm; FT=1.8 s; FoT=1.5 s; FF=2500 N; FoF=5700 N). Values of anchoring depth (Dp) and maximum width of the deformed rivet tip (W) shown in millimetres [44].

Considering the mechanical energy input and the resulting performance of the joints, the energy efficiency of the process was assessed. Figure 10 depicts this comparison. A relatively clear energy efficiency threshold was determined based on this evaluation, at 90 J. Above this level of energy being applied to the materials, the increasing rivet plastic deformation that was generated no longer contributed to an increase in global mechanical performance of the joint for this material combination.

Figure 10. Mechanical performance (ultimate tensile force, UTF) and total energy input (Em) comparison. The correlation for the energy efficient range (below the Em ≤ 90 J threshold) is seen in detail [44].

As a result of these findings, a simplified parameter correlation was defined, for the ranges investigated, which allows the maximization of the mechanical performance with minimal mechanical energy input, across the range of joint formation. This is illustrated in Figure 11, where a linear correlation between FF
and FT is defined by \( FF = 1189.8 \times FT + 403.6 \) (SI), with rotational speed set to 21000 rpm, which maximizes the ultimate tensile force (UTF) and both forging parameters kept at mid-range values (FoF = 4500 N and FT = 1.5 s).

![Figure 11. Optimization contour plot for achieved ultimate tensile force (UTF, in Newton) resulting from the combined ranges of FT and FF. RS set at 21000 rpm, FoT at 1.5 s and FoF at 4500 N [44].](image)

The outcome of this work allow for the setting of friction riveted process parameters aiming for specific values of mechanical performance, while minimizing the amount of energy that is delivered during the process.

### 3.3 Publication III

As discussed previously in the present work, the conventional friction riveting consisted on the use of both a frictional and forging phases before the final consolidation. The usage of such forging phase can pose limitations on the applications of this process, as the axial load increase on this phase might not be suitable for the joined structure to sustain and imposes greater requirements on the manufacturing equipment. As such, a possible approach to curb this constraint is to perform the process without the axial force increase. This work studied the feasibility of friction-phase-only friction riveting, designated as a single-phase process variant. The materials AA2024-T351 and PEI were successfully joined without applying the forging force phase. Hence, the process parameters used were only the friction time (FT), friction force (FF) and rotational speed (RS).

In comparison to other works on friction riveting (controlled by force) when joining the same materials, the rotational speeds (RS) used in the present one is similar to that used in those. Friction time (FT) and friction force (FF) were slightly increased as it was expected that higher frictional mechanical energy input (\( E_m \)) would be necessary to successfully produce joints with relatively good global mechanical performance. The process temperatures observed varied from 461 to 509 °C. Given the increase in friction time (FT) and friction force (FF), the mechanical energy input (\( E_m \)) also increased considerably. The highest value reaching 529 J and the lowest 151 J. This led to high joint formation, with rivet penetration (H) and width (W) reaching maximum values of 11.4 and 11.6 mm, respectively. Friction time (FT) was found to have the highest contri-
bution to the mechanical energy input ($E_M$). Figure 12 displays how the considered joint formation measurements evolve with increasing mechanical energy input.

Figure 12. Joint formation measurements evolution with increasing mechanical energy input ($E_M$): a) rivet penetration; and b) rivet tip width.

In the case of rivet penetration ($H$), the correlation can be described as close to linear. The same is not valid for rivet width ($W$). This was found to be explained by the occurrence of over-deformation which in some specimens led to rupture of the highly plastically deformed rivet tip. An example of this occurrence can be seen in Figure 13. Where excessive energy applied to the materials promoted abrupt changes in rivet plastic deformation, due to local variations in the viscosity of the polymeric material.

Figure 13. Cross-section of a single-phase friction riveted joint (Condition 12) with over-deformation and material rupture being evident (highlighted in the figure).

The quasi-static testing of the produced joints yielded values of ultimate tensile force (UTF) from 5416 to 7568 N. The latter value corresponds to a medium to high performance joint, for the combination of materials used, when comparing to joints produced by the conventional process with forging phase. All the joints investigated failed by rivet pullout with back plug. Two of the highest performing joints were found to have been produced both by the lowest and the highest mechanical energy input. A comparison between these joints is shown in Table 7.

Table 7. Energy efficiency comparison between lowest and highest mechanical energy input ($E_M$) joints and their respective global mechanical performance via ultimate tensile force (UTF).
Here a proposed simple energy-performance ratio (EPR) clearly distinguishes an energy efficient condition from one which despite being produced with three and half times more energy, yielded a similar mechanical performance. Establishing, also for the single-phase process variant, the importance of minimizing the energy applied to the materials without being detrimental to the performance of the joints produced.

Figure 14 shows the joint formation of Condition 9. It is characterized by a bell-shaped rivet plastic deformation, in contrast with Condition 12 (Figure 13) where over-deformation and rupture were observed. Pina Cipriano et al. have established the bell-shape type of deformation as preferable, being capable of achieving higher mechanical performances and presenting greater energy efficiency. The present results are in accordance with those findings.

Figure 14. Cross-section of a single-phase friction riveted joint of Condition 9, exhibiting a bell-shaped rivet plastic deformation.
4. Ongoing Work

Ongoing work on computational simulation of the plastic deformation the metallic rivet tip has been produced in parallel with the thesis work, already published. This computational work, will be shortly introduced in this chapter.

The computational simulation of the process has been done using a finite element method (FEM) envisaging to simulate how the metallic material flows – plastically deformed – during the friction riveting process. The software used for this computational work was *Abaqus*. The knowledge on the force-control process variant gathered with the publications previously introduced in this document, serves as basis for this computational investigation.

Given the complexity of the process phenomena involved and the drastic behavioural changes experienced by the polymeric material, with important contribution of the molten shear flow, an initial simplified approach to the problem was used in order to greatly reduce the workload and computational requirements involved. This approach takes into consideration only the metallic rivet component, modelling and applying to it the results from its interaction with the polymeric material. As the plastic deformation of the rivet, resulting from friction riveting, is essentially axisymmetric, an axisymmetric finite element model was considered. The material model used to characterize the AA2024-T351 behaviour was a strain hardening Johnson-Cook model. An explicit fully-coupled thermomechanical model approach was used for this simulation. Where an adaptive mesh domain (Arbitrary Lagrangian-Eulerian) was used to accommodate the extensive material deformation.

The axial force applied to the rivet during the production of the joint was modelled as a pressure applied to the bottom surface of the rivet. The top surface of the rivet was constrained. The rotation of the rivet was not modelled, assuming the effect of rotational inertia and centrifugal forces as being negligible. The importance of the rivet rotation arises from how the heat is generated during the process. Amancio et. al [32] has proposed a heat input model for friction riveting, covering the present combination of materials. They concluded that the only significant source of heat generation was internal viscous dissipation by shearing in the molten polymer ahead of the rivet, for the AA2024-T351 and PEI material combination. The same analytical heat input model (Equation 3) was used to set the instantaneous heat flux, dependent on the process parameters. This heat flux was applied to the bottom surface of the rivet, modelling the portion of the heat generated during the friction phase of the process and transferred to the metallic rivet.
The model is thermo-mechanical and comprises the coupled effect of structural analysis with thermal analysis. The thermal field results from the externally applied heat flux and the heat generated during the internal plastic deformation of the metallic rivet. Figure 15 shows a comparison between experimental and initial studies on corresponding simulated plastic deformation of the rivet.

Using a reduced statistical regression model capable of predicting process temperature, the temperature evolution of the rivet was compared to the predicted data. Here some differences were expected, as heat generated by plastic deformation also contributes to the increase in temperature inside the material, which is not directly taken into account by the statistical analytical process temperature model. The plastic deformation observed experimentally and characterized by joint formation measurements was used to validate the FEM.
5. Conclusions and Outlook

While considerable work had been published on the displacement-controlled variant of friction riveting, the force-controlled variant was yet to be extensively investigated, before the first two publications summarized in this work. These publications describe the research on how the process parameters of force-controlled time-limited friction riveting influenced the joint formation, process temperature, mechanical energy input and global mechanical performance of the dissimilar joints produced. The third publication, studied the feasibility of friction-phase-only friction riveting, designated as a single-phase process variant.

The knowledge generated by this work also aimed at investigating how to better control the generation of energy during the process, by evaluating what are the process parameter contributions to that energy. Following a systematic statistical approach on understanding the investigated responses, analytical models were established. They provide a broad and continuous assessment on how the materials respond to the process. This will support the transfer of friction riveting process to industrial applications, as specific requirements and constraints can be readily addressed by the analytical predictive models. Hence, bringing down cost associated with development of new sets of process parameters. This is now possible in a direct and energy efficient manner, for the material combination investigated, i.e., joining of AA2024-T351 to PEI.

In Publication I, the first part of this investigation dealt with the complex process parameter interactions and contributions which shape the final plastically deformed rivet tip geometry, i.e. joint formation. Here, the energetic balance between the contributions resulting from friction and forging phases of the conventional force-controlled process, was assessed. Fundamental knowledge was developed on how, and which parameters could be fine-tuned in order to tailor a desired joint formation.

Publication II addressed the mechanical performance of the friction riveted joints. This was done considering the joint formation and mechanical energy input. Conclusions were drawn on how these material responses directly correlated with which other and how the process parameters could be optimized in order to produce energy efficient joints. Not only for the optimal region in terms of mechanical performance, but across its entire range. As for each application, the connection needs only to sustain a pre-determined load.

From the conclusions of the works reported in Publications I and II, it was necessary to explore the possibility of producing joints with good mechanical
properties while minimizing production requirements such as, forces applied to the materials being joined. Publication III addresses this issue, with the work demonstrating the feasibility of friction riveting without the use of a forging phase. Demonstrating that it is possible to achieve relatively high mechanical performance with slight increase in friction time and friction force parameters. This opens friction riveting to more flexible applications and lower cost of the manufacturing equipment.

With the cumulative knowledge gathered from this doctoral work, it was possible to understand how the process parameters promote heat generation and consequently rivet plastic deformation. As greater understanding on process control, material response and energy efficiency have been achieved. It was also demonstrated that simpler and less robust equipment are able to perform sound friction riveting connection.

The achieved process understanding is driving ongoing work on finite element based modelling of friction riveting. The possibility of using computational simulation to test different material combinations and setup features will constitute another stride in raising the technology readiness level of this process and industry openness to new fields of applications.
References


19. Amancio-Filho ST, Abibe AB, Dos Santos JF (2013) Method for connecting a plastic workpiece to a further workpiece. US 8,518,1:9


The rapidly growing public concern and awareness on issues related to climate change, has forced a fast shift across several industries toward more sustainable practices and products, namely the transportation sector. In the referred work, a variant of an alternative dissimilar material joining technology has been investigated. Designated as Friction Riveting, this process allows multi-material overlapping joints to be performed in a fast and relatively simple manner. One variant of this process is designated as force-controlled. The work studied how the parameters, influenced the amount of energy applied to the materials being joined. Statistical analytical models were established, allowing the production of fine-tuned joint formation and resulting mechanical performance. The knowledge gathered in this investigation has further demonstrated the potential of friction riveting for dissimilar material joining and allows the process to be considered for a wide range of industrial applications.