

FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Characterization of electrical and mechanical properties of aluminium/copper joints made by FSW

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**Masters Degree in Mechanical Engineering, Specialization in Materials and
Technological Processes**

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Resumo

A relevância e a procura crescentes da indústria dos veículos elétricos neste mundo da mobilidade potenciaram a investigação em todo o mundo na busca de formas de melhorar o sistema de distribuição de energia destes veículos elétricos. Mais especificamente, a importância da poupança de custos e da redução de peso é tida em grande consideração.

No sistema de barramento que alimenta todo o veículo elétrico, o principal material utilizado é o cobre (Cu), uma vez que oferece grande condutividade elétrica, resistência à corrosão e propriedades mecânicas. No entanto, apresenta desvantagens críticas, como o custo elevado e o aumento significativo do peso da estrutura. O alumínio (Al), com uma excelente relação força/peso, resistência à corrosão e um baixo custo sem comprometer o desempenho elétrico, pode efetivamente ser uma boa opção para substituir as zonas de barramento anteriormente feitas de cobre, o que pode melhorar o desempenho dos veículos elétricos e reduzir o consumo de energia. No entanto, estes dois materiais, quando unidos, tendem a formar Compostos Intermetálicos (IMCs) na interface Al-Cu, comprometendo a resistência da junta e a ligação dos materiais. Com isto, torna-se necessário realizar estudos e compreender como estes materiais dissimilares, com propriedades químicas e mecânicas distintas, podem ser unidos com sucesso.

Soldadura por fricção (Friction Stir Welding - FSW) e a soldadura de ponto por fricção (Friction Stir Spot Welding - FSSW) são processos que unem com sucesso estes dois materiais através da utilização de uma ferramenta rotativa que mistura a interface entre os materiais, criando uma ligação metalúrgica, sem perigo ambiental, sem atingir temperaturas de fusão e sem necessitar de material exterior para formar o cordão de soldadura.

O objetivo principal desta tese visa compreender extensivamente como o Al e o Cu se comportam quando unidos por FSW e FSSW, como a camada da interface afeta o desempenho mecânico e elétrico das juntas e o efeito de diferentes parâmetros de processo, através de configurações topo-a-topo e de sobreposição (*Butt and Single Lap Joint*). São também discutidas comparações entre as juntas de FSW e FSSW. Provetes foram produzidos a partir de ligas de alumínio 6XXX e Cu-ETP R240 e, para uma análise abrangente da junta, foram efetuados ensaios de tração, juntamente com microscopia eletrónica (SEM), ensaios de microdureza Vickers e ensaios de resistência elétrica.

Foi também desenvolvido um modelo numérico, com o objetivo principal de caracterizar a camada da interface, ou zona soldada, que é formada em juntas FSW/FSSW Al-Cu. Foram efetuadas simulações numéricas, mecânicas e termo-elétricas, que foram depois comparadas com dados experimentais, de modo a validar e calibrar o modelo.

Com este trabalho, foi possível criar uma junta FSW e FSSW Al-Cu eficaz, que apresentou um bom desempenho mecânico e elétrico. O modelo criado permitiu determinar as propriedades mecânicas das camadas IMC, fornecendo um método para prever a resistência da junta. Em última análise, foi demonstrado que este tipo de junta pode ser efetivamente utilizado para aplicações de baterias em veículos elétricos.

Palavras chave: Alumínio, Cobre, Soldadura por fricção (FSW), Soldadura de ponto por fricção (FSSW), Caracterização mecânica, Caracterização elétrica

Abstract

The increasing weight and demand of the electric vehicle industry in today's mobility world has catapulted researchers all around the world to focus on ways to better enhance the power distribution system of these EVs. Most specifically, the importance of cost-saving and weight reduction is taken in high regard.

Within the busbar system that powers the entire EV, the main material used is Copper (Cu), as it offers great electrical conductivity, corrosion resistance and mechanical properties. However, it presents critical setbacks, such as high cost and significant weight addition to the structure. Aluminium (Al), with excellent strength-to-weight ratio, corrosion resistance and a low cost without compromising electrical performance can effectively be a good option for replacing busbar zones previously made only from Cu, which can enhance EV performance and reduce energy consumption. These two materials when joined, however, tend to form Intermetallic Compounds (IMCs) in the Al-Cu interface, compromising the joint strength and material bonding. With this, it becomes clear that a study is needed to understand how these dissimilar materials, with distinct chemical and mechanical properties, can be successfully joined.

Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW) are processes that can successfully join these two materials through the use of a rotating tool mixing the interface between them and creating a metallurgical bond, without environmental danger, reaching melting temperatures and requiring filler material.

The primary objective of this thesis is to extensively understand how Al and Cu behave when joined together by FSW and FSSW, how the interface layer affects the joint's mechanical and electrical performance and the effect of different process parameters, through butt and lap configurations. Comparisons between FSW and FSSW joints are also discussed. Specimens were produced from Cu-ETP R240 and 6XXX aluminium alloys. For a comprehensive joint analysis, tensile tests were made, along with Scanning Electron Microscopy (SEM), Vickers microhardness tests, and electrical resistance tests.

A numerical model was also developed, with the main objective of characterizing the interface layer, or the welded area, formed in FSW/FSSW Al-Cu joints. Mechanical and thermal-electrical simulations were made and then compared with experimental data in order to validate and improve the model.

With this work, it was possible to successfully create effective FSW and FSSW Al-Cu joint, which exhibited good mechanical and electrical performance. The model created allowed to determine the mechanical properties of the IMC layers, providing a method to predict joint strength. Ultimately, it was shown that this type of joint can be effectively used for battery applications in EVs.

Keywords: Aluminium, Copper, Friction stir welding (FSW), Friction stir spot welding (FSSW), Mechanical and electrical characterization

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“A clear reminder that scientific advances don’t remove uncertainty, they simply move the borderline between certainty and uncertainty - the perfect space for an engineer to work.”

Bill Hammack

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Acronyms and Symbols

Al	Aluminium
BJ	Butt joint
BM	Base material
C	Carbon
Cu	Copper
CZM	Cohesive zone modelling
EV	Electric vehicle
FEUP	Faculdade de Engenharia da Universidade do Porto
FEM	Finite element modelling
FSSW	Friction stir spot welding
FSW	Friction stir welding
HAZ	Heat affected zone
MMC	Metal matrix composite
IMC	Intermetallic compound
SEM	Scanning electron microscopy
SLJ	Single lap joint
SZ	Stirred zone
TMAZ	Thermo-mechanically affected zone

Chapter 1

Introduction

1.1 Background and objectives

Industries such as those operating in the automotive and aerospace sectors have one continuous goal: make use of stronger, lighter and cheaper materials for application in their structures and equipments. Most specifically, the electrical vehicle (EV) industry is highly leaned into developing lighter components as more weight leads to higher energy consumption and less autonomy. The battery cells that generate the EV energy are connected and connect to other electric components, like the electric motor, through busbar systems [1]. An example of battery packs connected by busbars is represented in Figure 1.1. The most common used materials for busbar applications are Aluminium (Al) and Copper (Cu) [2]. A common way to join these two materials in busbar form consists of mechanical fasteners, such as bolted connections and riveting [3]. Some busbar joining processes can be seen in Figure 1.2 However, the joint interface air exposure is a catalyst for moisture accumulation, and joint electrical conductivity is affected by the lower conductivity of the fasteners. If these two materials are welded together, a good connection can be achieved, reducing thermal issues and enhancing electrical performance [4]. Many welding methods can be used to join these dissimilar materials, such as fusion welding and brazing. However, due to large differences in Al and Cu's chemical and mechanical properties, a uniform joining poses a challenge for investigators, with addition of high stress concentrations [4] and the formation of an Intermetallic Compound (IMC) layer which, if not controlled, can severely affect mechanical and electrical properties of the joint [5].

Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW) are solid-state welding processes that can join two materials with frictional heat generated by a rotating tool. It poses many advantages over conventional welding processes, as it is an environmental friendly process, does not force the materials to their liquid state, and operates at relative low temperatures, while also requiring no filler material. Additionally, the pressure applied by the tool can result in excellent busbar contact which can drastically reduce the joint's electrical resistance. Nonetheless, it still

forms IMC layers. An extensive study of the influence of process parameters in friction stir welded Al-Cu joints is necessary in order to enable consistent and reliable busbar production.

The objective of this thesis is to extensively understand the mechanical and electrical behavior of three FSW/FSSW configurations, given into account different process parameters and the interface layer presence and effect on the joint's performance.

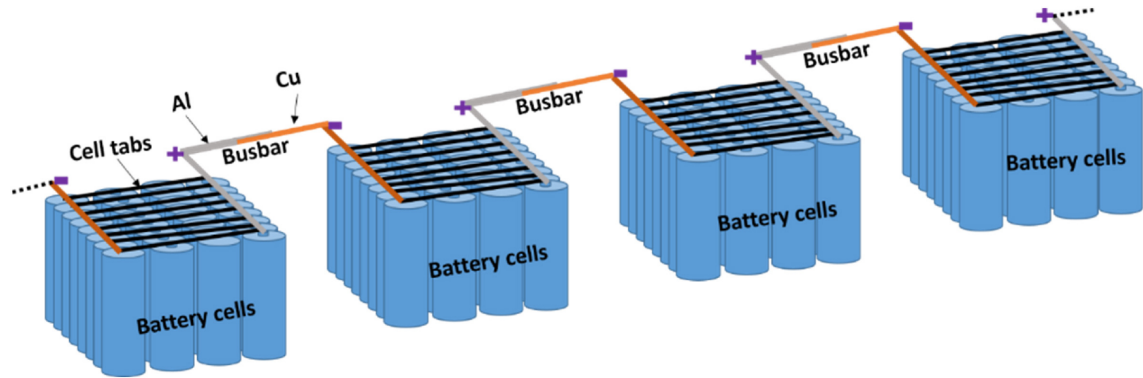


Figure 1.1: Schematic of battery packs connected by Al and Cu busbars [4].

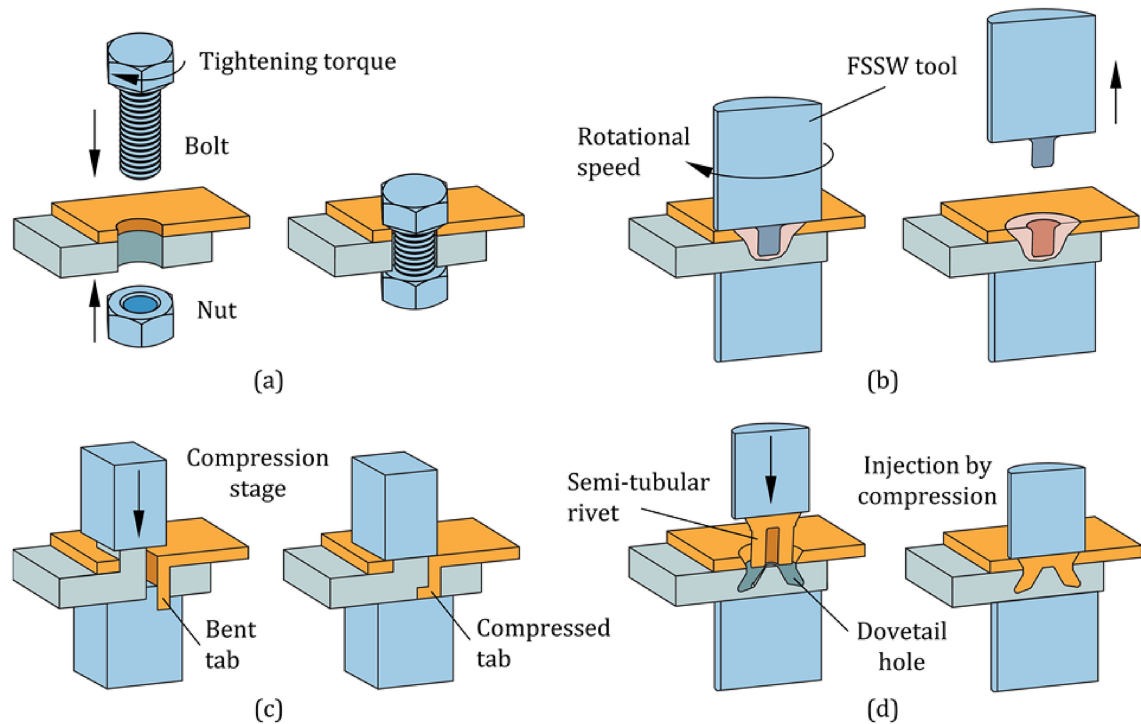


Figure 1.2: Schematic representation of the unit cells that are representative of the hybrid busbar lap joints fabricated by (a) fastening, (b) friction stir spot welding, (c) sheet-bulk compression, and (d) injection lap riveting with details of the corresponding cross-sections [6].

1.2 Research methodology

To achieve the objectives set for the thesis, a methodology was carried out following the steps presented below:

- An overview of FSW (and FSSW) process and dissimilar Al-Cu FSW joints was made in order to understand the status and discoveries regarding the behavior between both materials;
- A numerical model was developed to simulate and replicate the three approached variants: single lap joint (SLJ) made by FSW, SLJ made by FSSW, and butt joint (BJ) by FSW. The interface layer is assumed as a brittle cohesive material. This model was subsequently adjusted given the experimental results;
- FSW and FSSW Al-Cu joints were experimentally produced, taking into account different tool rotation speeds, plunge depths and tool rotation directions. After manufacture, the joints were analysed mechanically, electrically and microscopically, through tensile testing, Vickers microhardness measurements, electrical conduction tests, and scanning electron microscopy (SEM).

1.3 Thesis overview

The chosen structure for the thesis is described as follows:

Chapter 1: This chapter offers an introduction to the dissertation, and it presents an initial background contextualization to the field of study investigated, the research objectives and the methodology used to guide the work showcased.

Chapter 2: A state of the art is showcased in this chapter, starting with a brief chronology of FSW and its parent processes, the fundamentals of FSW and its process parameters and variables, the materials used in FSW with special attention to Al and Cu, its defects when joined, and the latest process technology developments, along with the main strategies used to control FSW challenges.

Chapter 3: Depicts the entire experimental procedure that was made in order to understand and study the mechanical and electrical properties of FSW Al and Cu joints. It describes the joint preparation and production, the process parameters used and the experimental testing made, such as SEM, fractography, tensile tests, micro hardness analysis and electrical conduction tests applied to the joints in order to obtain the electrical resistance's evolution with temperature.

Chapter 4: This chapter encloses all numerical model development, from initial simplifications and approaches for electrical and mechanical simulations.

Chapter 5: Offers a summary of two papers developed during the semester, complementing the master thesis and composing the discussion. It aims at the calibration and validation of the numerical models (Paper A) and at a mechanical, electrical and welding parameters comparison between the three variants produced.

Chapter 6: The last chapter draws out conclusions based on the collected experimental data and the numerical results. A comparison between process parameters sets is discussed. It summarizes the main findings of the entire work, highlighting mechanical and electrical performance of each welded configuration investigated, as well as finding parallelism between numerical simulation and experimental testing.

Chapter 2

State of the art review

In Chapter 2, a state of the art review involving the Friction Stir Welding (FSW) process is made, through the means of analysing published academic and investigation work. It starts with a brief historic contextualization and introduction, followed by the process's fundamentals, process parameters and variables, most common materials and its applications, microstructure and mechanical properties achieved through FSW, some recent advancements and techniques, and finally the possible challenges and directions this process can take.

2.1 Introduction

When two similar or dissimilar materials are permanently joined through the use of heat or pressure, they are welded. This joining technique is divided into four main processes:

- Resistance welding;
- Soldering or brazing;
- Fusion welding;
- Solid State Welding (SSW).

Focusing on SSW, this method bonds two pieces together using pressure at close contact and with a subsequent temperature lower than the melting temperature of both base materials. This process's high pressure results in base material softening due to friction-generated heat, and it is named Friction Welding (FW) [7]. Many friction-stir based techniques were later developed from this process, and are depicted in Figure 2.1.

Wayne Thomas, in collaboration with the National Aeronautics and Space Administration (NASA), created the FSW process in 1991 at the Welding Institute UK [7]. In this process, a mechanical stirrer penetrates the base materials interface in order to join them. This process was initially aimed and limited to weight reduction in aerospace industry and aluminium alloys [9], but with

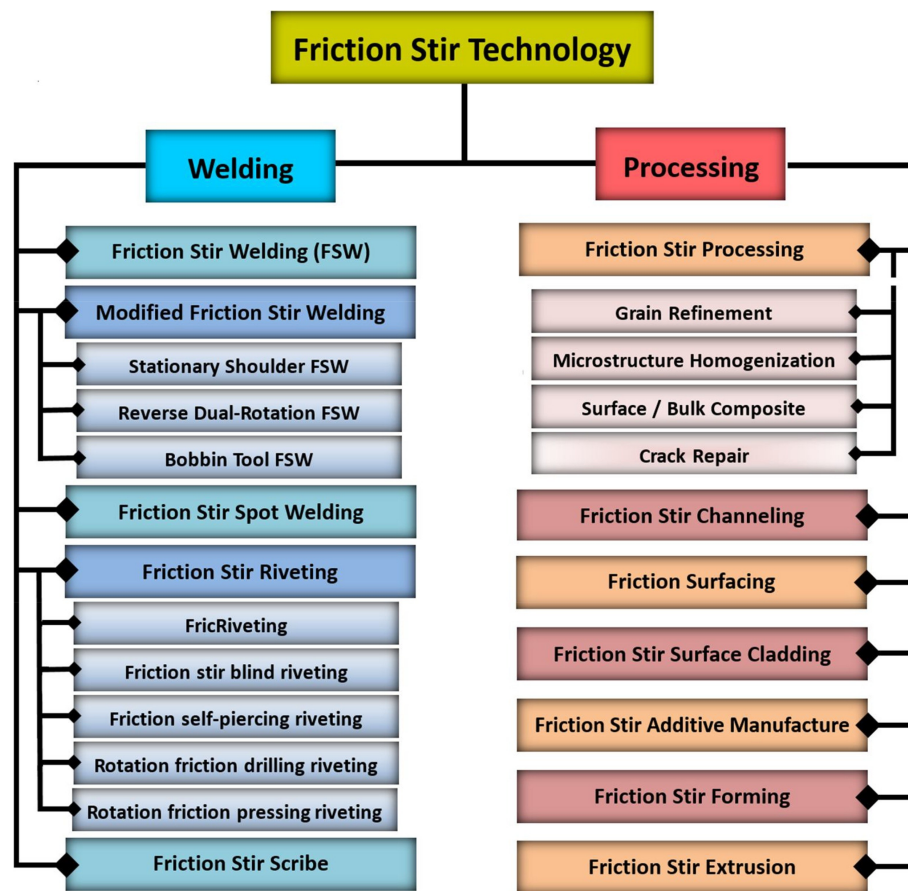


Figure 2.1: Stir-friction based techniques [8].

technology advancement, many different alloys (e.g. copper, titanium, magnesium and nickel ones) as well as materials (lead, stainless steel, mild steel, Metal Matrix Composites (MMCs), and even thermoplastics [10]) can be joined with this welding technique.

2.1.1 Fundamentals of FSW

The principle of FSW consists of a cylindrical tool with a certain profiled pin that is rotated and plunged into the interface of the two base materials to be joined, as depicted in Figure 2.2. This process is divided into four different stages (see Figure 2.3), which include [8]:

Plunging stage : The tool chosen which is at a constant spindle speed, is plunged, through the assist of a downward axial force, into the initial location of the joint until the tool's shoulder enters contact with the base material's surface, beginning the heating and plastic deformation process;

Dwelling stage : The tool keeps rotating in the initial plunged location for a short amount of time (typically 5 to 10 s [8]), depending on the base material variables, such as mechanical properties and substrate thickness. This phase is critical for the overall process, as it generates

the sufficient amount of friction heat (between the tool and materials) to cause the now-softened material to go under a high strain and strain rate [11], and flow around the tool, generating more heat and ensuring that the material ahead of the tool is already plasticized for the next stage to happen;

Welding stage : The tool starts advancing into the joint interface line at a constant (defined) welding speed. As the tool advances, heat is constantly being generated by shoulder/work-piece friction and deformation. The flowing material in the vicinity of the pin goes from the advancing side of the pin to behind it, thus filling the cavity left by the pin. The flowing materials also mix with each other through atomic diffusion [8], leaving a welded joint behind;

Retracting and cooling stage : When the weld is complete, the tool is retracted from the interface, leaving an exit hole. This however can be avoided by refilling the exit hole or using a run plate as sacrifice.

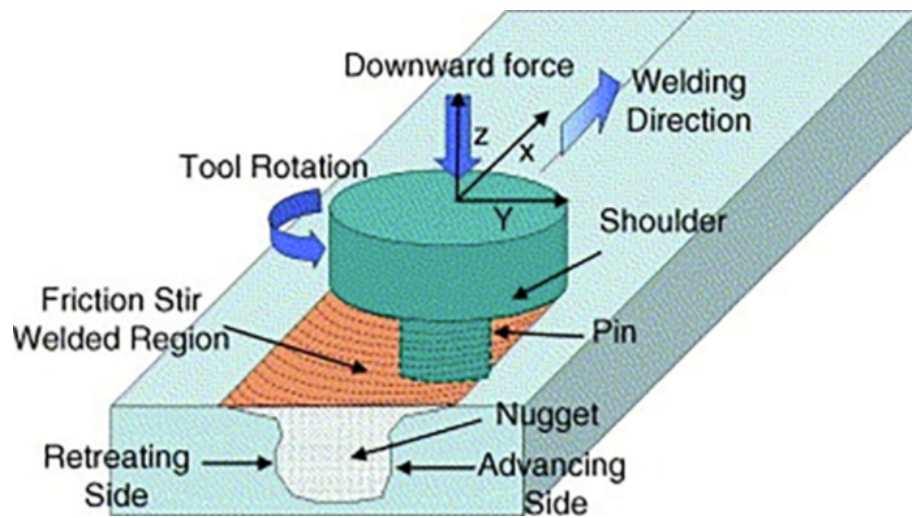


Figure 2.2: FSW schematic and elements [9].

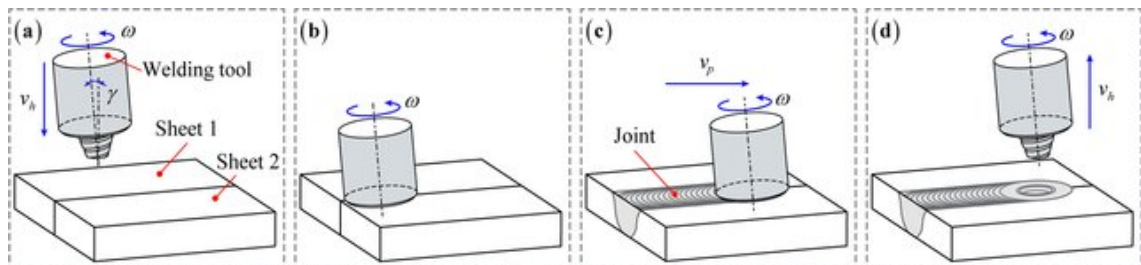


Figure 2.3: FSW process stages: a) plunging stage, b) dwelling stage, c) welding stage, d) retracting and cooling stage [12].

2.1.2 Friction Stir Spot Welding

FSSW is a FSW variant that focus on local welding applications, such as riveting for aerospace application [13]. Unlike FSW, it does not have a transverse movement, meaning that the welded area is left with a keyhole geometry, as depicted in Figure 2.4.

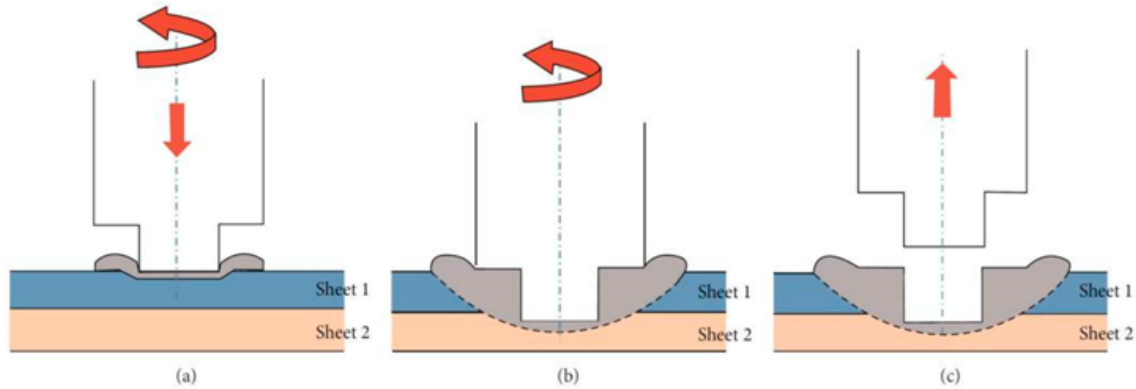


Figure 2.4: A FSSW process schematic of the tool's action steps: a) plunging while rotating, b) dwelling after plunging to the specified depth, c) FSSW tool extraction [14].

2.2 Process parameters and variables

FSW process parameters are divided in three main groups, and a correct selection of these parameters is essential for a desired joint: Tool geometry and design, welding parameters and joint design.

2.2.1 Tool geometry and design

As explained in Chapter 2.1.1, the tools used in FSW have a shoulder and a pin (or probe). Its typical geometry is represented in Figure 2.5.

The shoulder is responsible for continuously applying pressure to constrain the plasticized material around the pin area, for heating the base material's surface area and for providing the plunging forming action required for creating the weld [16]. The most common types of shoulder end surface features are:

- A flat and smooth surface (most common and direct one, but can't trap material within contact area so it gets flushed out [17]);
- With scrolls;
- With ridges;
- With contours/edges;

- With grooves;
- With concentric circles.

All shoulder features are depicted in Figure 2.6, as well as their end surface, which could be flat, concave or convex. The point of altering the shoulder feature is to alter the contact with the workpiece. For example: a tool shoulder with ridges tends to result in reduced axial forces during FSW and produce good mechanical properties [18]; a scrolled shoulder facilitates the movement of the softened material from the edge to the tool centre [17].

Another variable shape is the shoulder's outer surface, which can be cylindrical or conical (the conical shape allows the material to be pushed into the cavity centre [18]) but it is expected that a conical shape has minimal impact on the welding process, as shoulder thrust depth is usually minimal [9].

As for pin profiles, the five most common geometries are: straight cylindrical, threaded cylindrical, tapered cylindrical, square and triangle (see Figure 2.7).

Studies have shown that one geometrical parameter for tool design can be defined with $\frac{D}{d}$, D being the shoulder diameter and d the pin diameter. A ratio of 3 is considered optimal [20]. Padmanaban et. al [15] investigated different pin profiles and their effects on 220x75x6 mm AZ31B magnesium alloy butt joints with different shoulder to pin ratios and concluded that threaded cylindrical pins achieve the best joint efficiency and overall mechanical properties when comparing to joints produced by different pin profiles. It was concluded that a shoulder to pin ratio of 3 seems to also achieve the best joint properties and efficiency.

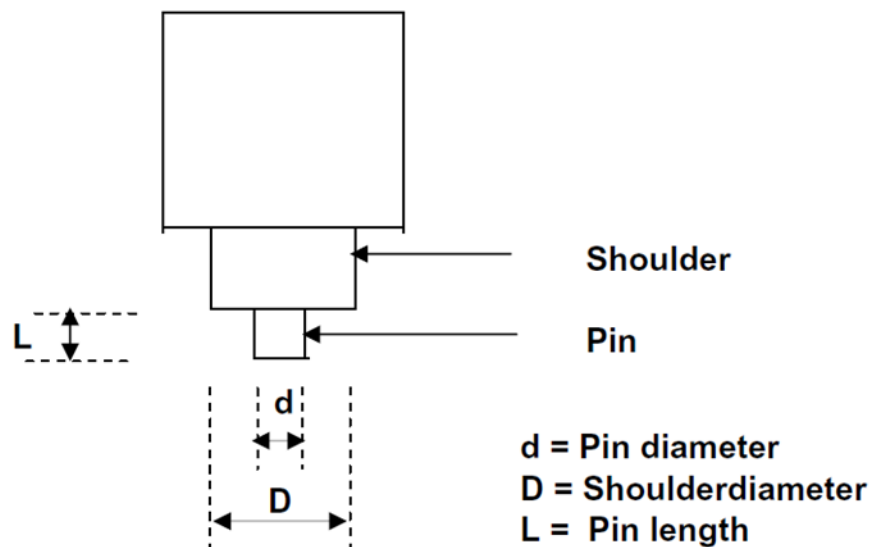


Figure 2.5: Typical FSW tool geometry [15].

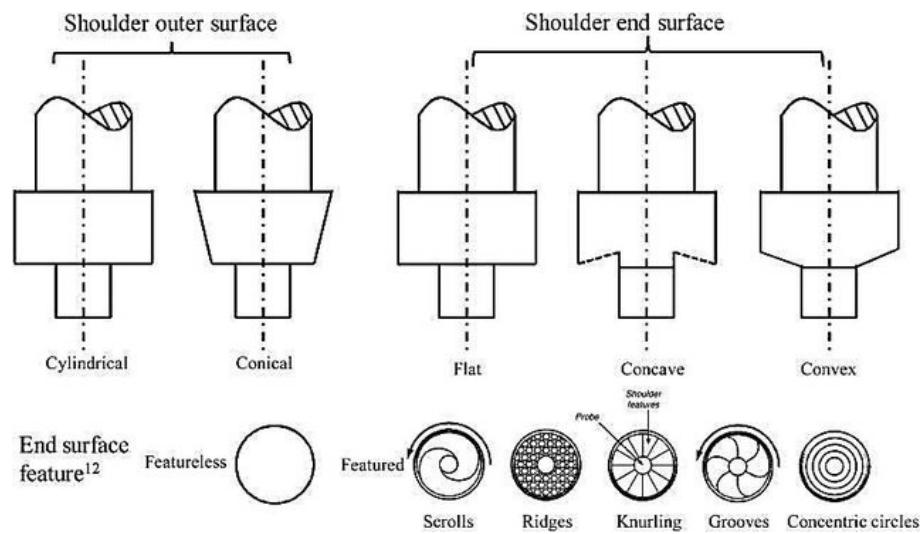


Figure 2.6: Types of shoulder shapes and characteristics [19].

The tool is non-consumable, which means that, for the materials selected for joining by FSW, the selected tool must have high hardness and corrosion resistance, as well as better mechanical properties than the materials to be joined [7]. It should also be dimensionally stable, resistant to creep, thermal fatigue and fracture, and chemically stable, as to not interact with the metals to be joined [21].

FSW tools can be divided into three types, as seen in Figure 2.8: fixed, adjustable and self-reacting tool. The fixed probe tool (Figure 2.8a) is the most conventional one. Due to the fixed probe length, only constant thickness workpiece can be used for welding. This type of tool is commonly used in Friction Stir Spot Welding (FSSW). The adjustable tool (Figure 2.8b) has a probe independent of the shoulder, and can adjust its length. With this tool type, the shoulder and the pin can be manufactured from different materials. There are advantages to this tool type over the conventional one, as the pin can be easily replaced if worn, and exit-hole filling strategies can be explored. The third and final tool type is the bobbin type tool (Figure 2.8c), which consists of a top shoulder, a probe, and a bottom shoulder. Because of this latter component, a back plate is not necessary to compensate the axial forces, and multiple joint thicknesses can be welded, since the probe length can be adjusted. However, this geometry limits the tool to work only perpendicularly to the workpiece surface, which does not happen in the fixed and adjustable tool, as a tilt angle can be applied. [22].

Many materials can be used the FSW tool, such as tool steel, stainless steels, High Carbon and Chromium steels, refractory metals, Carbides, MMCs and Polycrystalline Cubic Boron Nitride (PCBN) [20]. The correct tool material selection depends on the material to be welded. Tool steel is a cheap option but starts presenting tool wear over time. Refractory metals are used for high melting temperature materials such as steel, nickel and titanium alloys. PCBN tool material can weld various materials, as it has high wear resistance at high temperatures and is highly abrasive

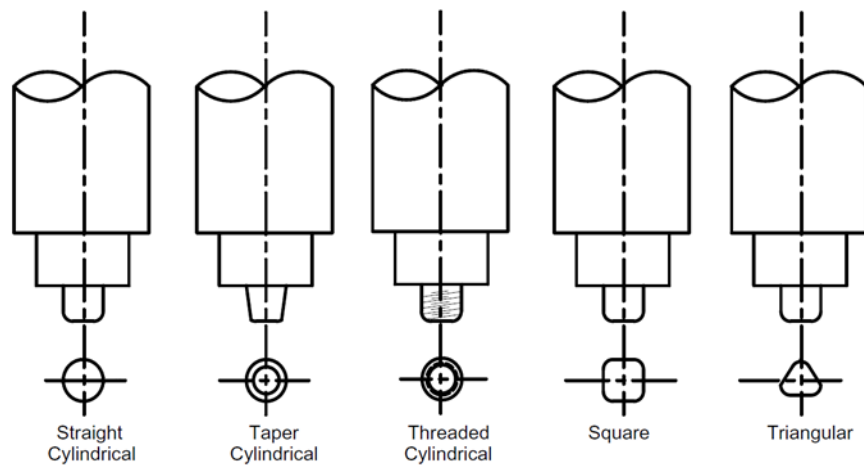


Figure 2.7: Types of probe shapes [15].

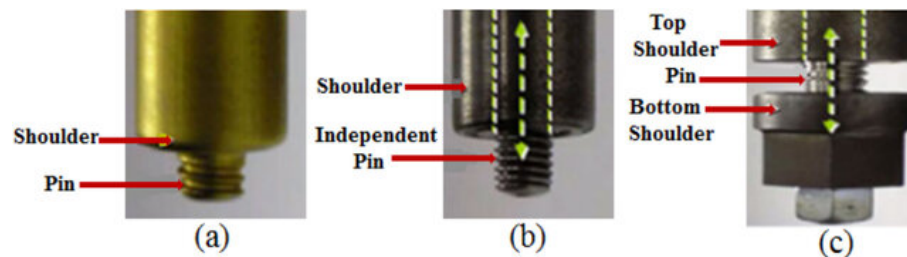


Figure 2.8: FSW tool types: a) fixed probe, b) adjustable, c) bobbin-type [23].

[20]. PCBN materials have low fracture toughness and are expensive, so procedure assessment must be made before selecting a certain tool material [24]. W based alloys are not as hard and wear resistant as PCBNs but are cheaper, having being used to weld steels and titanium alloys [24]. These characteristics are summarized in Table 2.1.

2.2.2 Welding parameters

Tool Rotational Speed/Spindle speed: Tool rotation is the crucial parameter on FSW process, and is measured in rpm. The varying of this parameter mainly affects the produced frictional heat, the stirring and mixing of the materials and the oxide layer's breaking [20].

Tool Linear Speed/Welding Speed: The tool linear speed or welding speed (measured in mm/s or mm/min) is the speed that the tool has when passing through the joint interface (see Figure 2.1.1). The heat generation is inversely proportionate to the linear speed and it is directly proportionate to the rotational speed, with the two speeds not interacting with each other [9]. A correct selection and balance of these two parameters can guarantee a quality welded joint and thus achieve better mechanical properties. Table 2.2 below shows the work made by Atharifar et. al, where concurring experimental and numerical data comparison of FSW AA6061 can lead to know how the various forces included in FSW processing vary with linear and rotational speed variation.

Plunging Depth and Tilt Angle: Plunging depth is defined as the depth at which the lowest end of the tool's shoulder penetrates beyond the limit of the top substrate. A plunge depth is usually applied to better guarantee a satisfactory mixing and bonding between two base materials. The tilt angle of the tool is applied in a weld so a better extraction of material at the advancing side can occur, as well as providing the material with additional downward forging action [8].

Table 2.1: Characteristics of FSW tool materials [17, 18].

Material	Benefits	Limitations	Applications
Tool Steels (e.g. AISI H13)	Ease to fabricate (good machinability) and	High tool wear especially for MMCs	Soft materials such as Al, Mg, Cu, etc.
Ni-Co Alloys (Inconel, Nimonic)	Good corrosion and wear resistance	Precipitate overaging and dissolution	Used for Al and Cu alloys, and Al Composites
Refractory materials (Mo and W alloys, Ta and Nb)	High strength nearly up to melting temperature; High melting temperature	Expensive, possibility of ductility degradation	High melting point alloys (e.g. Ni alloys)
Carbides and MMCs (WC, WC-Co, etc.)	Good fracture toughness and excellent wear resistance	Not compatible with Cu alloys	Mg, Ti, and steel alloys
PCBNs	High hardness (below diamond) and stability at high temperatures	Very expensive and extremely difficult to machine	Used for wear resistance materials

Table 2.2: Influence of welding and rotational speed increase on FSW forces [25].

		Linear/Welding Speed	Rotational/Spindle Speed
Effects on pin	Longitudinal force	+	-
	Axial force	~	+
	Lateral force	~	+
	Moment about tool axis	~	-
Effect on shoulder	Longitudinal force	+	-
	Axial force	-	+
	Lateral force	~	+
	Moment about tool axis	~	-
Total effect	Longitudinal force	+	-
	Axial force	-	+
	Lateral force	~	+
	Moment about tool axis	+	-

2.2.3 Joint design

Figure 2.9 displays the joint configurations available for FSW. The most common and convenient joint configuration for this process tends to be the butt joint configuration (Figure 2.9 a)). For this configuration, the joint tends to be clamped on both sides and have a backing plate. This is done so that the forces applied by the tool at the interface don't separate the base materials, as in the plunge phase base materials are not yet heated to the point that they can deform plastically. Lap joints are also vastly used and studied in the industry [26]. In the electrical industry, most busbars are in a single lap joint configuration and joined through the means of fasteners, such as bolts.

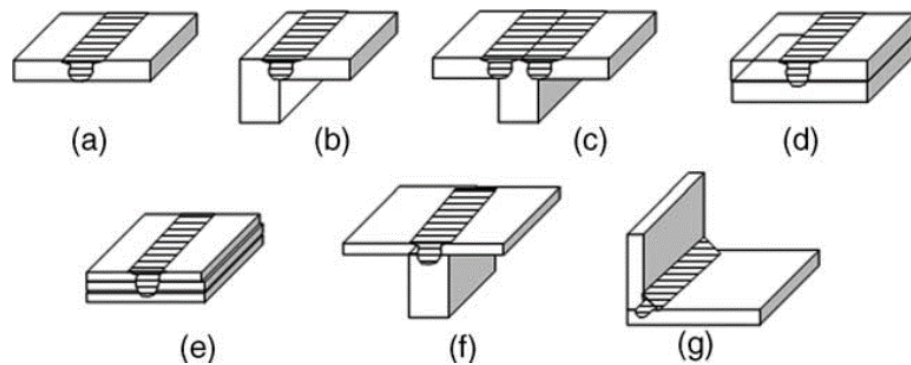


Figure 2.9: Joint configurations for FSW: (a) square butt, (b) edge butt, (c) T butt joint, (d) lap joint, (e) multiple lap joint, (f) T lap joint, (g) fillet joint [27].

2.3 FSW of Al to Cu

Since its development, FSW has been employed to join a wide array of materials, including metals and polymers. Many studies about friction stir welding of similar materials such as aluminium [28], copper and titanium [29] have already been published and investigated. However, in the context of this thesis, FSW between dissimilar materials, more specifically aluminium and copper FSW, is of the utmost importance and needs to be clearly understood.

2.3.1 Influence of welding configuration

Firstly, it is important to understand what is the best material placement for lap and butt welding, and how the welding configuration affects the rest of the welding process. As Al and Cu have very different chemical and physical properties, choosing which material gets penetrated first by the tool in lap configuration is critical. For butt joint, the way the flow occurs and the reactions generated also highly depend on material positioning relative to the Advancing Side (AS) and the Retreating Side (RS) [30]. The AS refers to the side in which the rotation and travel direction is equal to the tool's, and the opposite occurs in the RS. The Al and Cu positions greatly affect the FSW heat input, and an uneven heat distribution can result in joint defects [31].

Figure 2.10 showcases the possible material placement for butt and lap welding. It has been concluded in the literature that Al is most suitable as the top substrate for lap welding, as it has a lower melting point than Cu, resulting in a more smooth mixing and better welding area [30], and a lower thermal conductivity that helps generating more heat [32].

Focusing on butt FSW, there is a relevant discussion regarding the placement of Al or Cu in the AS or RS, which generates mixed conclusions. It can be said that the material with the highest melting should be placed on the high temperature side, equalling the plastic state for both sides [33]. If Al is placed on RS, tunnel defects could form during FSW due to Al adhesion to the shoulder root [30], shifting Al towards the AS. Dong Fengbo et. al [33] found that placing Al on AS can generate 1.36 times stronger joints. This can be justified by a more dense microstructure, with smaller alternating Al and Cu layers, unlike when Cu is in AS, which generates a more chaotic mixing with possible micro pores. On the other hand, it can be beneficial to place Cu in the AS. As Cu has a higher hardness, it should be wise to place Al in the RS, as most material flow occurs mainly in the Al side. This because Xue, P. et. al [34] believed that material flow travelled from the RS to the AS, resulting in a tight weld on the AS. If the harder material is on the RS, material transfer to the AS is lowered, forming a less sound weld [30]. All the complexity surrounding dissimilar material flow during butt FSW reflects the not yet reached consensus.

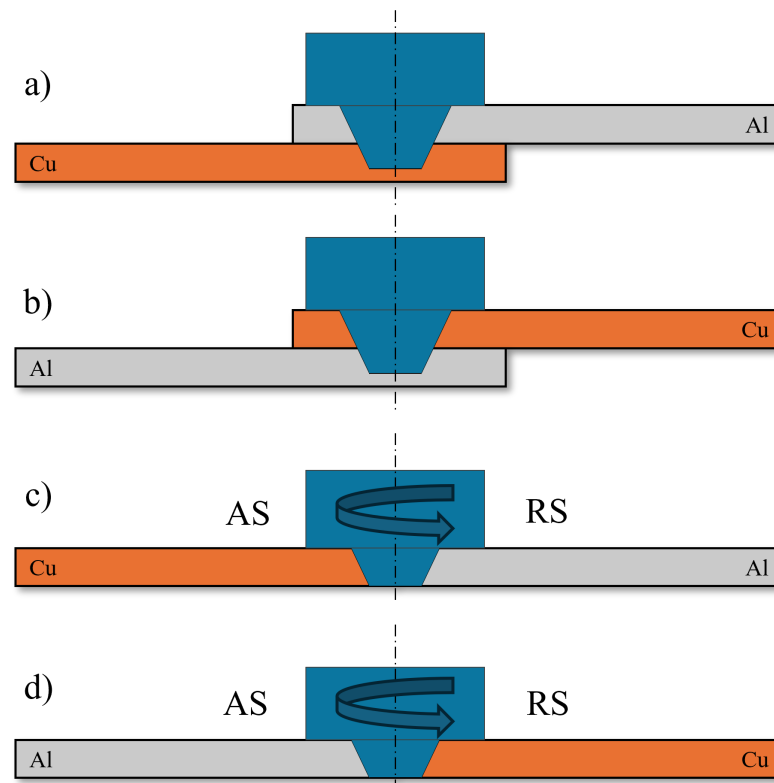


Figure 2.10: Base material placement in FSW: a) Cu on the top, b) Al on the top, c) Cu on the AS, d) Al on the AS.

The offset distance to the weld centre also greatly influences the quality of butt joints. Figure 2.11 depicts a tool offset applied to a Al/Cu butt joint. The tool can be biased towards the Al side or the Cu side. Due to differences in melting points and thermal conductivity, a 0 mm tool offset will not be able produce satisfactory plastic deformation in Al and Cu [32]. By shifting the tool pin towards the Al side during joining, the thermal stresses and the heat distribution is more uniform. It has been concluded that the tool pin offset distance affects the type and quantity of IMCs that are formed in the welded area [33], more specifically a smaller tool offset increases the IMC formation which decreases the joint's strength [35].

One possible approach is to apply a tool offset so that small particles get peeled away from Cu and lodged inside the Al matrix [32], which benefit the quality of the metallurgical bonding between both materials and reduce the amount of IMCs. When the offset is on the Cu side, the Cu content in the weld area increases and consequently the IMC presence tends to rise [36].

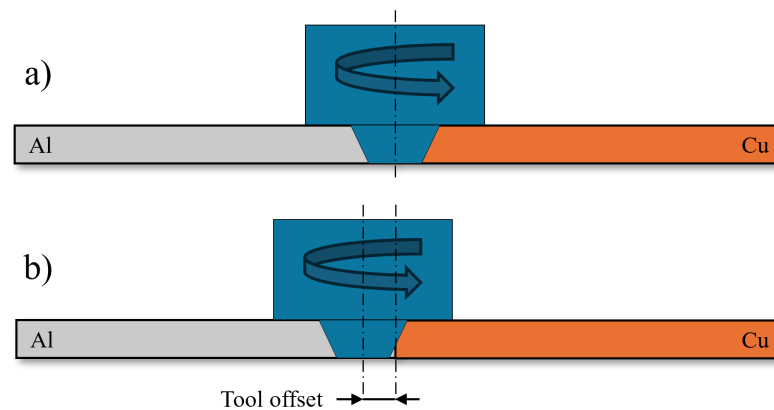


Figure 2.11: Tool offset principle: a) No tool offset applied, b) tool offset applied towards the Al side.

2.3.2 Influence of welding parameters

Another spectrum used to understand Al to Cu FSW is the welding parameters influence on the joined area.

Rotational Speed This parameter is of great influence in dissimilar Al and Cu joints by FSW as it is directly related to the heat generated by friction and thus the plastic deformation occurring in the stir zone. Higher rotational speed results in higher IMC formation due to the previously mentioned factors [32]. Additionally, high rotation speeds tend to subject steel tools to increased wear and decrease in tool life. On the contrary, low spindle speeds result in lower temperature input, which may not completely form a sound weld, decreasing its strength and increasing hardness [34].

Welding Speed Along with rotational speed, the tool's welding speed greatly influences the heat generation in the welded area and IMC formation. High welding speeds will result in a low heat

generation that isn't enough to form a complete welded interface [32]. On the other hand, low welding speeds will form more IMCs, which tend to develop cracks, reducing the joint's strength [37].

2.3.3 IMC formation and influence

It is clear that a major factor when friction stir welding Al to Cu is understanding the IMC layer formation and its composition, along with its influence on the mechanical properties. With help from line scanning and XRD phase analysis, researchers have concluded that the formed IMCs consist of Al_4Cu_9 , AlCu , Al_2Cu and AlCu_3 , and various combinations can appear depending on the material and welding conditions [30]. When Al and Cu are being joined by FSW or FSSW, a high heat generation, caused by high tool rotational speeds and dwell times, lead to the formation of these IMCs due to thermal activation [38] and Al-Cu diffusion through extreme deformation [39]. The thickness of the joint to weld also affects IMCs, as it is believed that thinner joints result in shorter reaction times and higher cooling rates, making IMC formation more difficult [30].

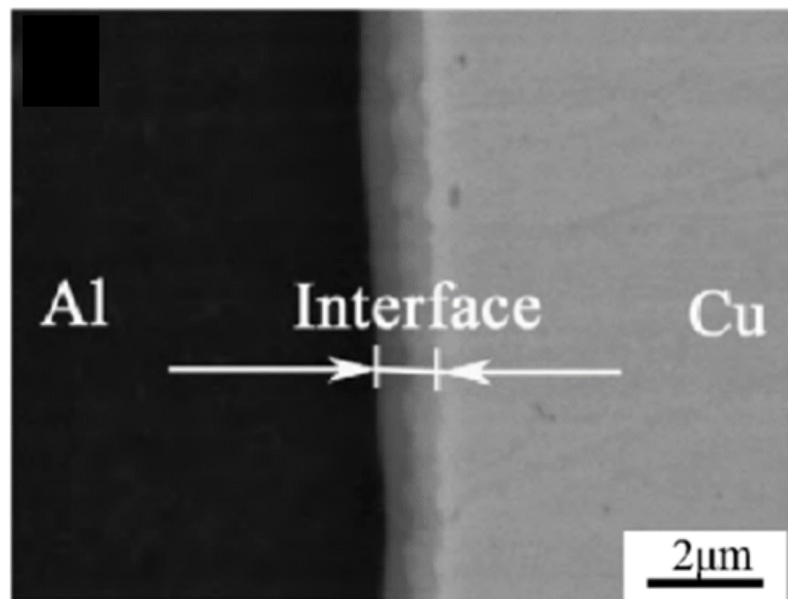


Figure 2.12: Microscopic image of a usual Al/Cu IMC layer [40].

2.3.4 Common defects

If FSW is not executed with a correct and balanced set of process parameters, the welded area will tend to reveal defects as pictured in Figure 2.13. Some factors that can promote defect formation include the spindle speed, welding speed, tool design, tilt angle and pin offset, plunge depth, workpiece thickness, etc. [41]. By understanding how to prevent the formations of these defects, sound joints can be produced.

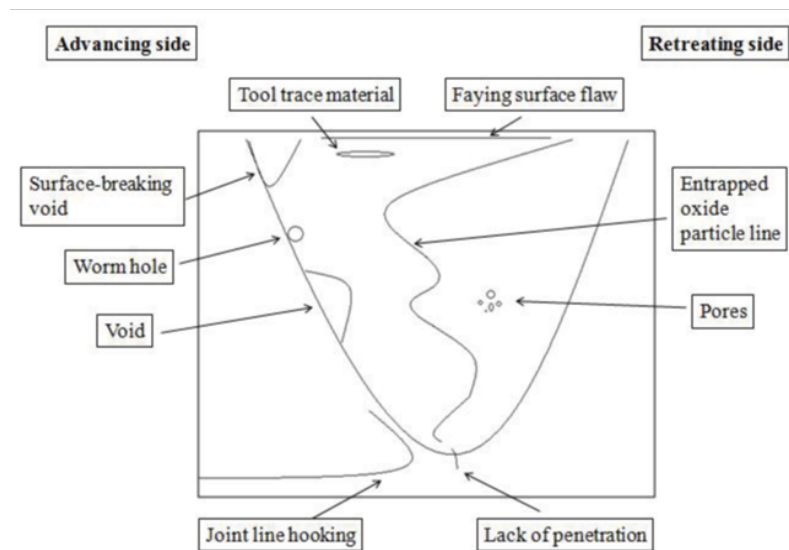


Figure 2.13: A schematic presentation of the location of different welding defects in copper FSW welds [42].

Cracks: Cracks can be usually found in dissimilar material FSW or FSSW, like Al and Cu joints. This is due to the big difference in material properties which does not allow a proper flow in the stirred zone, leading to the previously mentioned hard and brittle IMCs [41]. These compounds are highly likely to crack, and a larger IMC layer will lead to more cracking and a weaker joint [43]. An example of a crack in a dissimilar FSW joint can be seen in Figure 2.14.

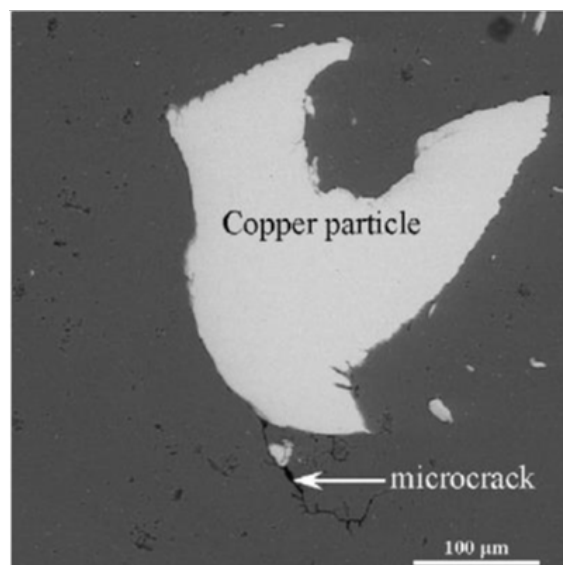


Figure 2.14: An example of a copper fragment in the Al matrix causing the propagation of a microcrack [44].

Voids/Tunnels: A void is a volumetric defect. It contains no material and is commonly found at the bottom weld zone in the AS [34, 40]. These bottom zones are often subjected to less heat

and plastic deformation, causing the materials to not adequately fill all the available space. This results in less joint ductility [32]. When a void is continuous and runs through the entire weld, it is called a tunnel defect.

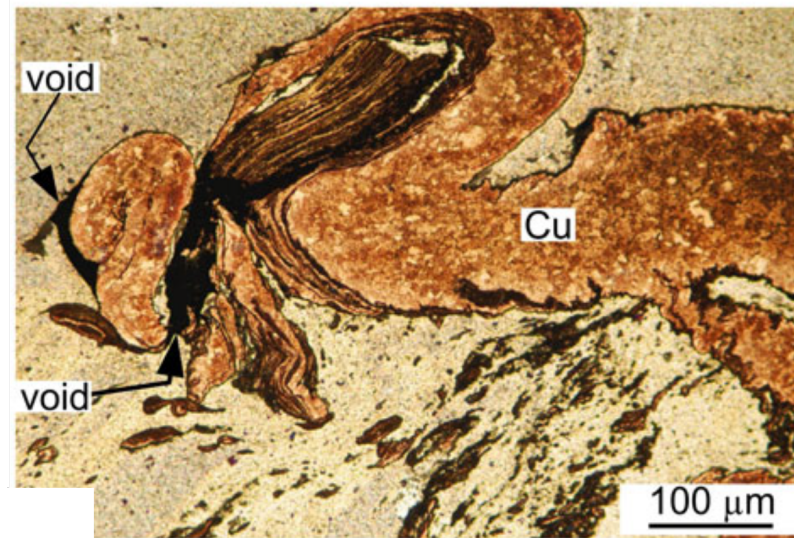


Figure 2.15: Example of voids in Al to Cu FSW [45].

Pores: Porosity is generally encountered within the stir zone through single pores or porosity lines [32], decreasing the joint's strength, as well as the heat input and material plasticity throughout the FSW process [46]. Parameters such as low tool tilt angle and plunge depth will not generate the necessary pressure to eliminate the formation of porosity [47, 48].

Lack of Penetration: The process variants that cause lack of penetration in FSW joints include short tool pins or low plunge depths. As heat generation is not enough in the interface zone farthest from the tool, joining can not be totally achieved, creating high stress zones around the non penetrated area [32].

Fragmental Defects This defect is exclusive to dissimilar material FSW, as it consists of scattered material particles unevenly distributed in the other material's matrix, increasing chances of void and microcrack formation [32]. Lower rotational speed and appropriate tool pin selection help reducing fragmental defects across the welded area [23].

Flash Flash defect occurs when the heated material escapes the area under the tool and gets expelled to the joint's top surface (see Figure 2.16). Flat shoulders tend to produce these defects as they can not contain the highly plasticized material, forcing it to escape outwards [49]. A correct tilt angle selection helps directing the material downwards reducing the risk of flash.

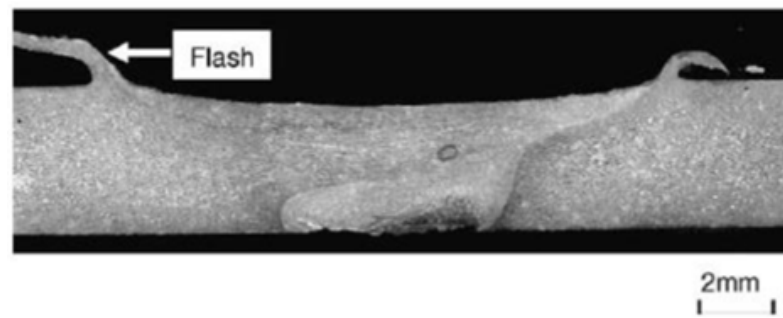


Figure 2.16: Typical flash defect of FSW [50].

2.4 Developments

As FSW is currently one of the most investigated novel methods for material joining, the area's development is constantly growing. However, the more relevant advancements for the Industry 4.0 of the FSW world belong to the use of Artificial Intelligence (AI) to determine beneficial process parameters that enhance the quality of welded joints. Mohanty et. al studied the prediction of effect of tool geometries on friction stir-welded aluminium joints using artificial neural networks (ANN) and fuzzy logic techniques [51] and concluded that such AI techniques could help choosing the correct input parameters in order to produce good joints even with the uncertainties associated with this process. Dehabadi et. al [52] used an ANN to predict the Vickers micro-hardness of AA6061 FSW sheets and got a mean absolute percentage error (MAPE) of less than 5%, which in fact indicates that this is a viable way of hardness prediction and evaluation within FSW processing. Hugget et. al [53] also used machine learning metaheuristic algorithms like K-nearest neighbour (KNN), fuzzy KNN and artificial bee colony (ABC) to predict friction-stir weld quality for specific process configurations. Their models achieved one hundred percent classification accuracy, which confirms that such AI can be used to aid humans and investigators when studying FSW.

2.5 Challenges and control

Meng et. al exposed and explored the most inherent issues that occur in FSW and presented solutions for each one of these problems [54], also depicted in Figure 2.17:

Back support: During FSW, due to the shear amount of friction generated in the process, the materials subjected to welding need to be highly fixed in all directions, as well as having a rigid back support, which can induce lack of mechanical properties and defects from lack of root penetration;

Weld thinning: Stress concentrations and decrease of bond area caused by the plunge depth of the tool;

Keyhole: After the retraction phase, the existence of the keyhole in the weld causes a decrease in the overall quality of the weld, as well as its mechanical properties.

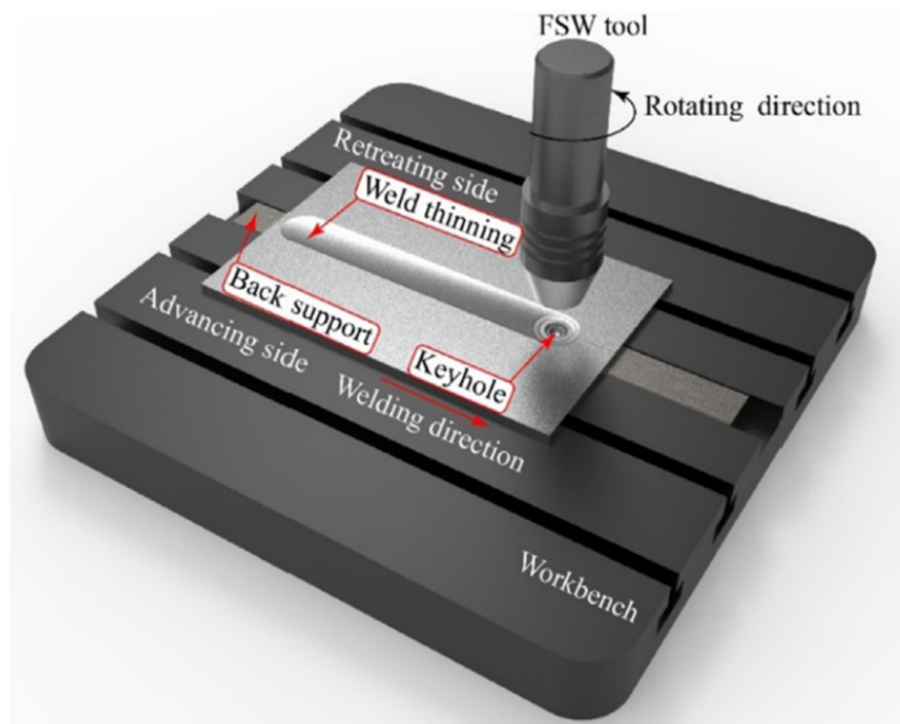


Figure 2.17: Inherent issues during FSW process [54].

When it comes to back support issues in FSW, the most common solution, already mentioned in Chapter 2.2.1, is the use of a bobbin tool to perform bobbin tool friction stir welding (BT-FSW). The use of this technology allows the reduction of the vertical load along the FSW direction, the avoiding of a rigid back support for the weld (reducing welding complexity), the reduction and elimination of lack of root penetration (mainly caused by the improper tool choice), and allows a constant and uniform heat generation across the total thickness of the weld, increasing welding uniformity [54].

Other technologies that address this issue include self-support friction stir welding (see Figure 2.18), which does not use a backing plate, but instead uses a tool with a concave upper shoulder, a low diameter convex lower shoulder (which adjusts the tilt angle needed for the weld) and a rotating pin, which enables this process to never need the entrance and exit holes that BT-FSW needs, as well as being more convenient for structures with narrower back spaces.

Weld thinning nearly always happens in FSW processes, as contact of shoulder with the base material, no matter how small the plunge depth is, causes plasticized material to overflow and abandon the nugget zone, causing this issue to be recurrent and taken into account. Besides the decrease of the joint's integrity and strength, the surface finish quality is diminished [54].

One of the main FSW derivative technologies to reduce weld thinning is stationary-shoulder FSW, developed by TWI, where a stationary shoulder contacts the top material at zero plunge depth, and a rotating pin penetrates and forms the welded area (see Figure 2.19) [56]. Compared to FSW, this process allows a smoother joint surface that reduces the need of post-machining

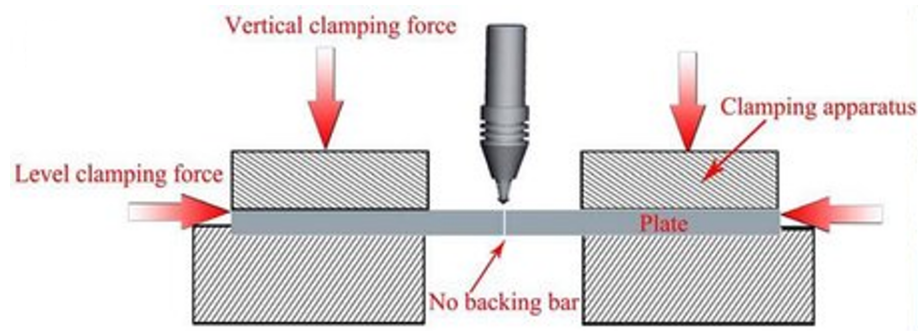


Figure 2.18: Self-support friction stir welding schematic [55].

processes, a reduction in residual stresses across the weld, joining of materials with a low thermal conductivity, welding "T" or corner joints, a reduction of torque and advancing resistance, and others [54].

Other explored processes used to diminish weld thinning include zero-plunge depth FSW [57], where a tool with a concave and scrolled shoulder keep the plasticized material enclosed and with a center-directed traction force, erasing weld-thinning possibility. This novel approach is depicted in Figure 2.20.

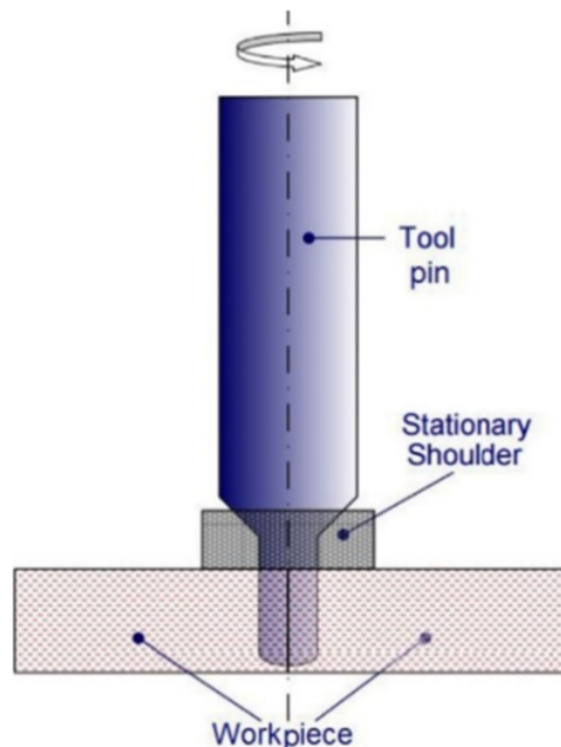


Figure 2.19: Stationary shoulder friction stir welding schematic [56].

Furthermore, the inevitable presence of a keyhole in FSW processes led to the development of many technologies to cover that keyhole with a certain filler material, such as: friction plug

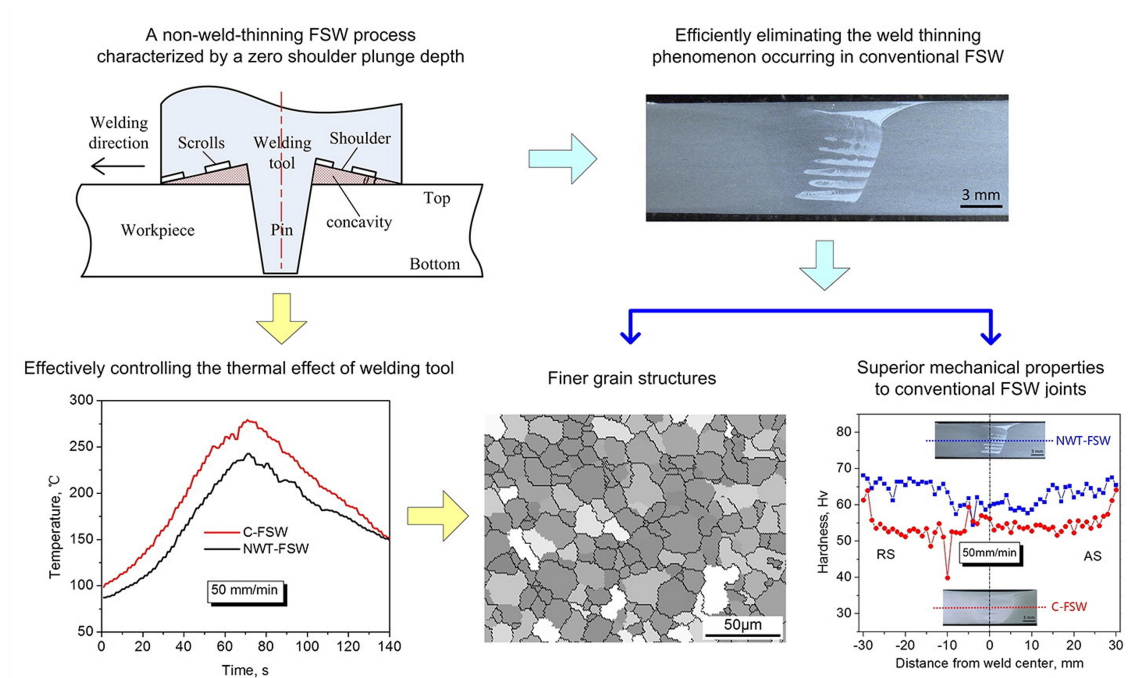


Figure 2.20: Graphic abstract of the zero plunge FSW [57].

welding, used by TWI and NASA [58, 59], where a plug is inserted in the keyhole area by use of friction between the taper plug and the keyhole's surface, with a post machining process to remove plug excess material (see Figure 2.21); filling friction stir welding, or FFSW, proposed by Huang et al. in 2011 and 2013 [60, 61], consists of a 3 stage process to refill the FSW keyhole with a consumable tool pin that, with the use of frictional heat caused by the shoulder, fractures at the lower shoulder level and is joined to the weld as depicted in Figure 2.22.

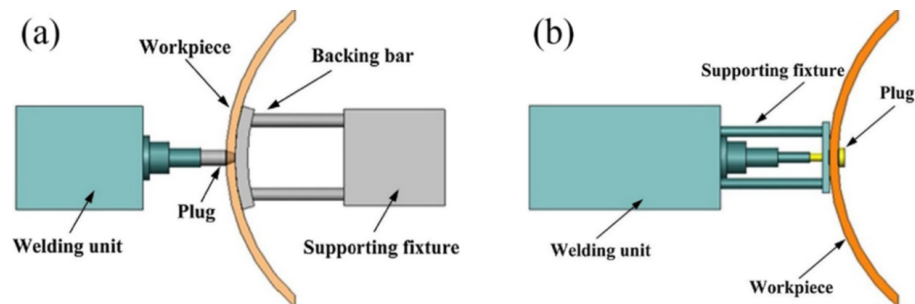


Figure 2.21: Schematics of FPW: (a) friction push plug welding, (b) friction pull plug welding [54].

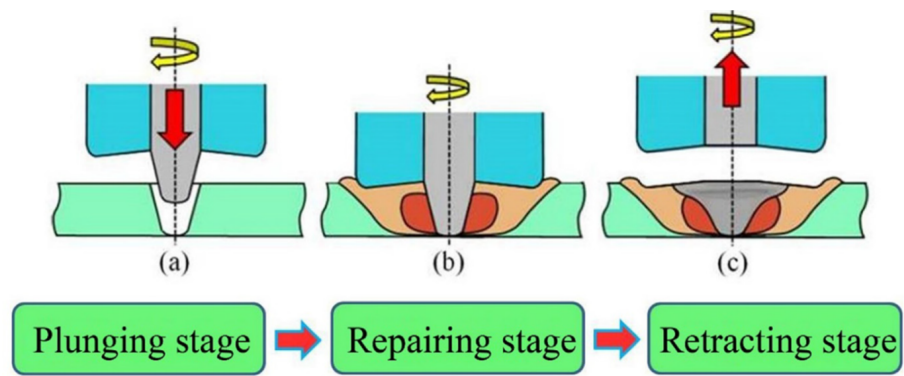


Figure 2.22: Schematics of FFSW: (a) plunging stage, (b) repairing stage, (c) retreating stage [54].

Chapter 3

Experimental procedures

In this chapter, the experimental procedure employed in this work will be explained and described, from materials used to the setup and machinery used to produce the joints.

After production, non-destructive tests were made, such as Scanning Electron Microscope (SEM), analysis of the fracture surfaces and measuring the joint's electrical resistance when subjected to electrical current at different temperature values. Furthermore, destructive tests were also executed, such as tensile tests and Vickers micro hardness tests.

3.1 Introduction

For a better understanding of how Al and Cu behave electrically and mechanically, two joint configurations were chosen: single lap and butt joints. While the latter configuration will be only tested through FSW, SLJ will be made by FSW and FSSW. The chosen overlap dimensions for the lap joints is 25x25 mm. The schematics for both configurations are depicted in Figure 3.1.

The alloys/materials chosen for the substrates were Cu ETP R240, a copper with a high degree of purity, AA6082-T4 and AA6061-T6, two 6XXX series aluminium alloys with better mechanical properties than for example 1XXX series, a more close-to-pure aluminium series, but without compromising its thermal-electrical properties. Two different aluminium alloys were used in joint production due to shortage of material availability. However, both alloys are identical regarding their mechanical and electrical behaviour [62]. Raw sheets of these materials (rolled-form) were bought, and then cut into the above-depicted dimensions. Table 3.1 lists the main mechanical and electrical properties of these materials.

Table 3.2 summarizes which analyses were made for each configuration, and Table 3.3 showcases the process parameters applied for each sample.

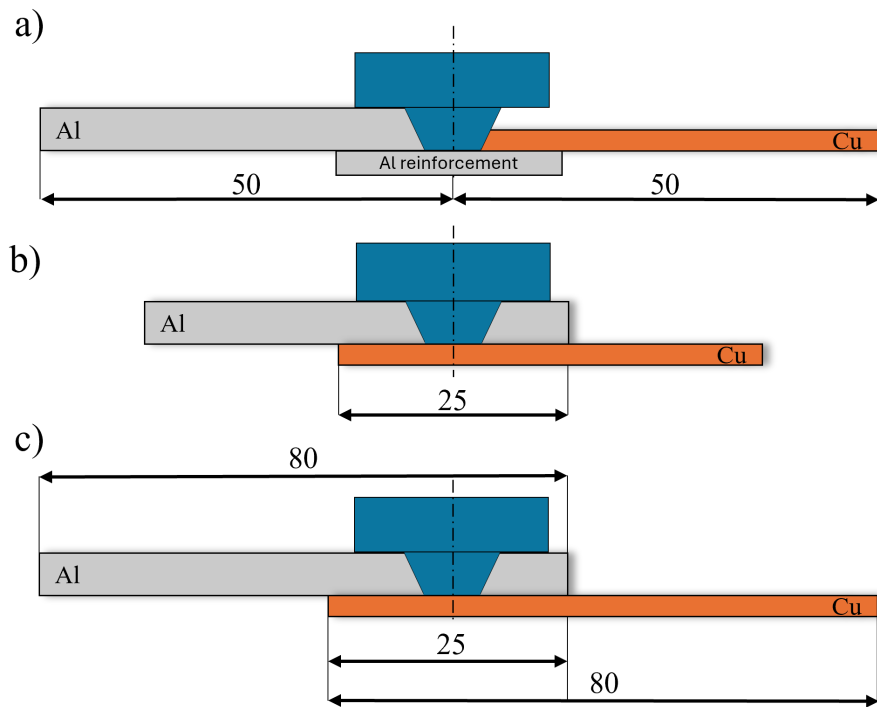


Figure 3.1: Joints schematic and dimensions [mm]: a) FSW Butt Joint, b) FSW SLJ and c) FSSW SLJ.

Table 3.1: Materials used and their main mechanical and electrical properties [62].

	Cu ETP R240	AA6061-T6	AA6082-T4
Young's modulus [GPa]	127	~70	~70
Poisson's Ratio	0.34	0.33	0.33
Density [g/cm ³]	8.96	2.7	2.7
Elongation at fracture [%]	15	3.4-20	6.3-18
Electrical Conductivity [% IACS]	98.5	43	42

Table 3.2: Analysis made for each configuration.

	BJ by FSW	SLJ by FSW	SLJ by FSSW
Tensile testing	Yes	Yes	Yes
Thermal-electrical analysis	Yes	Yes	Yes
SEM analysis	No	No	Yes
EDS analysis	No	No	Yes
Microhardness measurement	Yes	Yes	Yes

Table 3.3: Process parameters applied to each welded configuration. C - clockwise; CC - counter-clockwise.

	Spindle Speed [rpm]	Welding Speed [mm/min]	Tool Rotation Direction	Plunge Depth [mm]	Dwell Time [s]
FSW SLJ/ FSW Butt Joint	800	50	CC	0.1	30
	800	50	C	0.1	30
	950	50	CC	0.1	30
	950	50	C	0.1	30
	1100	50	CC	0.1	30
	1100	50	C	0.1	30
FSSW SLJ	800	-	CC	0	60
	800	-	CC	0.25	60
	800	-	CC	0.5	60
	1000	-	CC	0	60
	1000	-	CC	0.25	60
	1000	-	CC	0.5	60
	1200	-	CC	0	60
	1200	-	CC	0.25	60
	1200	-	CC	0.5	60

3.2 Joint preparation and production

Friction Stir Welding The FSW joints were made in a FSW machine powered by a 11 kW servomotor, acting in *position control* mode. 130x50 mm sheets of AA6061-T6 and Cu were welded in lap and butt configuration (see Figures 3.2), then cut in 10 and 25 mm wide specimens for tensile and electrical analysis. The process parameters consist of three rotational speeds (800, 950 and 1100 rpm), two tool rotation directions (clockwise and counter-clockwise), a tool plunge depth of 0.05-0.1 mm, a tool tilt angle of 2.5° with respect to the welding direction, and a linear welding speed of 40-60 mm/min.

The tool used in this procedure has a concave shoulder and a truncated conical pin (see tool dimensions in Figure 3.3 a)). It is made of H13 steel and heat treated to a hardness of 42-48 HRC. Made FSW sheets and subsequent joints are depicted in Figure 3.4.

Friction Stir Spot Welding The FSSW joints were also made with a H13 steel tool with a truncated conical pin and concave shoulder (see tool dimensions and representation in Figure 3.3 b)) in an HAAS *MiniMill* CNC machine. Because of this, a special setup had to be designed and machined from steel blocks, fixed to the CNC table and capable of holding the joints in place while the significant loads are being applied by the tool. The table fixation is made possible through 6 CHC bolts that are tightened to T-nuts with the help of a torque wrench. The compression of the setup applied to the joint was taken into account in the design stage, as it avoids the SLJ from distorting due to the high force applied in the overlap area. The setup and its assembly are depicted in Figures 3.5 and 3.6 respectively, and the technical drawings for the machined setup are available in Appendix D.

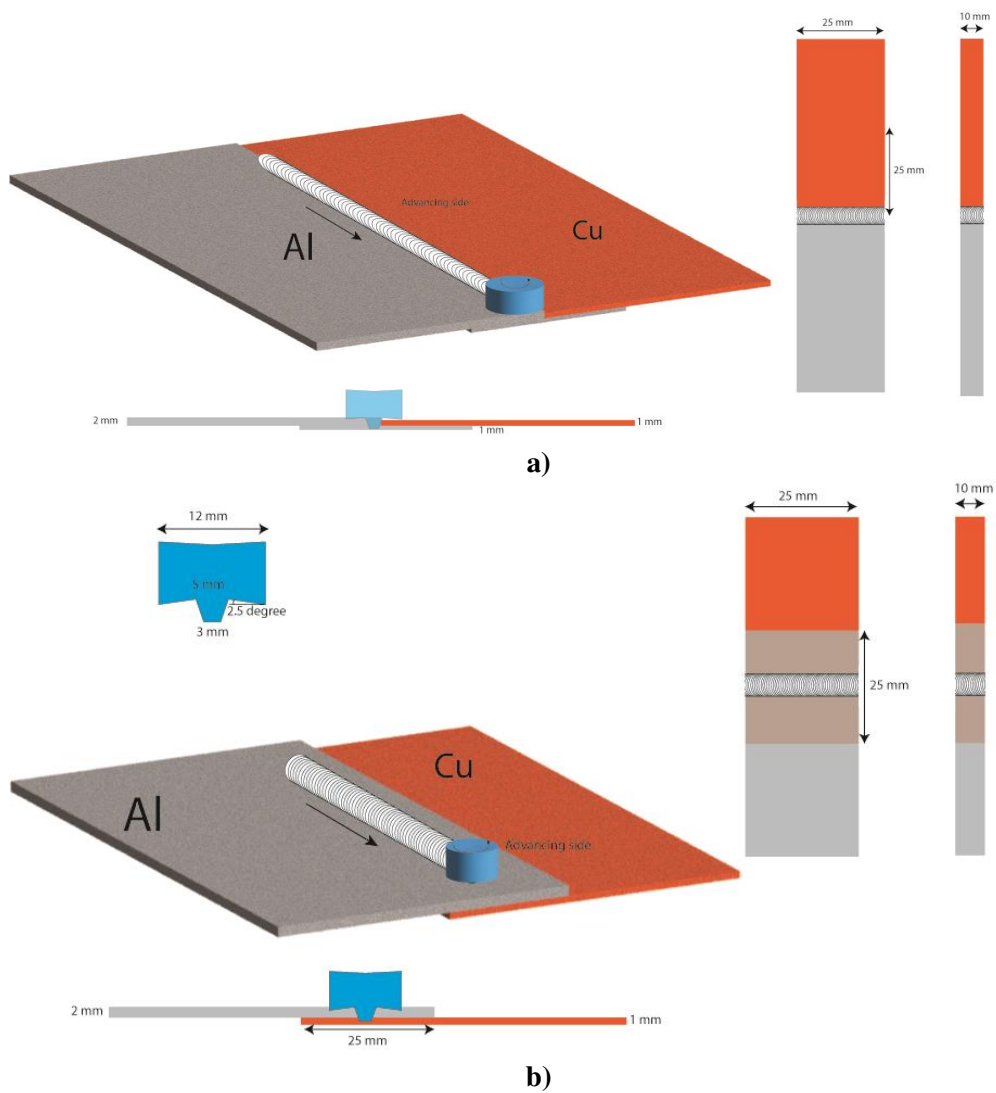


Figure 3.2: FSW schematic: a) butt configuration, b) lap configuration.

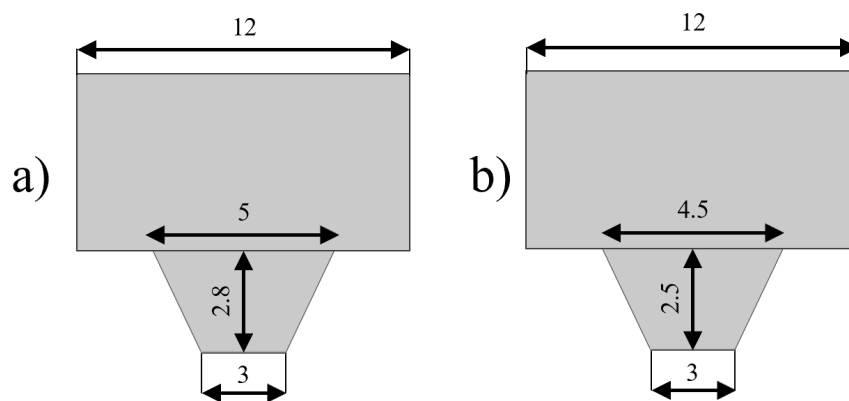


Figure 3.3: a) FSW tool dimensions, b) FSSW tool dimensions,

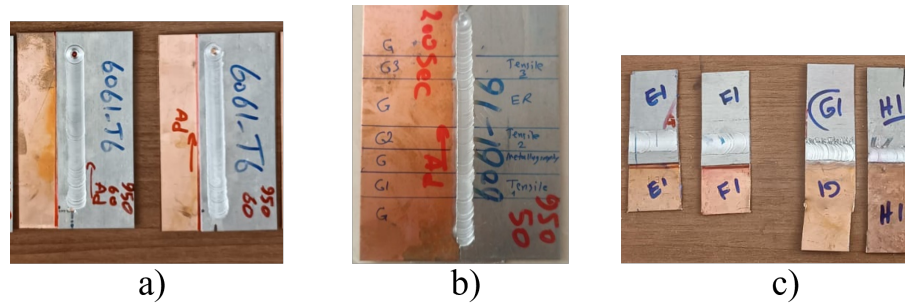


Figure 3.4: a) FSW lap joints, b) FSW butt joints made, c) 25 mm wide FSW cut specimens.

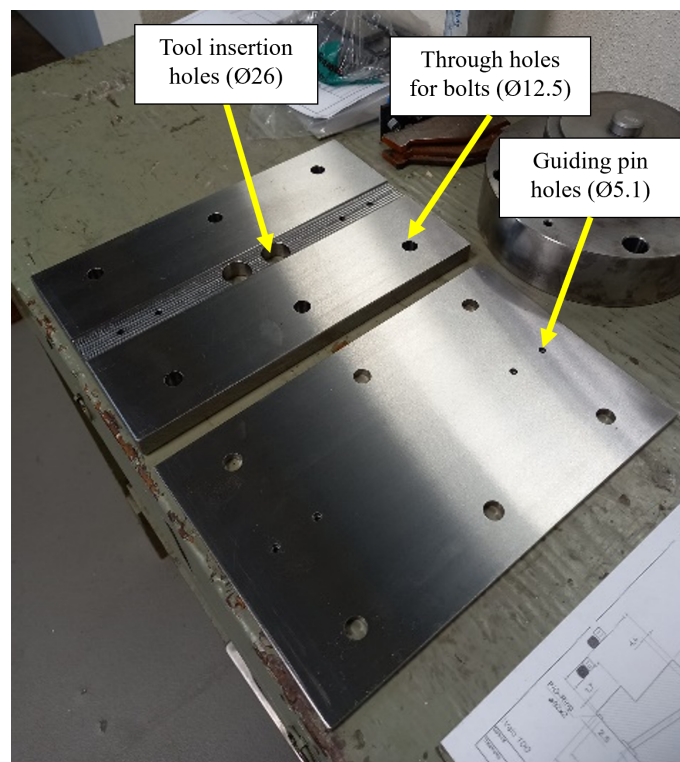


Figure 3.5: Machined setup.

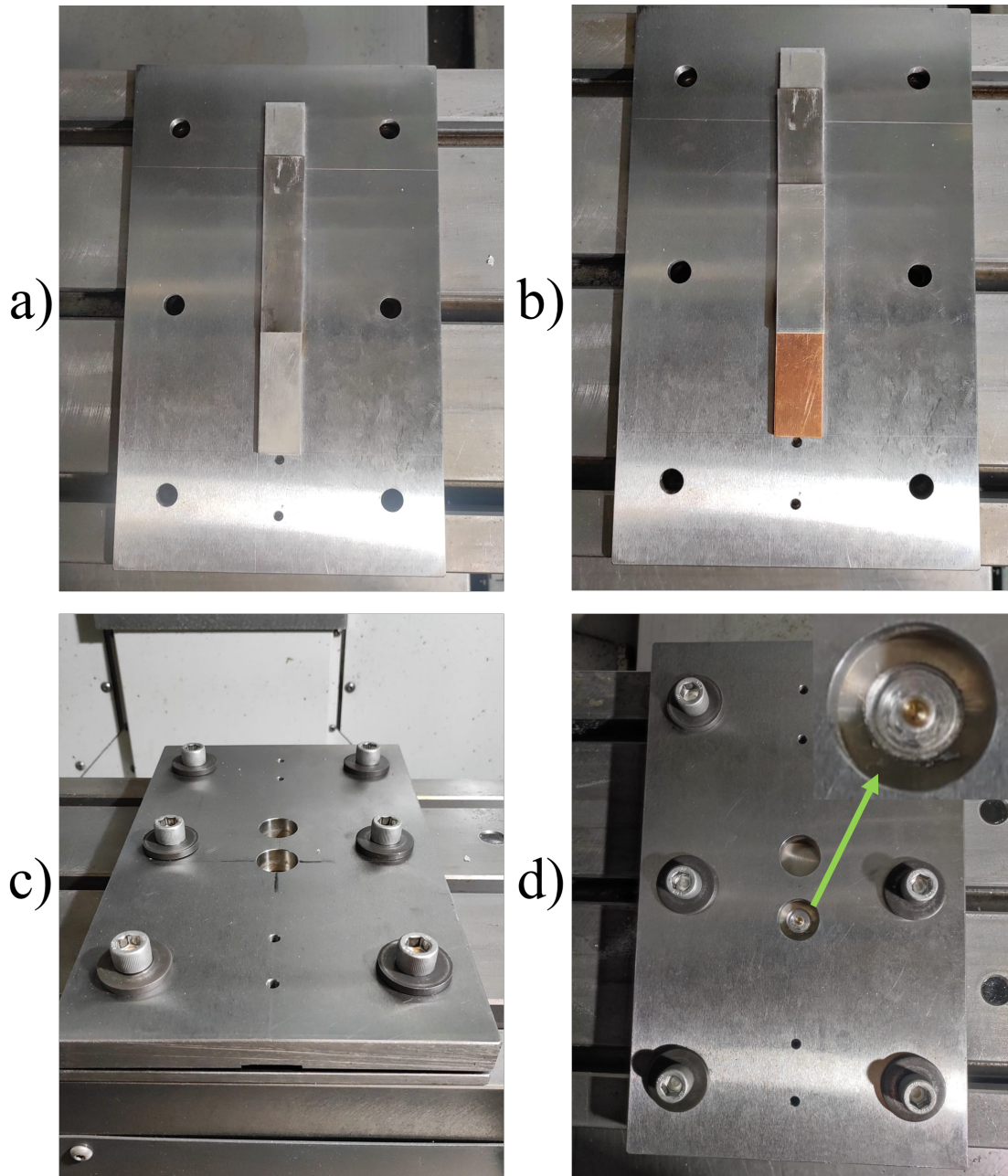


Figure 3.6: FSSW setup and joint assembly: a) setup's bottom plate with two back-up steel plates, b) Al and Cu substrates placed on top of the back-up plates and aligned, c) top plate encloses the SLJ and the setup is tightened and locked with M12 bolts and T-nuts, d) Top view of the setup after spot welding is achieved.

Some to-be-made joints were attached to a thermocouple at the extremity of their overlap. However, the values of temperature given would not reflect the values at the centre of the keyhole, where all the major heating generation is happening. Furthermore, placing the thermocouple inside the overlap area would most likely damage the thermocouple wire, as well as disturb the overlap applied pressure by the tool and consequently the bonding process itself. Nonetheless, temperatures of around 200 to 250 °C were achieved during spot welding. An example of a thermocouple being used in the designed setup is shown in Figure 3.7.

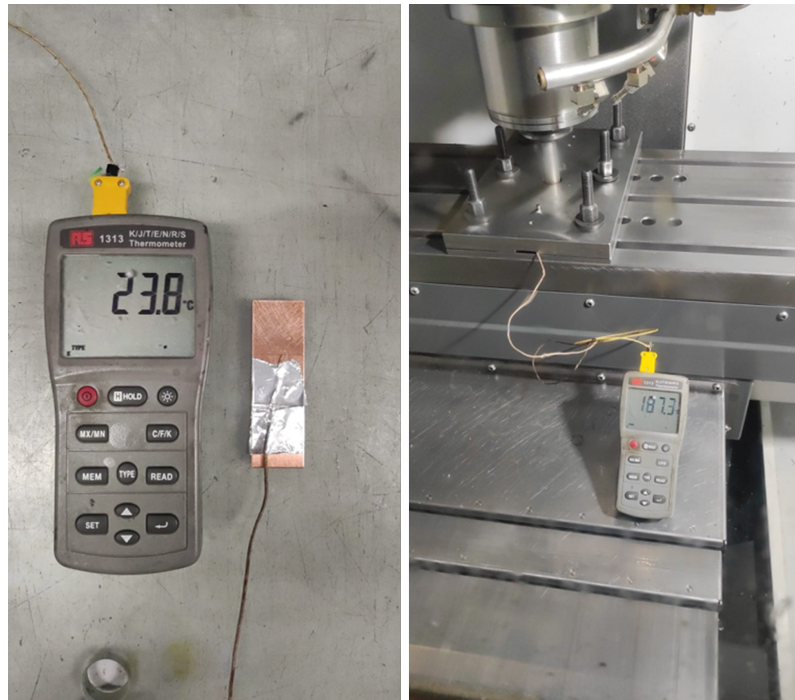


Figure 3.7: Thermocouple attachment to Cu lower substrate (left) and thermocouple measuring temperature during joining (right).

After all specimens were cut and produced, they were electrically and mechanically tested.

3.3 Experimental testing and analysis

3.3.1 Macro-analysis

FSSW Figure 3.8 shows keyholes from four made joints. As seen, specimens A and D produce a very notable flash defect, which contributes to weld thinning and decrease of joint strength. Specimen B has a rather non-uniform flash defect. This is probably due to a lower plunging time, which forces the material to be expelled from the stirring zone more abruptly. It can also be seen that there is a clear lack of penetration and shoulder contact at a 0 mm plunge depth (Specimen C). As it was already explained, it is impossible to observe the shoulder contact with the joint during joining, which initially led to joints with improper shoulder contact, and therefore not enough mixing and heat generation to produce a strong weld.

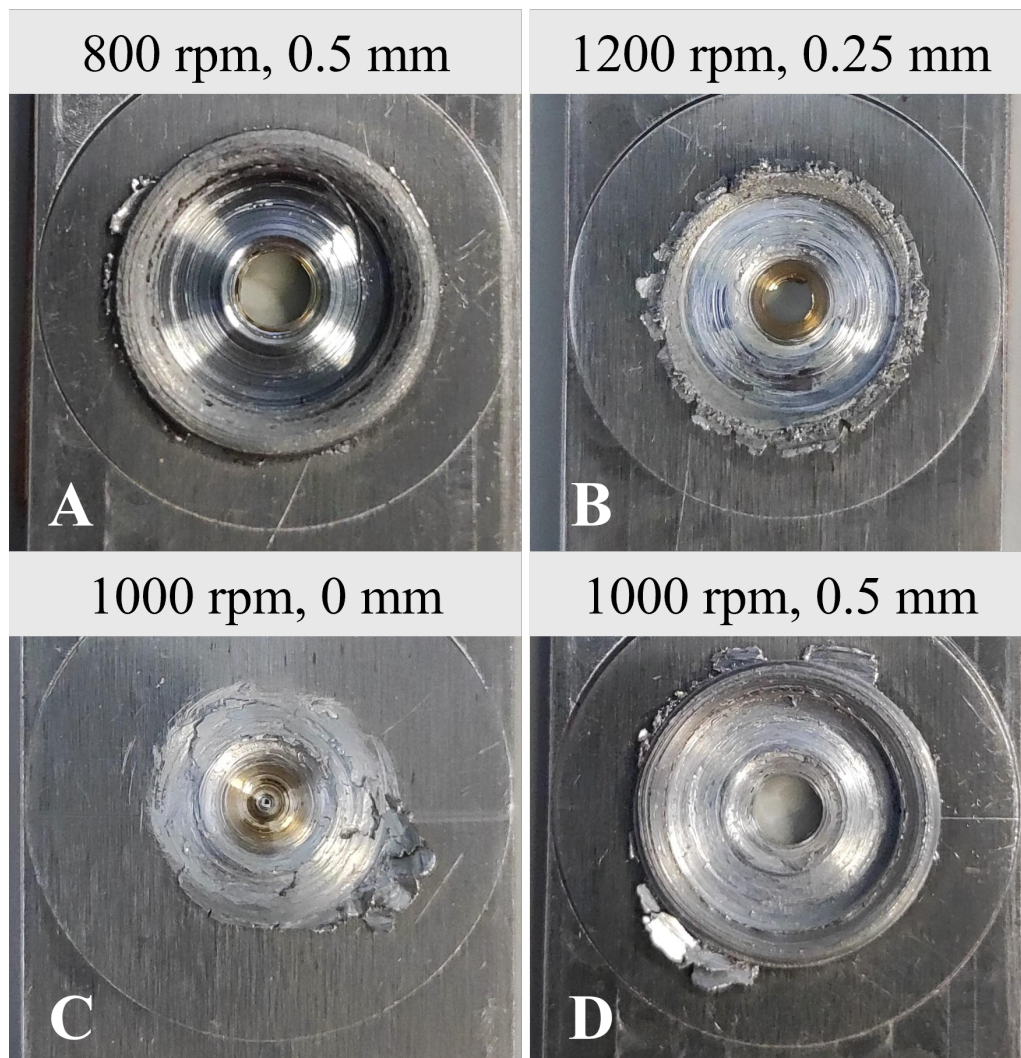


Figure 3.8: Macro images of FSSW keyholes from four produced specimens.

Different tightening torques of the manufacturing setup were used through the specimen production. Figure 3.9 shows two specimens with different tightening torques. It can be noted that higher tightening torques, although inducing bigger plastic deformation on the joint, especially on Cu substrate, seem to guarantee an exceptional contact between both base materials. On the other hand, a lower tightening torque does seem to provide a less ideal substrate contact, contributing to a more localized Joule effect and a rise in electrical resistance.

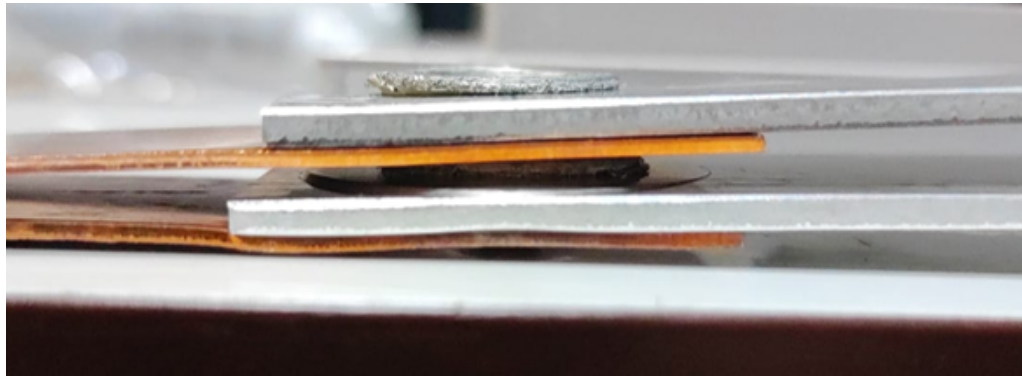


Figure 3.9: Side of FSSW specimens tightened with 60 N/m (top) and 120 N/m (bottom).

3.3.2 Tensile testing

FSSW An INSTRON® 3367 universal test machine (Norwood, MA, USA) with a load cell capacity of 30 kN and a 1 mm/min speed for quasi-static tensile testing. A total of 27 joints were tested, three for each set of parameters. The values for their maximum loads are shown in Figure 3.10.

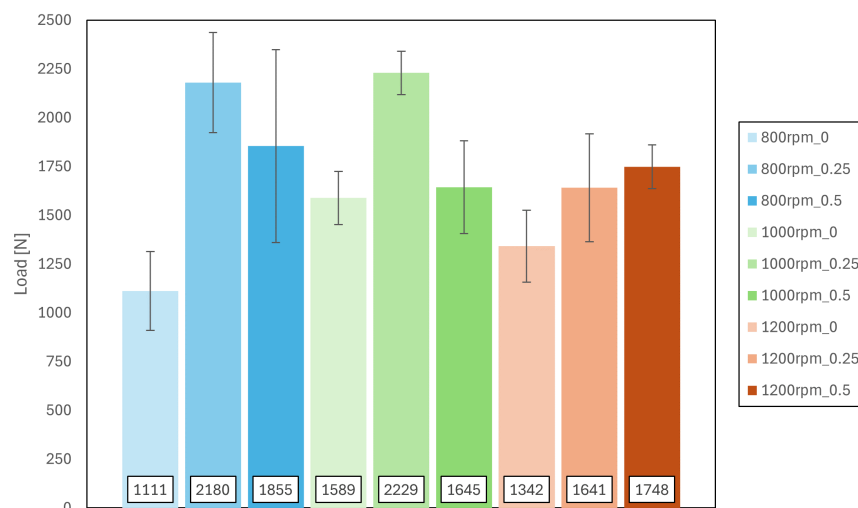


Figure 3.10: FSSW peak loads per parameter set.

FSW As explained previously, six welding parameters were defined for FSW. The lap joints were all produced, however the butt joints could only be produced when Cu was on the AS. When Al was on the AS, bonding wasn't achieved, and therefore this welding parameter set was discarded. The peak load values for FSW joints are depicted in Figure 3.11.

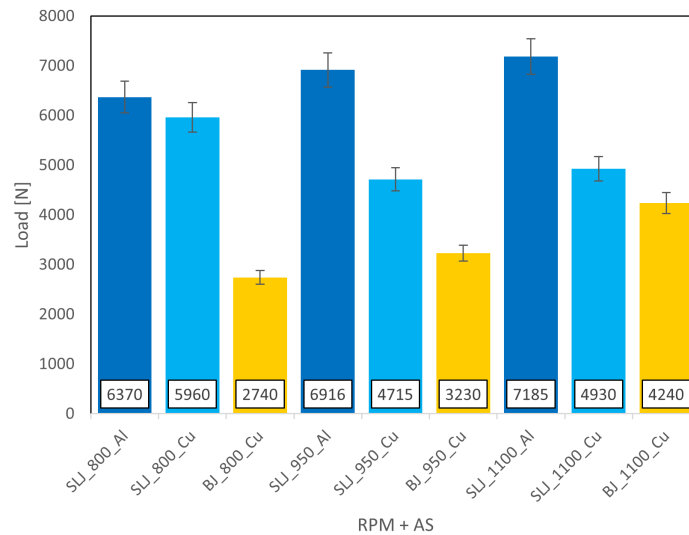


Figure 3.11: FSW peak loads per parameter set.

3.3.3 SEM analysis

FSSW Joints The four FSSW specimens shown in Figure 3.8 were chosen for SEM analysis. In order to achieve good SEM observations, a thorough procedure was made, consisting of cutting the joints by their overlap area with a Silicon Carbide (SiC) saw disc, followed by a cut across the keyhole with the assist of a Struers Accutom-5 machine and diamond disc, and enclosure of the cross section in resin. This initial preparation is depicted in Figure 3.12 Finally, grinding with 320 and 800 size grain sand paper and polishing with 3 and 1 μm diamond took place, until the SEM specimens were ready to observe, as seen in Figure 3.13.

The SEM analysis was performed at CEMUP lab, using a High resolution (Schottky) Environmental Scanning Electron Microscope with X-Ray Microanalysis and Electron Backscattered Diffraction analysis (FEI Quanta 400 FEG ESEM /EDAX Genesis X4M). The samples were coated with a Carbon (C) thin film, by vapor deposition, using the JEOL JEE – 4X Vacuum Evaporator equipment.

3.3.4 Microhardness testing

FSSW Vickers Micro hardness tests were performed on the joints cross sections. A Vickers micro hardness machine with 15 s of loading and 5 N of load was used. Prior to keyhole measurements, the base materials hardness was measured, with Cu having an average of 83 HV and Al 93

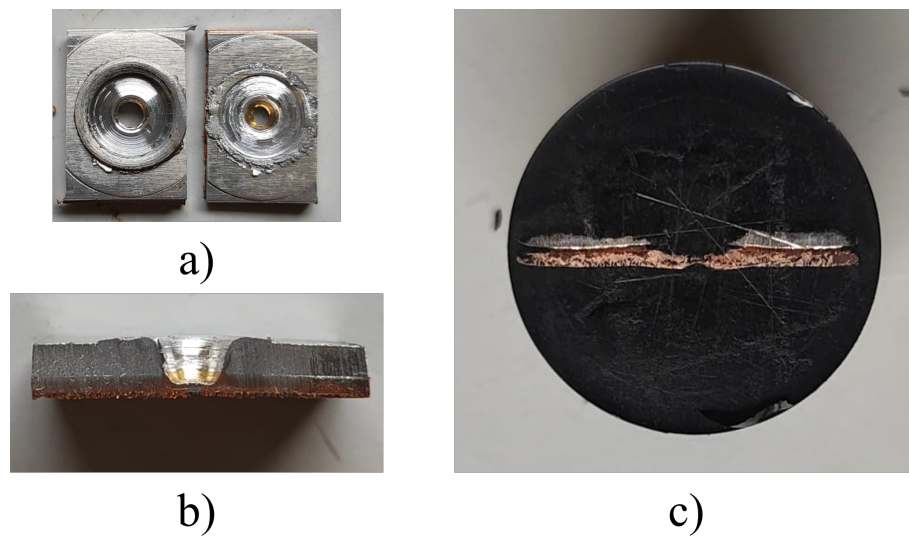


Figure 3.12: FSSW specimens SEM preparation: a) specimens overlap, b) cross section of keyhole area, c) enclosure of specimen in resin.

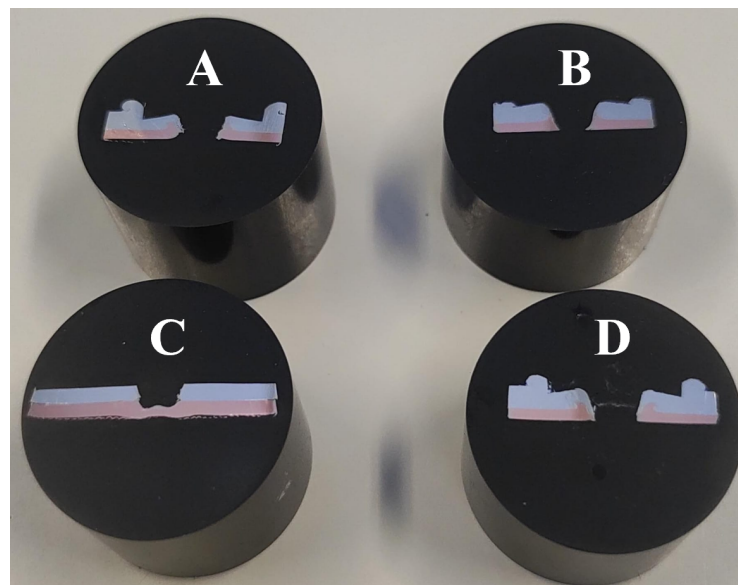


Figure 3.13: FSSW specimens ready for SEM analysis.

HV. Figures 3.14, 3.15 and 3.16 reveal the micro hardness maps for FSSW specimens A, D and C, respectively.

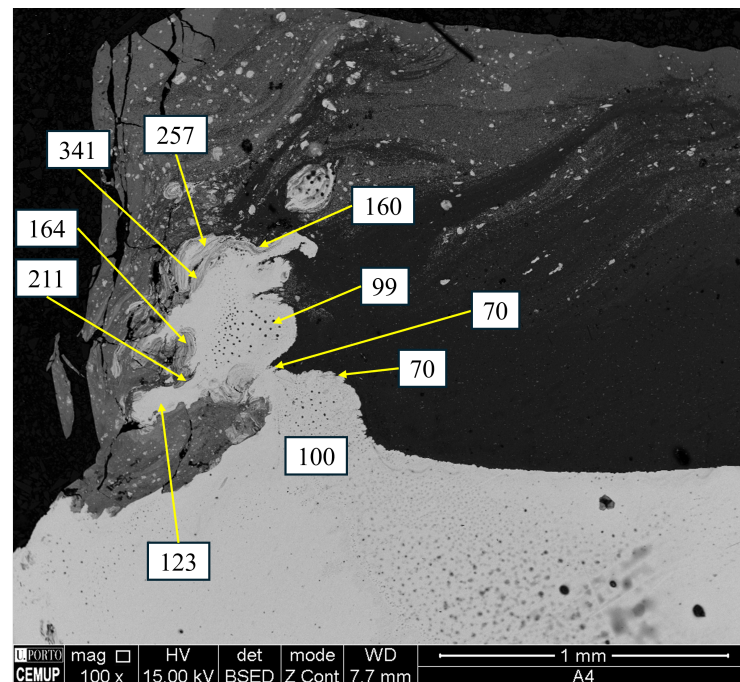


Figure 3.14: Micro hardness values map for the 800 rpm FSSW specimen with 0.5 mm of P.D.

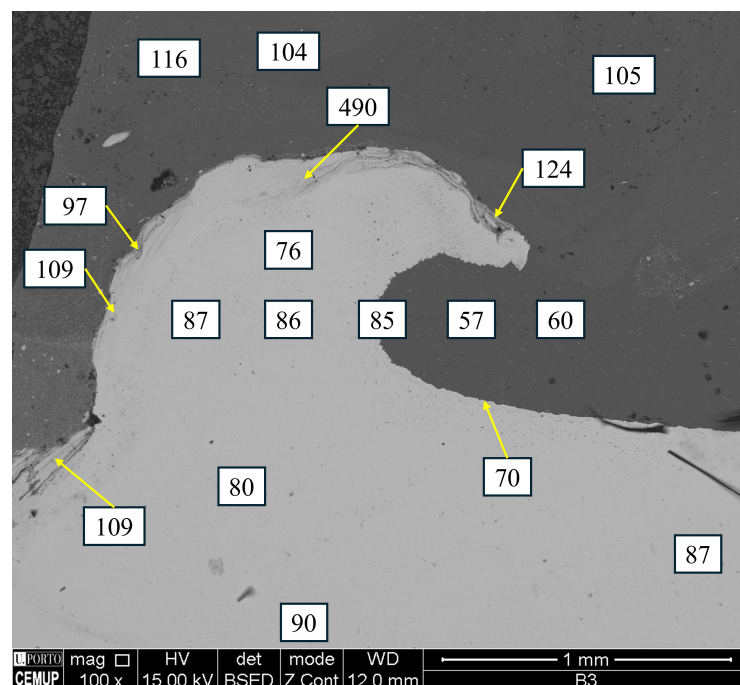


Figure 3.15: Micro hardness values map for the 1000 rpm FSSW specimen with 0.5 mm of P.D.

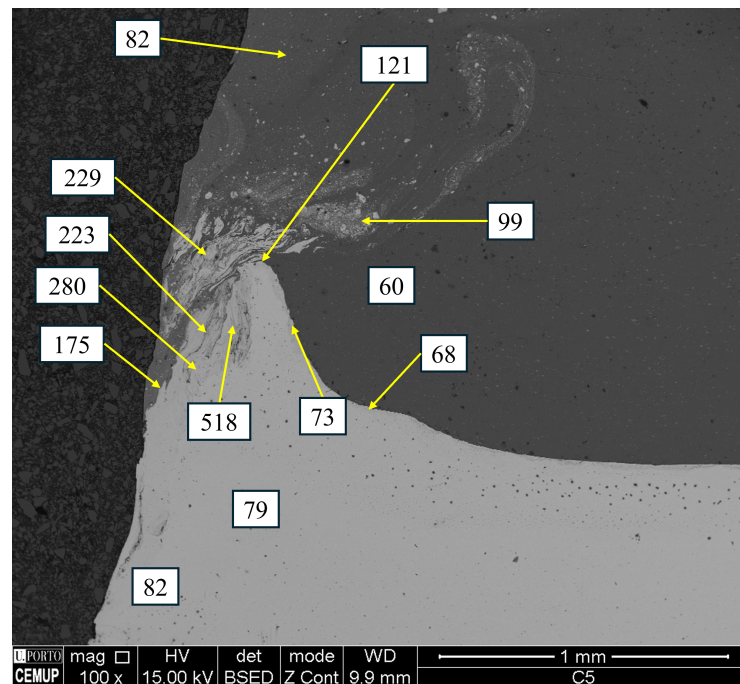


Figure 3.16: Micro hardness values map for the 1200 rpm FSSW specimen with 0.25 mm of P.D.

3.3.5 Electrical analysis

The electrical analysis was made with the help of a DC power source. The joints would be connected to the power source, so that a 10 A current would flow through the joint. At the same time, a voltmeter would be measuring the voltage drop. A schematic of the probe placement is represented in Figure 3.17. Since this current value is too low for Joule effect to take place, a heat gun was used in order to raise the joint's temperature to the maximum busbar service temperature (105 °C) (see Figure 3.18). A thermal camera was set up in order to monitor the decreasing temperature. The results of this analysis can be found in the appended papers.

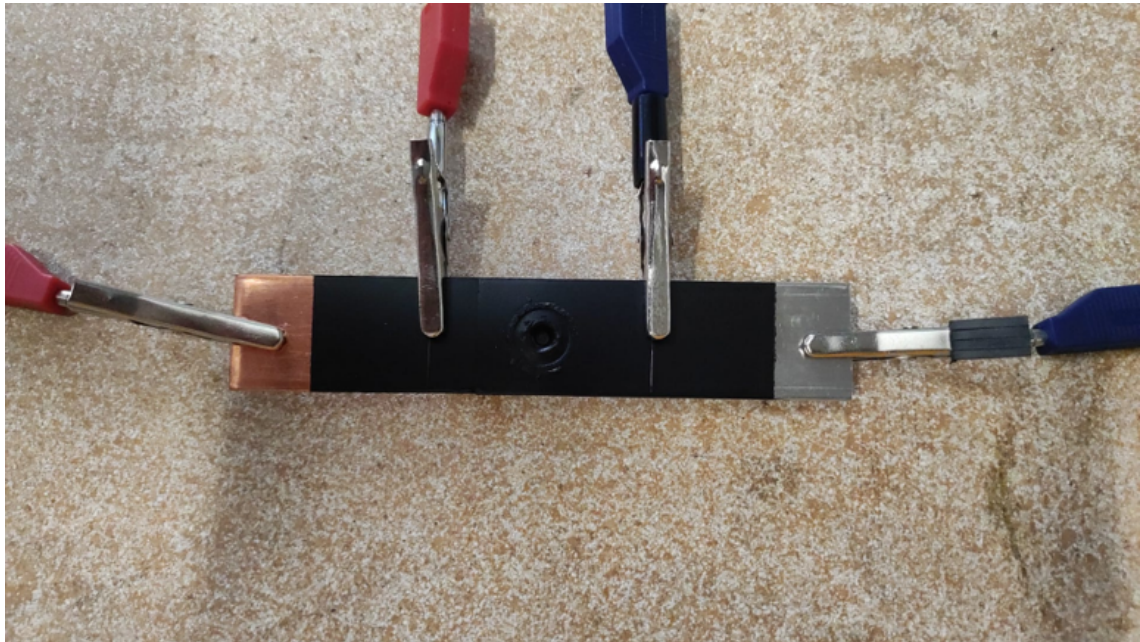


Figure 3.17: FSSW joint ready to be tested electrically.

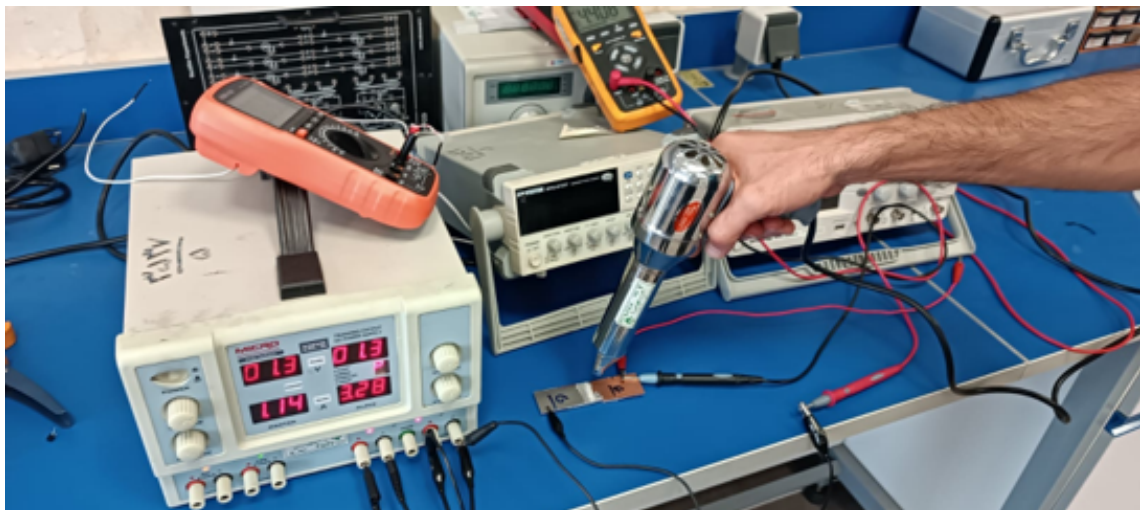


Figure 3.18: Thermal-electrical setup and heating of the joints made by FSW.

Chapter 4

Numerical procedure

This chapter describes the numerical approach adopted in this work, used to provide a way to model the experimental data and used to support the determination of key material properties and failure processes. The software used for finite element modelling is ABAQUS 2022.

Since both mechanical and electrical properties are being analysed, six different models were created, one for thermal-electrical analysis, and another for destructive testing. Both models had the three welding configurations studied. In all configurations, it is assumed an interface layer between the aluminium substrate and the copper substrate, which represents the layer where the Al-Cu IMCs would be found. The main objective of the numerical modelling is to find the correct interface layer characterization by calibrating it with the experimental procedure.

4.1 Modeling

As there are two joint configurations (SLJ and butt joint), joining processes (FSW and FSSW) and analysis types (thermal-electrical and mechanical), numerical models were developed for all these cases. The FSW joints interfaces have a constant cross section across their width, hence 2D models were chosen over 3D ones, for simulation facilitation. The FSSW joint was modelled as a 3D-symmetric part.

The interface layer between the Al and the Cu substrates, where IMCs are formed, was initially introduced as a simple 10 μm . horizontal layer, and then later adjusted to the actual geometry that is formed, which is usually a hook-like shape, increasing the mechanical properties of the joint. Figure 4.1 depicts each configuration's model geometry as well as their IMC layer location.

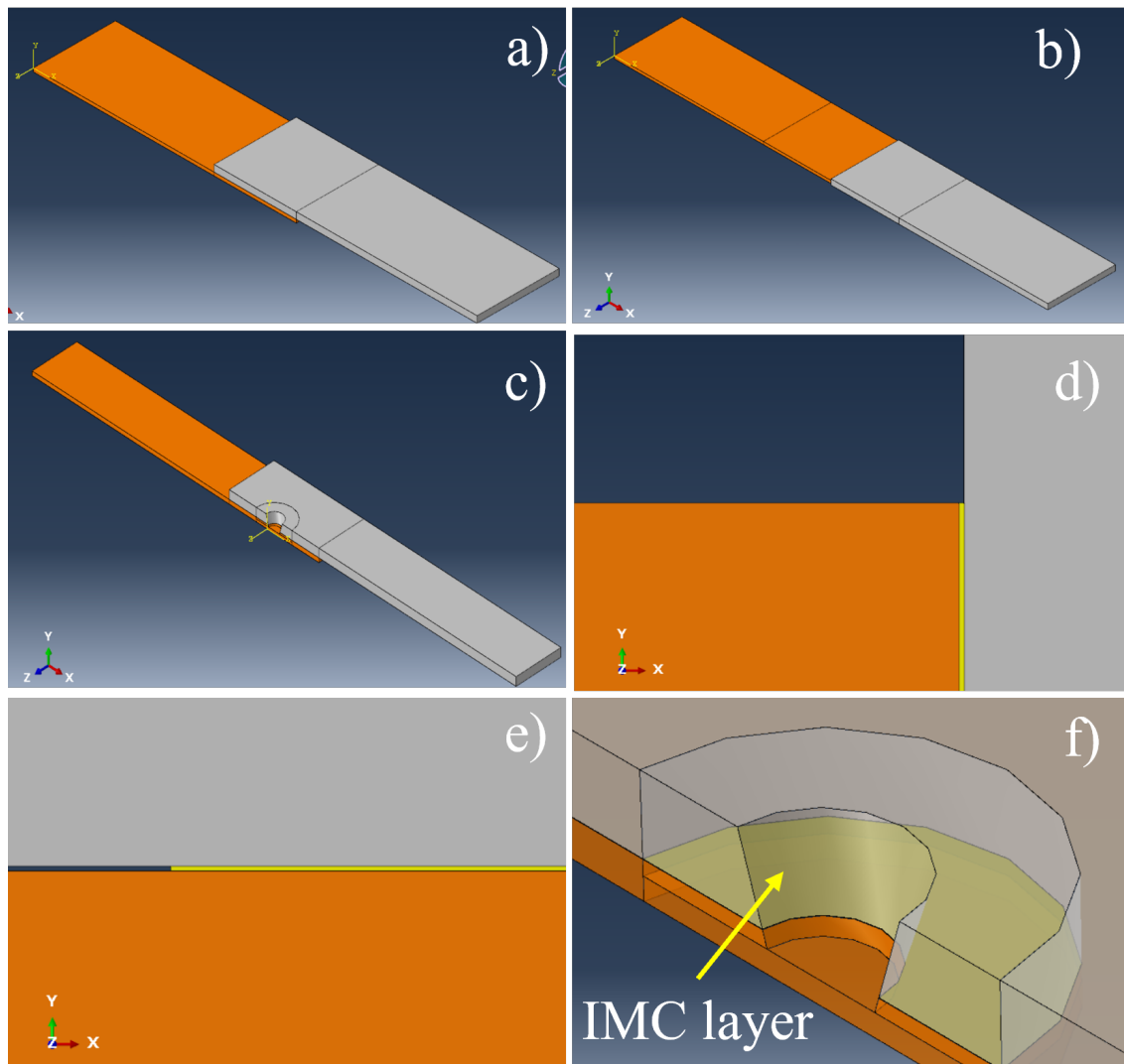


Figure 4.1: Models geometry and IMC layer location: a) FSW SLJ, b) FSW Butt Joint, c) FSSW SLJ, d) magnification of FSW BJ interface, e) magnification of FSW SLJ interface, f) magnification of FSSW SLJ interface.

4.2 Properties

The substrate's mechanical and electrical properties used in the model are provided in Table 4.1. Furthermore, its plastic properties and evolution of electrical conductivity with temperature are shown in Appendix C.1 and C.2, respectively.

Table 4.1: Substrates' mechanical and thermal-electrical properties.

	AA6XXX	Cu ETP R240
Density [kg/m ³]	2700	8960
Young's modulus [GPa]	70	127
Thermal conductivity [W/mK]	180	360
Specific heat [J/kgK]	900	394
Poisson's ratio	0.33	0.34

For the IMC layer properties, some assumptions and simplifications were initially made. The stiffness was assumed to be the double the average of both base materials (187 GPa), as IMCs tend to behave as brittle materials, reducing the joint's displacement load and compromising it. The IMC's maximum chosen Ultimate Tensile Strength (UTS) was 175 MPa, as reported by Reza et. al [63]. However, other UTS were tested initially, such as 50, 100, 125 and 150 MPa.

As it is assumed the IMC has a brittle behaviour, a feasible simplification consists in considering the IMC as a cohesive material, and therefore following a bilinear traction separation [64], which is depicted in Figure 4.2. An initial fracture toughness of 0.1 N/mm is assumed in the numerical model.

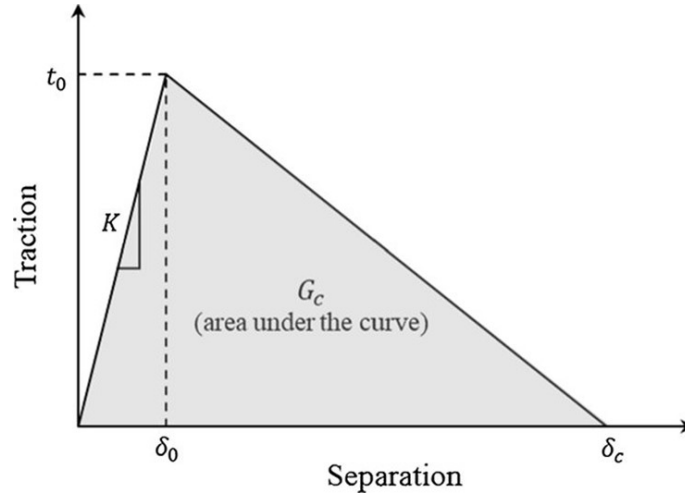


Figure 4.2: Bilinear traction-separation law: K is stiffness, t_0 the tensile strength and G_c the fracture toughness of the material [64].

4.3 Step, boundary conditions, interactions and meshing

4.3.1 Step

For mechanical testing, as the objective is to simulate a quasi-static tensile testing, the time period was defined as 1 s, with a "Static General" type.

For thermal-electrical analysis it was initially intended to test the joint when subjected to a full battery discharge as well as sudden voltage drops. For experimental validation, a 1500 A power source would provide the 1500 A for battery discharge simulation and 600 A for the sudden voltage drops. The joint would heat up due to Joule Effect caused by the high current. However, due to equipment delays, the joints could only be tested by heating them up to 105 °C and providing them with 10 A as it cools down. The numerical steps would be composed of intermittent "Cooldown" and "Spike" steps with 15 and 2 s, respectively (see Table 4.2).

Table 4.2: Thermal-electrical analysis steps.

Step Name	Time (s)
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	15
Spike	2
Cooldown	50

4.3.2 Loads, boundary conditions and predefined fields

To correctly simulate the tensile test, an encastre is applied at one substrate's ends (in this case, Cu), and a displacement is applied in the other end (in this case, Al), as depicted in Figure. The FSSW joint was modelled as symmetrical, so a symmetry boundary condition was applied to all faces in the symmetry axis. These are depicted in Figure 4.3.

For the thermal-electrical models, to correctly reproduce a current discharge through the means of a power source, a "Surface Current" load (applied to each step) was applied to the Cu ends.

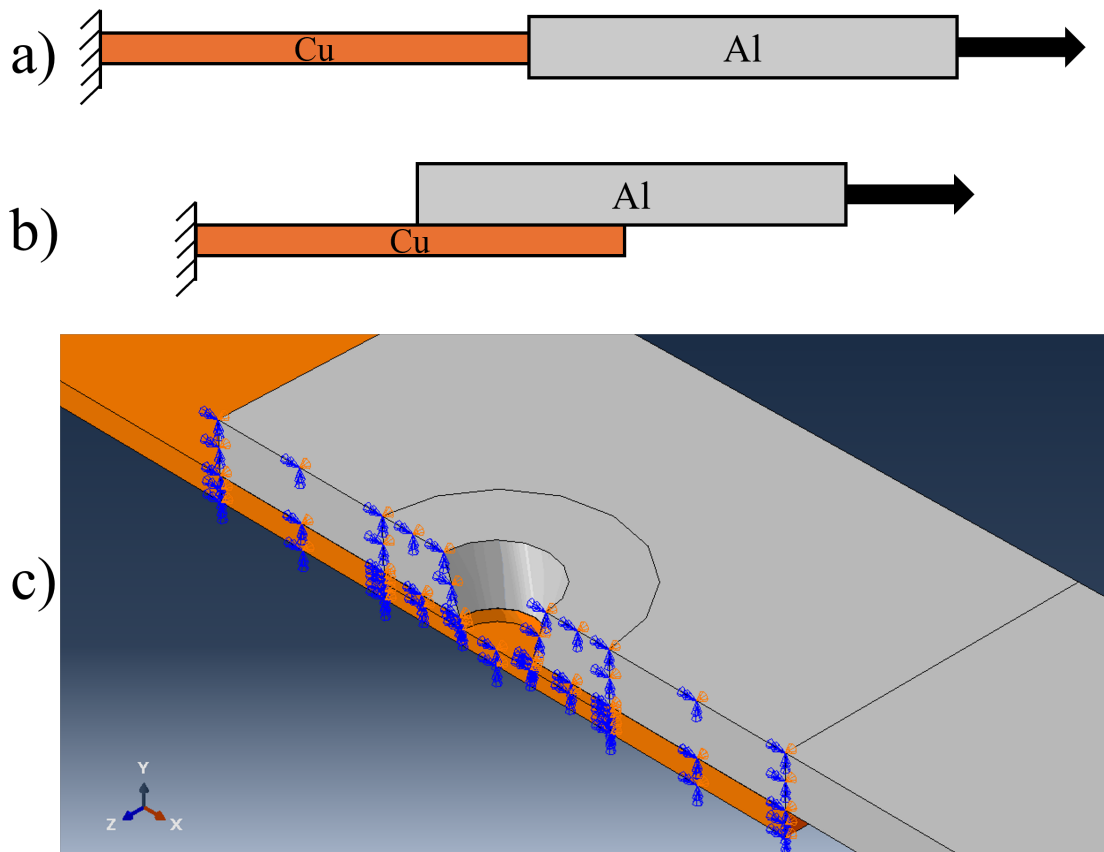


Figure 4.3: Boundary conditions applied to the tensile test model: a) FSW BJ, b) FSW SLJ, c) close-up of symmetry boundary condition applied to the FSSW model.

Furthermore, for the current to actually flow from the Cu to Al, a 0 magnitude "Electrical Potential" boundary condition is applied to the Al ends. Finally, a "Temperature" Predefined Field of 293 K (20 °C) is applied to all joint surfaces (see Figure 4.4) so the initial simulation's temperature is adjusted to ambient temperature.

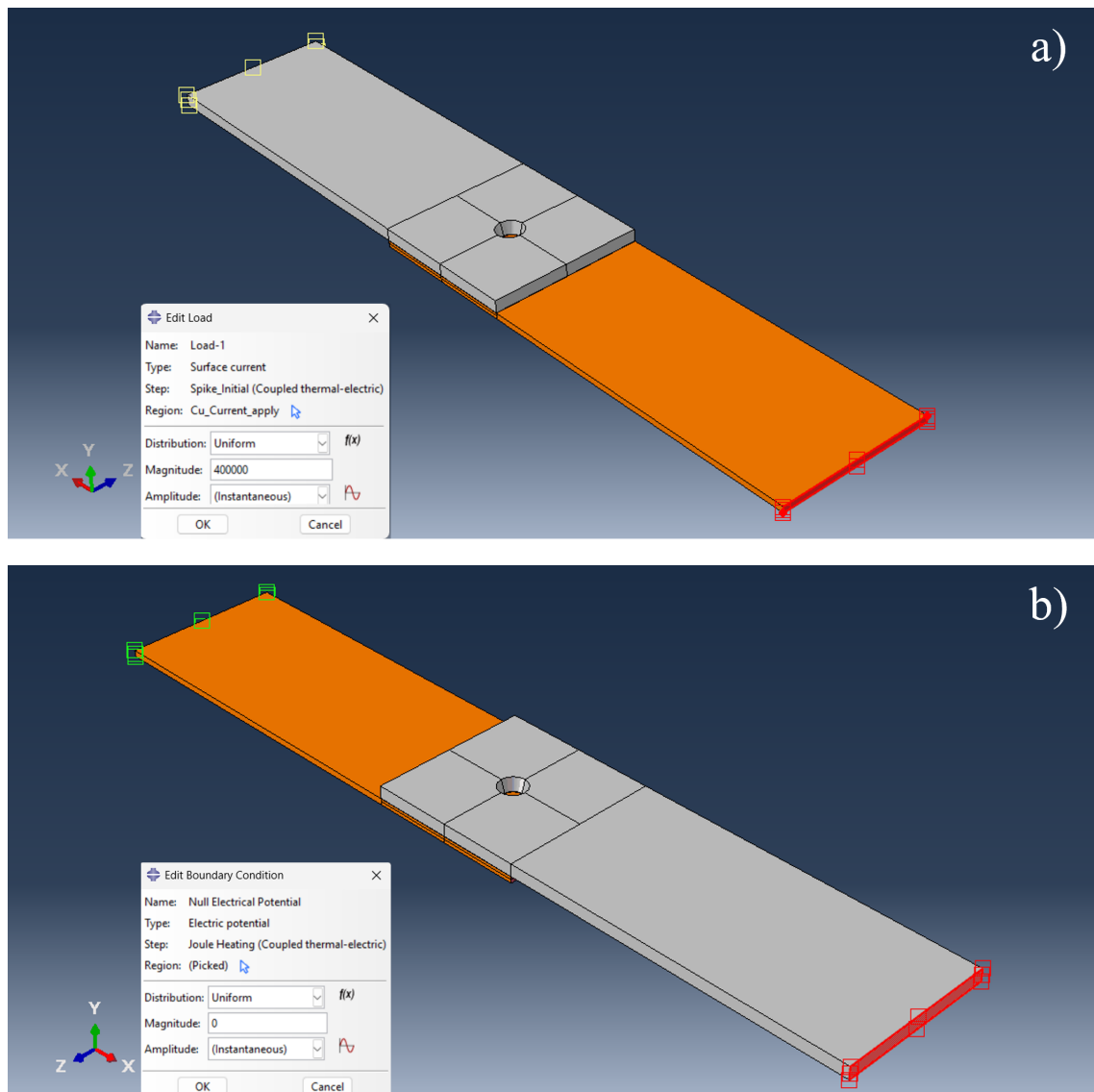


Figure 4.4: Boundary conditions applied to thermal-electrical model: a) Surface Current applied on Cu ends, b) Null Electrical Potential applied on Al ends.

4.3.3 Interactions

In order to more correctly simulate the thermal-electrical analysis, some interactions were applied, namely a "Surface Film Condition" to represent the natural convection that cools the whole joint down in between current spikes. Furthermore, "Surface-to-Surface Tie" Constraints were applied to the intersecting surfaces between Al and interface layer, and between Cu and interface layer. An example of this constraint is depicted in Figure 4.5.

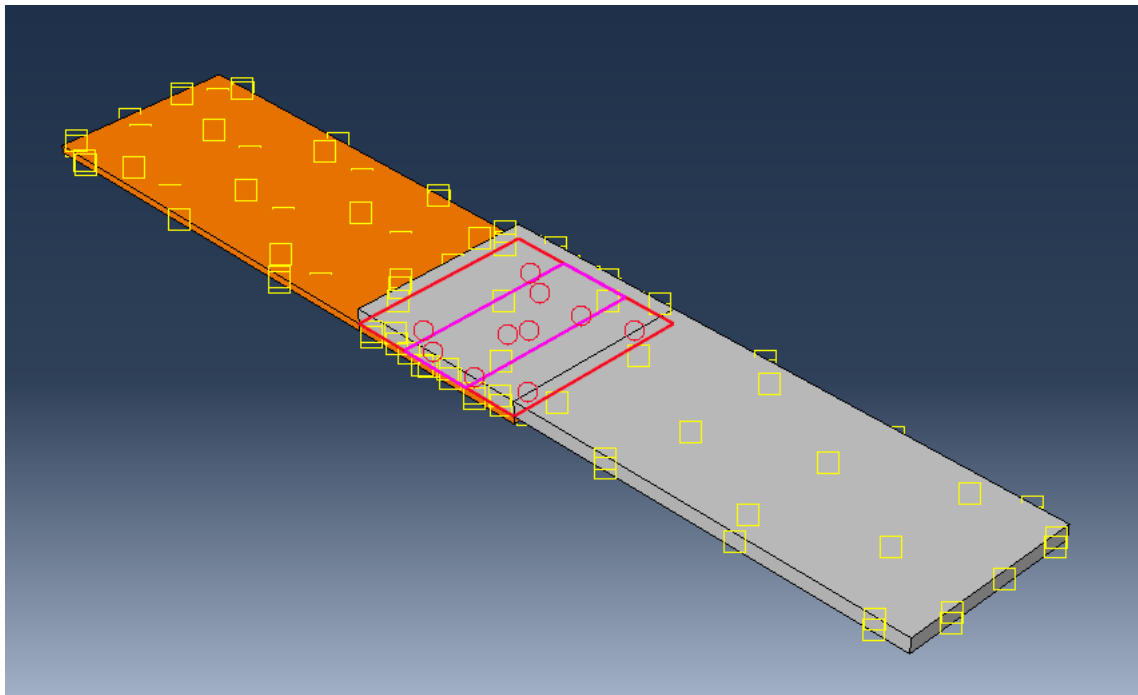


Figure 4.5: Example of a "Tie" constraint between Cu overlap area (red) and IMC layer (purple) in the FSW SLJ model.

4.3.4 Meshing

For the mechanical testing models, both the Al and Cu substrates have a "Plane Stress/3D Stress" Element Type, and had mostly Quad-Dominated Free/Structured Shape. However, for the IMC layer, it was assumed that its Element Type is cohesive. Moreover, its element shape had to be defined as Quad-Dominated Sweep, for compatibility with the cohesive nature of the element. The variants meshes are represented in Figure 4.6. The sweep path of the elements has to be perpendicular to the crack propagation direction.

For the thermal-electrical models, the elements size and shape were rather identical to the mechanical testing models, with the only difference being the element type. For a thermal-electrical analysis to be made, all parts of the model (Al, IMC layer and Cu) were defined as "Thermal Electrical".

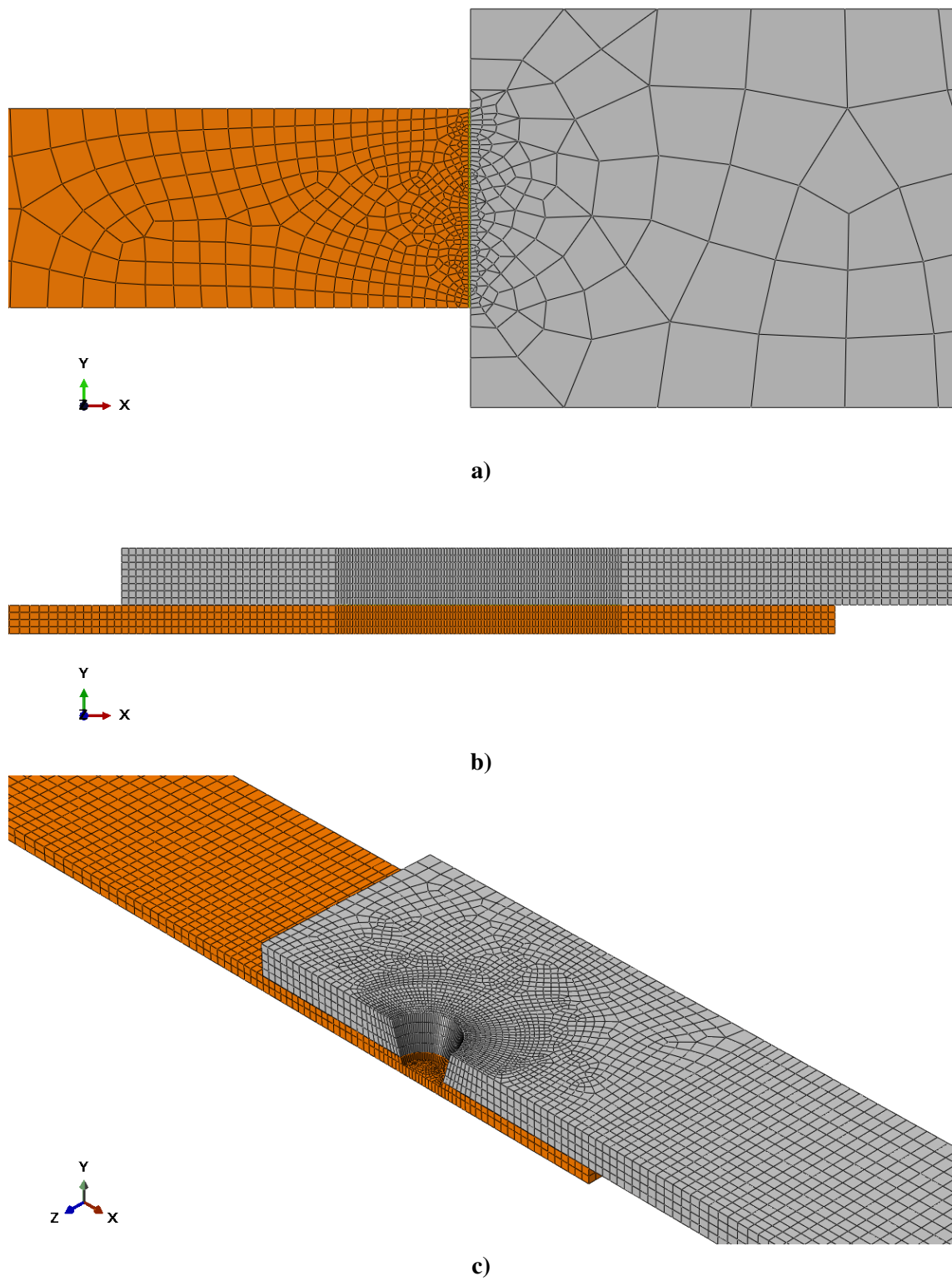


Figure 4.6: Configurations mesh: a) FSW butt joint mesh, b) FSW SLJ mesh, c) FSSW SLJ mesh.

Chapter 5

Summary of the appended documents

The papers summarized in this chapter compose all the discussion that took place during the thesis, as well as the main results and analysis of such results. They are available at Appendix [A](#) and [B](#), respectively.

5.1 Paper A

Numerical modeling of Al-Cu single lap and butt joints made by FSW and FSSW for mechanical and thermal-electrical analysis

This paper primary focuses on a new approach to develop a numerical model of Al-Cu SLJ and Butt joints by FSW, and SLJ by FSSW. Firstly, for mechanical analysis a 10 μm brittle cohesive layer is assumed as the interface layer/welded area between Al and Cu, where most of the IMCS are present. Secondly, a thermal-electrical analysis is made by simulating an electrical current of 10 A flowing through FSSW model as it cools down from 105 °C to ambient temperature. Load vs Displacement curves and Resistance vs Temperature curves are extracted from the initial simulations. For model validation and future calibration, experimental FSW and FSSW butt and single lap joints are produced, being subjected to mechanical analysis, such as tensile testing and SEM analysis. An electrical analysis is also executed through electrical conduction tests. Discussion between numerical and experimental data is made.

5.2 Paper B

A critical comparison between 3 variants of Friction Stir Welding for joining Al to Cu

This paper aims to understand how three variants of FSW Al-Cu joints (SLJ by FSSW, SLJ and butt joint by FSW) perform mechanically and electrically. A comparison between the three variants is also made, as is a comparison between different welding parameters sets. Specimens joined by both processes are made using a CNC machine and a FSW Machine at 800, 950-1000 and 1100-1200 rpm. For mechanical analysis, quasi-static tensile tests were made, along with Scanning Electron Microscopy (SEM) that allows a close understanding of the interface layer and interaction between the base materials and Vickers micro hardness measurements. Thermal-electrical analysis is achieved through electrical conduction tests.

Chapter 6

Conclusions and future work

6.1 Conclusions

Cohesive zone modelling (CZM) proves to be a reliable method for simulating the behaviour of joints created using FSW and FSSW. This is achieved through cohesive elements that effectively replicate the failure process of the Intermetallic Compound (IMC) layer, which is critical for joint failure.

The study revealed that reducing the interface layer thickness in the FSSW model, regardless of hook presence, yielded results that closely resembled the behaviour observed in experimental specimens. Furthermore, for a constant dwell time, FSSW joints achieved optimal mechanical performance at a tool rotation speed of 1000 rpm. Plunge depth was also found to influence hook formation, which in turn enhances load transfer and mechanical strength.

SEM analysis identified the formation of continuous, sub-5 micron thick IMC layers across the hook interface with aluminium at a tool speed of 1000 rpm. Conversely, these layers were discontinuous and exhibited copper separation at 800 and 1200 rpm.

For FSW joints, a higher rotation speed generally benefited the peak load of both BJIs and SLJs with aluminium as the second material (AS). However, for SLJs with copper as the AS, 800 rpm emerged as the superior parameter for peak load.

Micro-analysis of FSW surfaces revealed the formation of smooth, defect-free interfaces for butt joints, with minimal mechanical interlocking. In contrast, SLJs exhibited a tendency to develop hooks along the weld zone, particularly on the side opposite the AS.

While the primary focus of this study was on electrical performance for busbar applications, not structural integrity, the mechanical performance of FSSW joints was generally inferior to that of FSW joints. This can be attributed to the smaller weld area in the FSSW configuration, combined with a more pronounced IMC layer formation.

The study also found that increasing the tool rotation speed led to a decrease in FSSW electrical resistance values. This indicates a superior level of contact between the joining surfaces. Overall, FSSW joints demonstrated superior electrical conductivity compared to FSW joints. This can be

explained by the larger contact area achieved through the designed FSSW steel setup and tool plunge depth, leading to a significant reduction in resistance.

From an economic point of view, FSSW will likely be the most beneficial process. The exclusion of a transverse movement of the tool in FSSW, unlike FSW, may prolong the tool's wear life. However, it is important to assess the heat conditions to which the FSSW tool is subjected, due to this lack of movement. FSSW also appears to be more practical than FSW, as spot welds can be made in the work site, using a robotic arm with a spindle on its tip, enabling the joining of complex parts in complex locations. Usually, linear friction welds must be removed from the assembly site and transported to the FSW machine.

Ultimately, this work has demonstrated both processes can be successfully employed in the creation of joints for busbar applications, providing a good level of mechanical strength and electrical performance.

6.2 Future Work

Although the study performed helped achieve a better understanding of how Al and Cu behave when welded by FSSW and FSW, some missing elements during the investigations, either through lack of time and delays or technical shortage, should be approached and studied in the foreseeable future.

Since the current investigations takes into account the applicability of these welded busbars in the EV power distribution system, a higher current should have been provided for electrical analysis. A 1500 A power source was ordered with the intent of testing the FSSW joints electrically, however it did not arrive on time due to delays at the manufacturer. By testing the joints at these high current values, they heat up by Joule Effect, without any external heat source (such as the heat gun), which is a more accurate representation of what happens in an EV application.

During the numerical model development, the base materials ductile damage properties were not added. Although the existence of ductile damage was not the main factor of the model's investigation, it ended up being present in most of the FSSW joints tensile tests. A deeper numerical investigation could take place by adding this factor. Besides this, for better load vs displacement precision and closer mechanical behaviour prediction, a realistic hook geometry should be modelled and simulated. The author's approach is insightful and produces good results, although simplified.

A thorough comparison between FSW and FSSW joints was achieved. Unfortunately, joints made by these two processes were not produced in the same work conditions and equipments. If the contrary happened, more consistent and coherent results could have been drawn. A temperature measurement equipment for the welding area, such as a thermal camera, should also be present in the next studies, as temperature values during joining can lead to more and better explanations after mechanical and electrical testing.

The specimens tested electrically and mechanically were not the same specimens. In an ideal investigation, without delays, the produced joints would be tested electrically and then mechanically. This was not the case, as the specimens had to be firstly tested mechanically, and only in the thesis end phase were the joints able to be tested electrically.

Finally, an interesting approach to further develop the interface layer's characterization lies in finding the best FSW parameter set that enables a complete interface failure between Al and Cu, contributing to a more precise IMC layer investigation.

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Appendix A

Paper A - Numerical modeling, mechanical and thermal-electrical analysis of Al-Cu lap and butt joints made by FSW and FSSW

Numerical modelling, mechanical and thermal-electrical analysis of Al-Cu lap and butt joints made by FSW and FSSW

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Abstract: In modern electric vehicles, electrical conduction is carried out with the use of complex, multi-material busbars, which require complex optimized manufacturing processes. In this work, a new approach to develop a numerical model of Al-Cu single lap joint (SLJ) and butt joints (BJ) by Friction Stir Welding (FSW), and SLJ by Friction Stir Spot Welding (FSSW). Firstly, for the mechanical analysis, a 10 μm brittle cohesive layer was assumed as the interface layer/welded area between Al and Cu, where most of the IMCs are present. Secondly, a thermal-electrical analysis was made by simulating an electrical current of 10 A, flowing through the various joint configurations. Load vs displacement curves and resistance vs temperature curves were extracted from the initial analysis. For model validation and future calibration, experimental FSW and FSSW butt and single lap joints were produced, being subjected to multiple experimental testing procedures, including tensile testing and SEM analysis. An electrical analysis was also executed through temperature-dependent electrical conduction tests. Discussion between numerical and experimental data was made. A successful calibration of the model was achieved, replicating an identical behaviour to the experimental data. Furthermore, an offset error of 10 $\mu\Omega$ was found between the numerical and experimental thermal-electrical tests, due to external factors in voltage measurement.

Keywords: Welding, FSW, FSSW, SLJ, Butt Joint, IMC, interface layer

1. Introduction

The importance of materials responsible for the electrical power distribution (as electric conductors) across the electrical automotive industry, such as copper (Cu), is increasing every day. The high cost and weight of Cu is leading the industry to replace certain busbar configurations (see Figure 1) with ones using materials that can reduce the mentioned disadvantages without compromising the electrical performance. This is the case for Aluminium (Al) and its alloys, which are substantially lighter and cheaper than pure copper, yet with remarkable electrical conductivity and low thermal expansion coefficients [1]. It is of great interest to understand how these materials behave when joined, both mechanically and electrically, thus allowing the development of more efficient and economical energy storage and transfer systems. The friction stir welding (FSW) process has been used to join these two particular materials, as it can provide a satisfactory metallurgic bond within the

solid state of both materials [2]. This process is economically feasible, as it does not use consumable filler material, does not produce gases [3], and its heat generation can be controlled through adjustment of multiple parameter variables, such as tool spindle speed and transverse speed. However, in FSW of Al and Cu, its subsequent heat generation, intense pressure and plastic deformation [4] all lead to the formation of brittle intermetallic compounds (IMCs), even at the low temperatures generated during FSW [5], that affect the joint's mechanical and electrical properties and performance [6]. This IMC layer is usually continuous and results in a drastic decrease of the joint's strength [7]. It has been reported that when FSW produces a weld free of defects, the joint will tend to fail in the heat affected zone (HAZ) [6], more specifically in the weaker material's HAZ, which is usually Al [8]. Nonetheless, these IMC formations, if not controlled through the FSW joining process, can lead to a poor welded joint mechanically and electrically, hence being one of the main subjects of focus in Al to Cu FSW investigation. Reza et. al [9] studied the fracture mechanism of the IMC layer in AA1050 to pure Cu FSW butt joints and reported that, with the use of notched specimens, the crack propagated through IMCs Al_2Cu , $AlCu$, and between Al_2Cu and Al_4Cu_9 IMC before eventually failing at 173 MPa. A maximum process temperature of 336 °C was also achieved, given IMC growth kinetic formulations. Ólafsson et al. [10] compared mechanical and electrical properties of clamped Al and Cu base materials with a FSW butt joint of these two materials and concluded that such joints have 85% tensile strength compared to base Al components and have about 200 times lower electrical resistance than the clamped setup, proving the reliability of FSW for electrical applications.

The current work contributes to the literature by providing a systematic study on how Al-Cu joints achieved with FSW and FSSW behave when subjected to electrical currents and tensile forces, a numerical model was developed to simulate these two distinct situations, with a simplified approach when it comes to the IMC layer. Furthermore, it allows for better understanding of the properties of these IMCs in the welded area, using an iterative method for calibration. Firstly, the entire numerical model development was described, including geometry details, materials, boundary conditions and meshing, as well as other settings applied throughout the model build. After an initial set of results was obtained from the model, the experimental procedure was also explained and the joints made were presented, as well as its mechanical and electrical tests results. With all the experimental data collected, the numerical model's validation was made, leading to an adjustment of the IMC layer geometry. Further simulations were made in order to calibrate the model, if needed. Finally, the main conclusions were drawn.

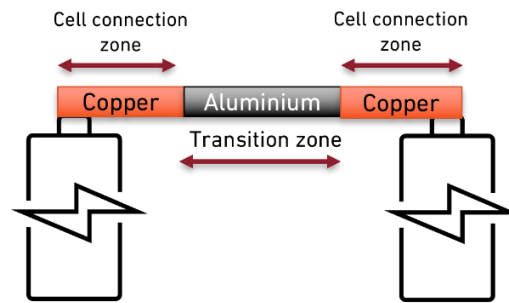


Figure 1 - Example of Al implementation with Cu in busbar system between two cells.

2. Numerical model development

2.1 Joint geometry and material properties

The geometrical configurations chosen for the base materials (BM) are depicted in Figure 2. Each substrate has a width of 25 mm, with the Cu being 1 mm thick and the Al alloys 2 mm thick. This ensures that the cross-sectional area ratio of Al to Cu is near the ideal value of 2.3 [11]. As for materials chosen, the aluminium alloy (AA6082-T4 for FSSW and AA6061-T6 for FSW) and copper's (Cu ETP R240) mechanical and electrical properties applied to the model are showcased in Table 1. An overview of the numerical model can be seen in Figure 3.

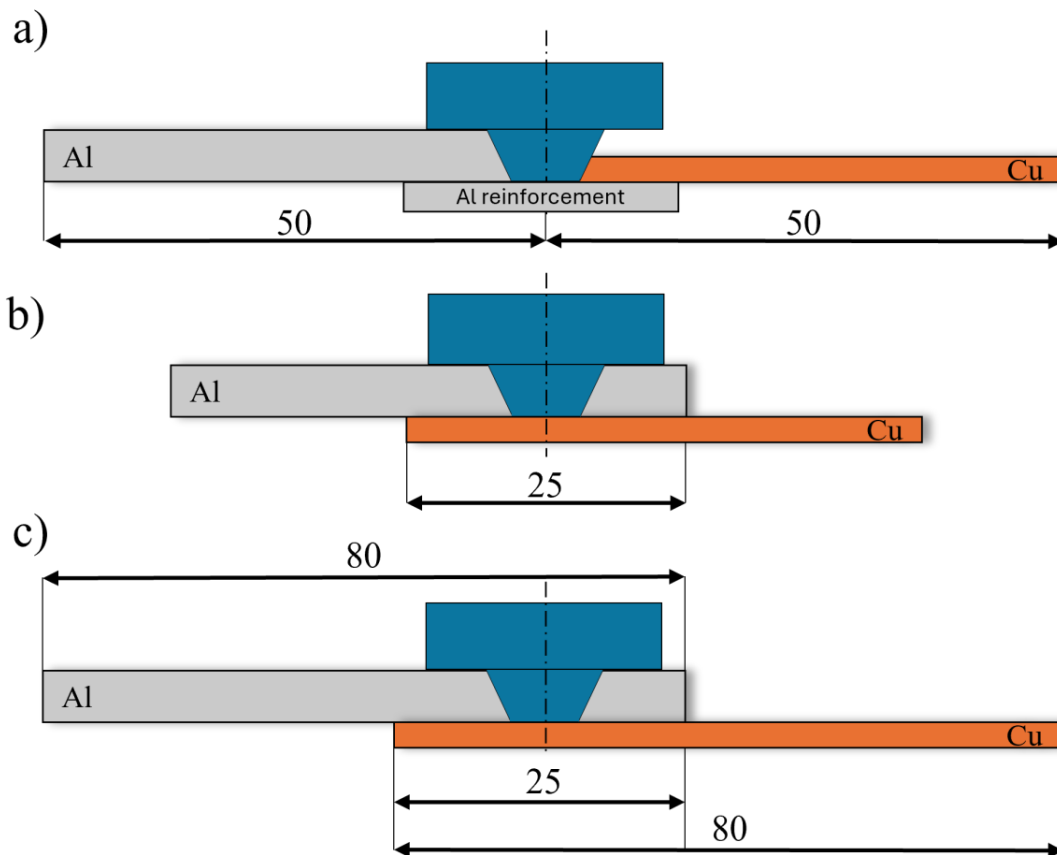


Figure 2 – Dimensions [mm] of a) FSW BJ, b) FSW SLJ and c) FSSW SLJ.

Table 1 - Mechanical and electrical properties of the base materials [12, 13].

	Al Alloys	Cu ETP
Young's Modulus [GPa]	70	127
Poisson's ratio	0.33	0.34
Density [kg/m ³]	2700	8960
Thermal conductivity [W/mK]	160-170	360
Specific heat [J/kgK]	900	394

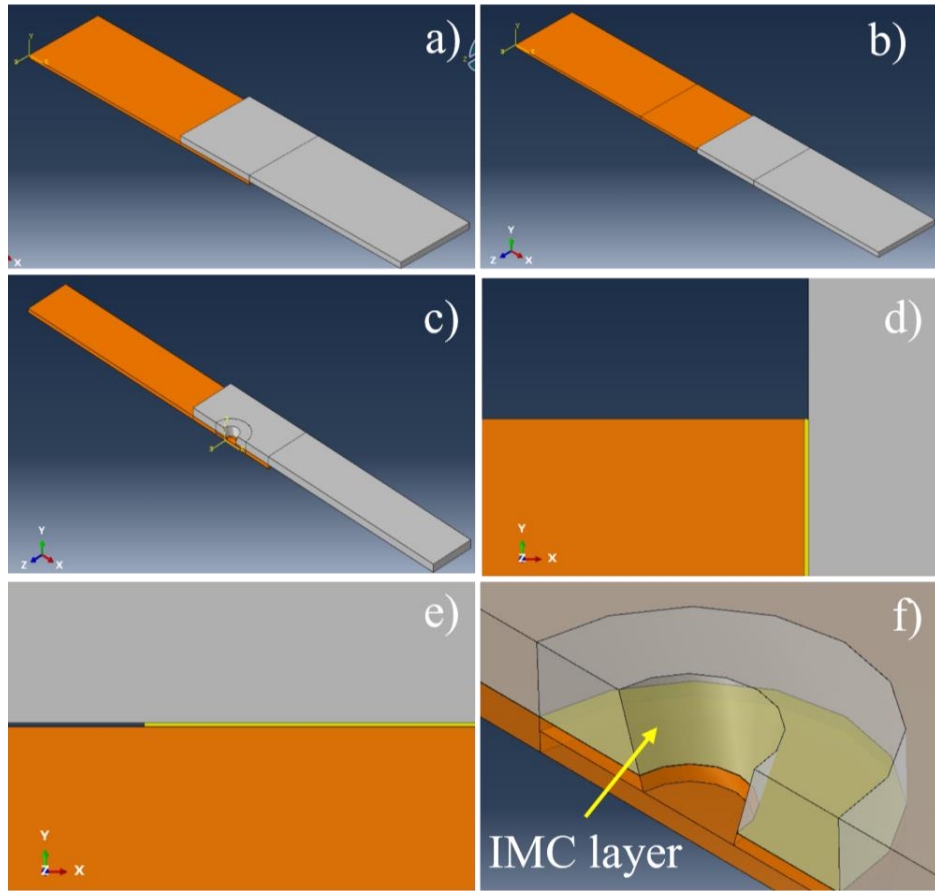


Figure 3 - Models geometry and IMC layer location: a) FSW SLJ model, b) FSW BJ model, c) FSSW SLJ model, d) magnification of BJ interface, e) magnification of SLJ interface, f) magnification of SLJ welded spot.

An initial 10x25 mm horizontal and a 1x25 mm vertical interface layer were modelled for the IMC layer in the FSW single lap and butt configuration, respectively, which was later adapted to match the IMC geometry is encountered on experimental joints. Since the focus of this model was to understand the behaviour of the IMC layer, both the Thermo-Mechanically Affected Zone (TMAZ) and the Heat Affected Zone (HAZ) of the joint were not modelled. The IMC layer was initially characterized with a stiffness equal to double the average of both base materials (187 GPa), as some IMCs tend to be more brittle than their base materials [14]. The chosen ultimate tensile strength (UTS) for the initial IMC analysis was 125 MPa. Reza et. al studied notched butt specimens of Al and Cu joined by FSW to better understand the behaviour of the IMC layer formed between the two materials, and a strength of 173 MPa was reached [9], a high strength value compared to similar literature. As this layer has a brittle behaviour, a feasible simplification consists in considering the IMC as a cohesive material, following a bilinear traction separation law [15]. The initial assumed fracture toughness G_{1c} is 0.1 N/mm, and G_{2c} is 2 N/mm.

As the maximum busbar service temperature is 105 °C [16], this temperature value corresponds to the upper limit for the thermal-electrical analysis made, although values of electric conductivity with temperature were inputted up until 120 °C. The IMC layer was assumed to have properties equal to the average of both base materials' properties. In order to expand the breadth of the analysis,

multiplication factors were applied to the IMC layer's conductivity (e.g. 1000 times lower than the base materials average electrical conductivity with temperature), thus simulating an increased joint's electrical resistance in the connected zone. Furthermore, with experimental data, the electrical conductivity variation with temperature was adjusted on the IMC layer for the results to coincide.

2.2 Definition of step, boundary conditions and meshing

For mechanical analysis, a “Static General” step of one second was assumed to simulate a quasi-static tensile test. The mesh of both base materials uses plane stress elements (CPS4R), and the IMC layer as cohesive element (COH2D4). The elements are “Quad-dominated Structured/Free” in the substrates, along with the necessary partitions to simplify the mesh, and “Sweep” in the IMC layer. The sweep path should be perpendicular to the crack propagation of the joint. Figure 4 depicts the two configuration's meshing and boundary conditions (BC). Both models were subjected to an encastre at the Cu end (left side) and had an imposed displacement of 0.5 and 2 mm (for the butt and SLJ by FSW, respectively) and 2 mm for the SLJ created by FSSW.

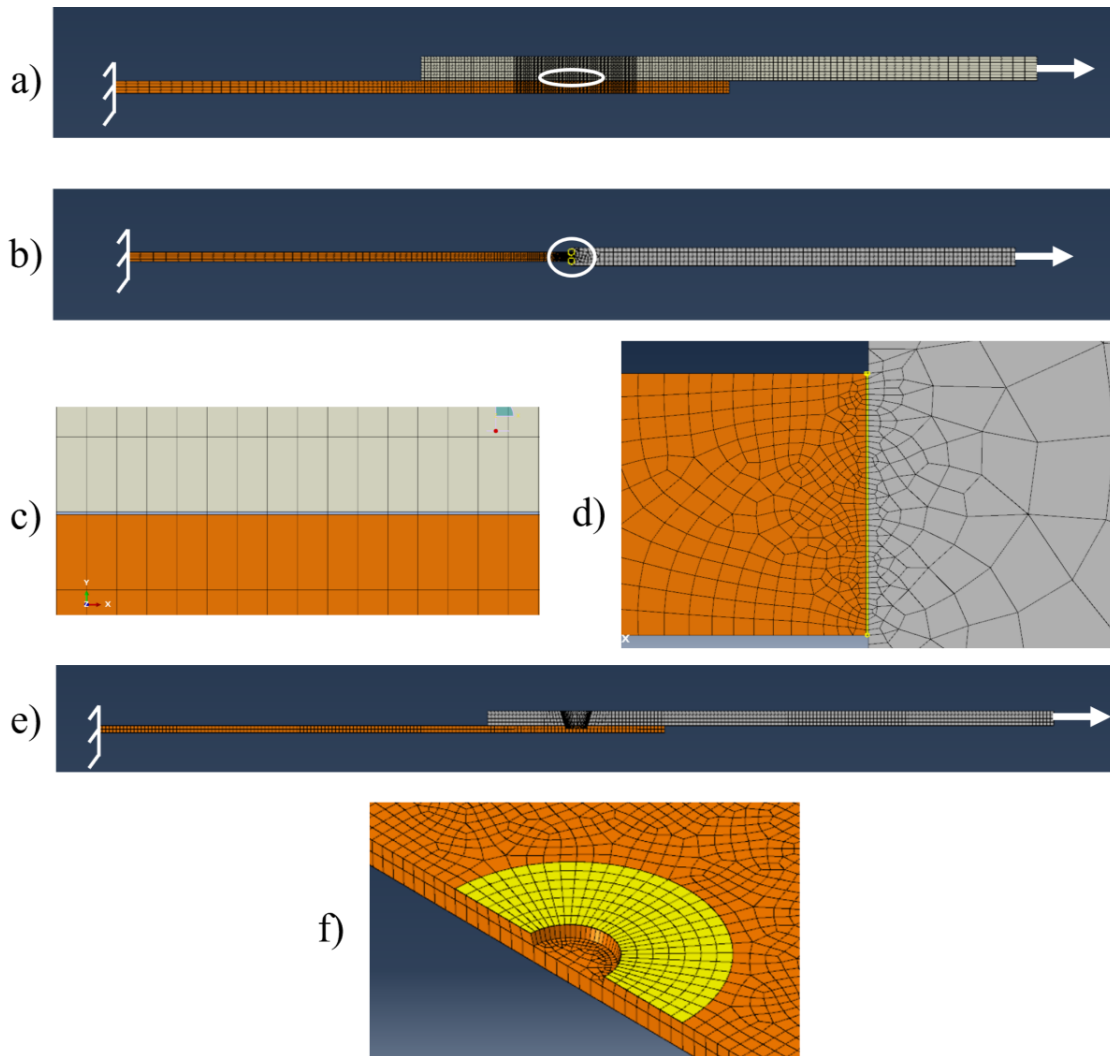


Figure 4 – a) FSW SLJ mesh and BC; b) FSW butt joint mesh and BC; c) FSW SLJ interface layer magnification; d) FSW butt joint interface layer magnification; e) FSSW SLJ mesh and BC and f) FSSW interface layer magnification.

For the thermal-electrical analysis, all elements were of the Thermal Electrical (DC3D8E) type. As for boundary conditions, a surface current density was applied on the Cu end. To replicate the current discharge applied in the experimental procedure, a 10 A current was chosen. As the Cu end's area is $25 \times 10^{-6} \text{ m}^2$, the current density's magnitude is 400000 A/m^2 . A further "Null Electrical Potential BC" was applied to the Al end, so that current can flow through the joint. A "Temperature" predefined field of 378K (105 °C) across the entire joint area was also applied.

The steps applied are "Coupled Thermal Electrical", divided in two intermittent phases: a 2 second 10 A current spike step is applied followed by a cooldown step for a total of twelve times, so the electrical resistance of the joint could be evaluated and measured over spikes. Lastly, some interactions were applied to the model, such as a "surface film condition", across the entire model, with a film coefficient of $13 \text{ W/m}^2\text{K}$ to simulate the natural convection affecting the joint during all times. A set of "thermal" and "electrical conductance" contact properties was applied, as well as two "surface to surface" tie constraints between the Al substrate and the IMC layer, and between the Cu substrate and the IMC layer.

2.3 Mechanical and thermal-electrical results

2.3.1 Tensile results

Figure 5 a), b) and c) shows the results of the initial tensile simulations performed in ABAQUS for FSW and FSSW. There is no sign of plastic deformation development in the BJ, and only the IMC layer is subjected to stress. The highest load and displacement values belong to the model with UTS of 175 MPa for the interface layer, at around 2900 N and 0.09 mm.

The SLJs created with the FSW process seem to withstand higher displacement than butt configuration, as now the substrates are subjected to plastic deformation due to the much higher welded area, reaching 1.3 mm and around 4000N for an IMC UTS of 175 MPa.

The FSSW joint's stiffness is lower than that of the FSW models, mostly due to elastic deformation of the substrate, which is less constrained by the singular spot. The spot-welded model demonstrated a level of stiffness which is in between that of the previously simulated two models, with reasonable agreement in peak loads and displacements. Figure 5 d) compares the three configurations for an interface layer UTS of 125 MPa and a $10 \text{ }\mu\text{m}$ IMC layer thickness. Across all simulations the failure occurs always at the interface layer, through the cohesive elements, until complete failure is attained.

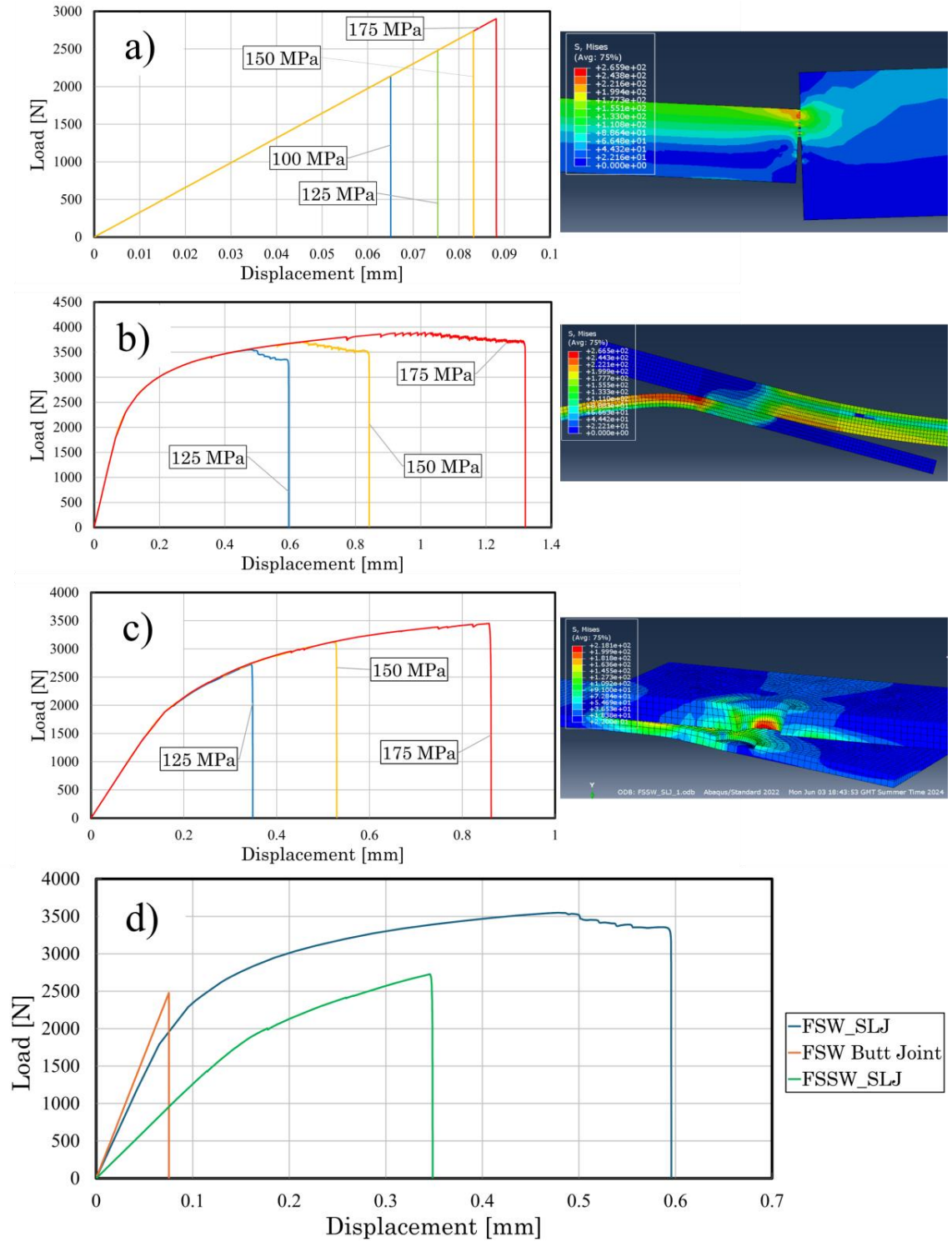


Figure 5 - Load vs displacement curves: a) FSW butt joint, b) FSW SLJ, c) FSSW SLJ and d) Comparison between 3 configurations for 125 MPa UTS and a 10 μ m thick interface layer.

2.3.1.1 Electrical results

For FSSW, an initial assumption of 50 μm for the IMC layer's thickness was made. Then, various interface layer area reductions were applied to the model in order to understand how much the quality of the substrate contact impacts the joint's electrical resistance, most specifically 80%, 50% and 30% of the joint's overlap area. These areas, as well as the two configuration's welding areas are indicated in Table 2. The measured resistance was calculated by measuring the electrical potential (EPOT) of two nodes, distanced 50 mm apart. This is 25 mm to each side from the joint's centre, as depicted in Figure 6.

Table 2 - All configuration IMC layer areas.

Configuration	Area [mm^2]
FSSW: Total area	616
FSSW: 80% area	493
FSSW: 50% area	308
FSSW: 30% area	185
FSW SLJ	250
FSW Butt joint	25

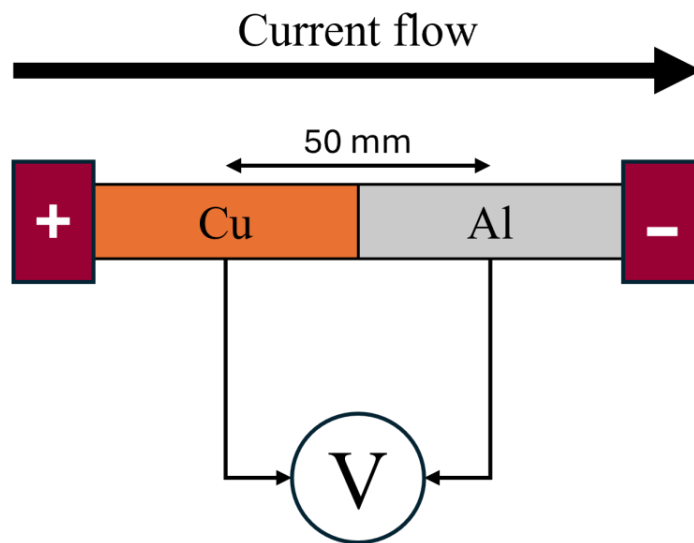


Figure 6 - Electrical setup and joint resistance measurement.

Figure 7 shows electrical resistance for different FSSW interface areas, with an interface layer's conductivity factor of 1000 applied. It can be clearly seen that with the reduction of the joint's contact area, an increase in resistance takes place, with the 30% interface area joint reaching the maximum busbar service temperature at 72 $\mu\Omega$.

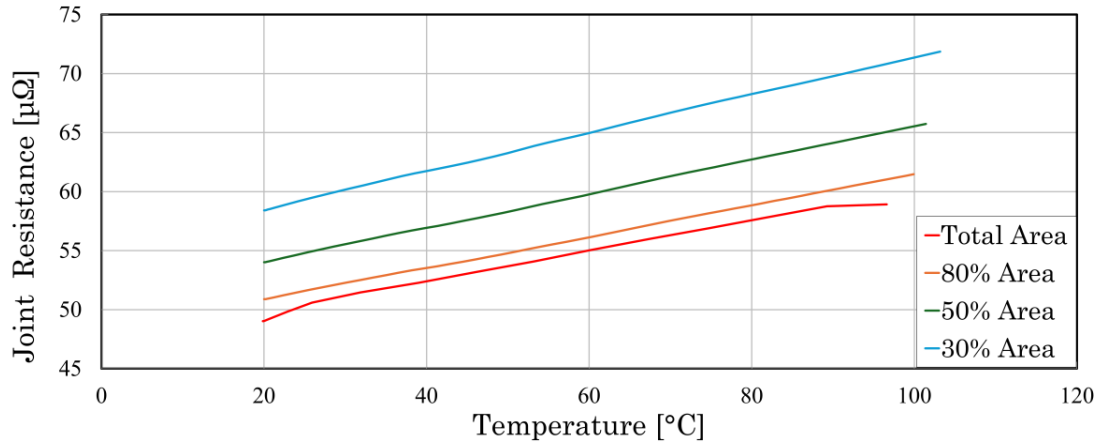


Figure 7 - Joint resistance in function of temperature for different FSSW interface layer areas.

A comparison of electrical resistance evolution with temperature between the three variants was also made. A 10 μm thick interface layer is assumed, as well as a 1000 factor for the electrical conductivity of the interface layer. Figure 8 shows that, for 10 A current spikes of 2 s while the model is cooling down from 105 °C to ambient temperature, the FSW BJ returns the highest resistance value and temperature due to the low contact area between substrates. The SLJ created with FSW has the second highest resistance, followed by an 80% of total overlap area SLJ by FSSW.

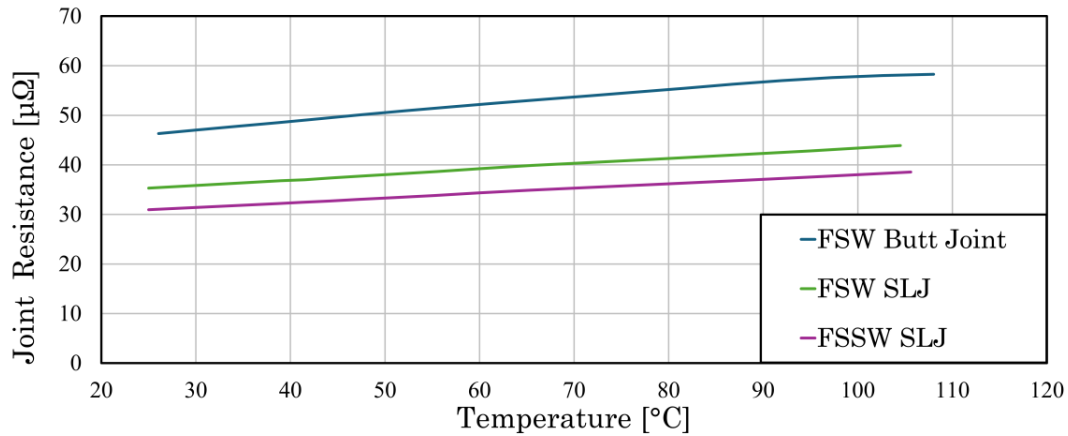


Figure 8 – Electrical resistance evolution with temperature for the three numerical configurations studied.

3. Model validation

The numerical model developed is to be compared and calibrated with the experimental data collected. The mechanical analysis will be validated for all three configurations, and the thermal-electrical analysis will be validated for the FSSW model.

3.1 Experimental procedure

3.1.1 FSW process details

Lap and butt joints manufactured by the FSW process were produced using a FSW machine acting in “position control mode” activated by an 11 kW servomotor, and an H13 steel tool with a flat shoulder and a truncated conical pin, whose geometries are depicted in Figure 9 a). Two 50 mm wide Al and Cu plates were joined and later cut into 25 mm wide specimens. The FSW specimens for electrical analysis also have 25 mm of width. The process parameters used for joint production consist of a 950 rpm tool spindle speed, a 2.5° tool tilt angle with respect to the welding direction, a plunge depth of 0.05 to 0.01 mm, a dwelling time of 30 s and a 40-60 mm/min linear welding speed. Both welded configurations are shown in Figure 10.

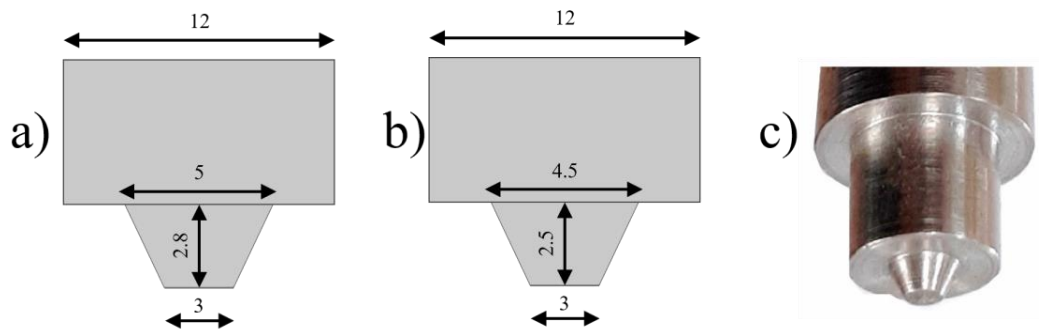


Figure 9 - Tool geometries used for: a) FSW single lap and butt joint, b) FSSW single lap joint. c) FSW tool representation.

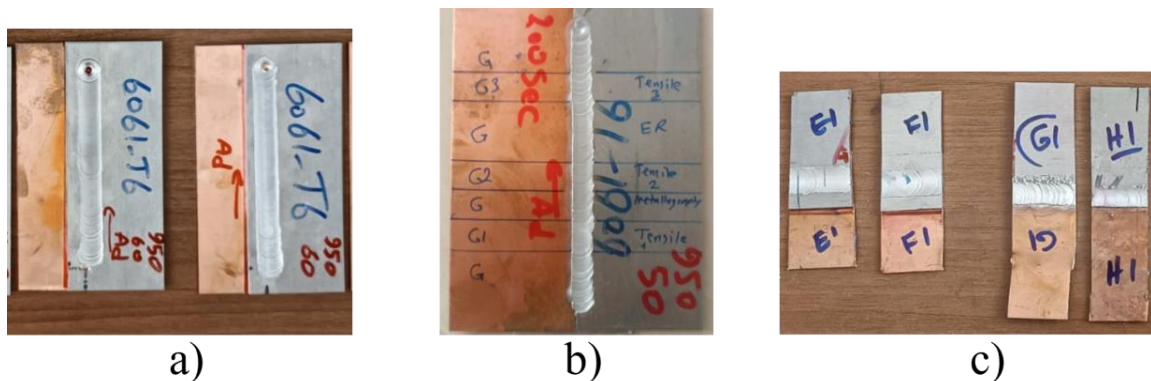


Figure 10 – a) FSW lap joints, b) FSW butt joints made and c) 25 mm wide FSW cut specimens.

3.1.2 FSSW process details

FSSW joints were produced using a HAAS “MiniMill” CNC machine and an H13 steel tool with a concave shoulder and a truncated conical pin (see geometry in Figure 9 b). In order to achieve good production quality, a special setup/jig was designed and machined to ensure that the joints are firmly fixed in place while welding, as well as preventing the substrates from bending while the tool applied the intense pressure on the overlap area. This setup consists of two plates, a top one and a bottom one, which are compressed together through the means of six bolts and nuts and tightened to the CNC table. Two central holes, with 26 mm of diameter, allow the tool to reach the joint to be welded. The setup and joint assembly are presented in Figure 11.

The process parameters for the FSSW process consist of a 1000 rpm tool spindle speed and a 60 s dwelling time before removing the tool. This dwell time allows for guaranteed formation of IMC layers across the joint interface. The plunge depth varied between 0 and 0.5 mm, as the setup design inhibited the possibility to directly observe the welding process and therefore visually determine when in fact the shoulder was in contact with the top substrate. A FSSW specimen manufactured with this process is shown in Figure 12.

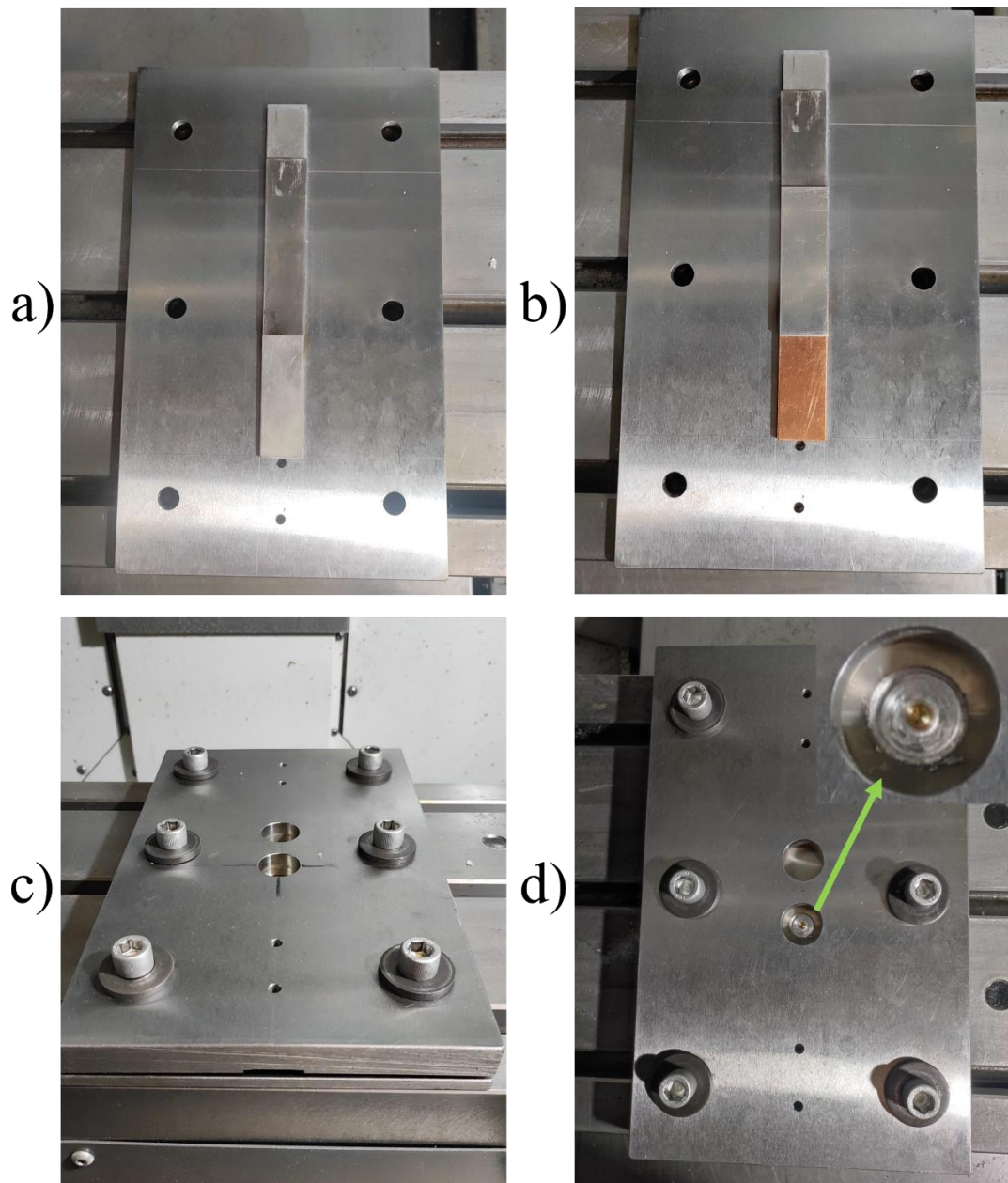


Figure 11 - FSSW setup and joint assembly: a) setup's bottom plate with two back-up steel plates, b) Al and Cu substrates placed on top of the back-up plates and aligned, c) top plate encloses the SLJ and the setup is tightened and locked with M12 bolts and T-nuts, d) top view of the setup after spot welding is achieved.

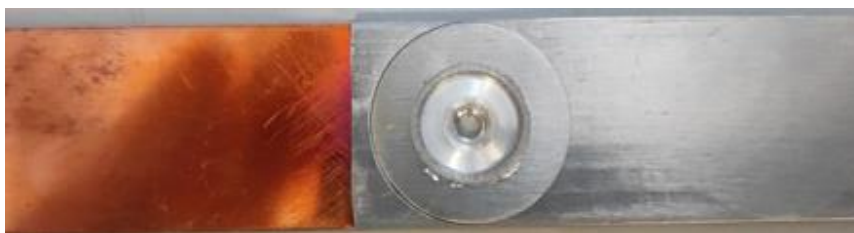


Figure 12 - FSSW specimen: 1000 rpm and 0.1 mm plunge depth.

3.2 Experimental results

3.2.1 Tensile testing

The FSSW joints were tested using an INSTRON 3367 universal test machine (Norwood, MA, USA) with a load cell capacity of 30 kN and a 1 mm/min speed for quasi-static tensile testing. Figure 13 shows the load displacement curve of the three samples tested.

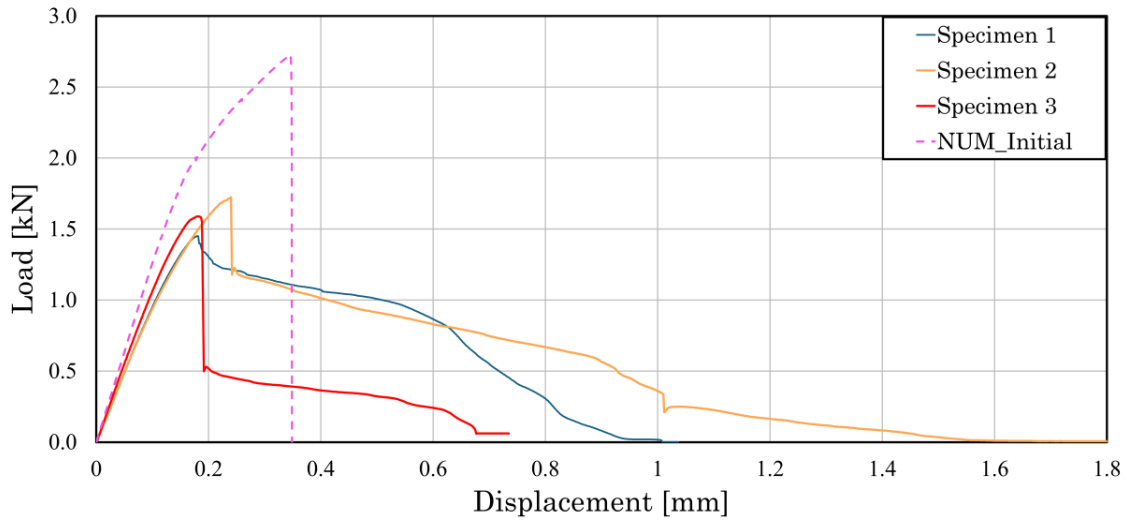


Figure 13 - FSSW load vs displacement curves.

As it can be seen, Specimen 1 (S1) does not appear to fail through the interface, and after achieving 1400 N of maximum load, ductile damage starts developing until the joint eventually fails at around 1 mm. On the other hand, Specimens 2 (S2) and 3 (S3) appear to have brittle failure, through the IMC layer, followed by Al ductile damage until complete failure. This ductile damage occurs in the HAZ of the Al substrate. A maximum load of 1724N was achieved.

Figure 14 shows the load vs displacement curves for the FSW joints in butt and lap configuration. Only FSW joints with Cu in AS were tested. BJ reached a maximum load of 3200 N, while SLJs reached nearly 4750 N.

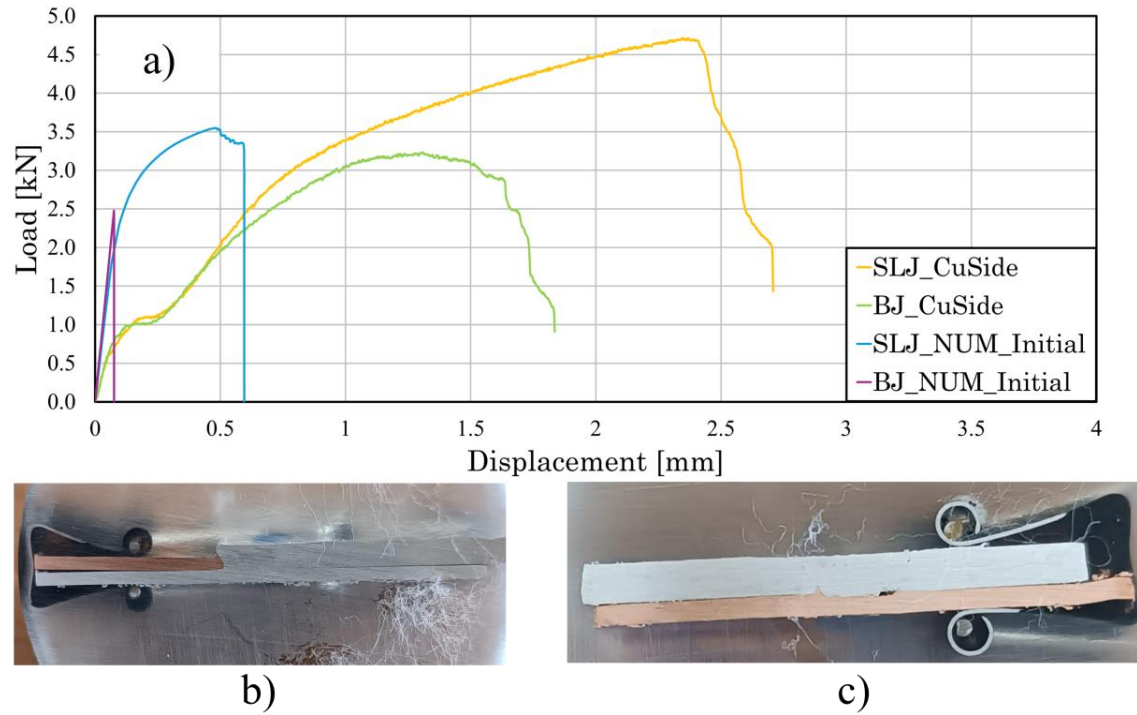


Figure 14 – a) FSW joints load vs displacement curves and initial numerical curves; b) FSW BJ longitudinal cross section; c) FSW SLJ longitudinal cross section.

Figure 15 shows the failure surface of Al and Cu of the FSSW joints. As it can be seen (Figure 15 e)), S1 does not seem to fail through the Al or the interface, but rather through the Cu, hence the almost complete absence of brittle failure. S2 reveals brittle failure on part of the welded area, followed with ductile damage in the Al HAZ. S3 seems to be the joint with an almost complete interfacial failure due to possible weak IMC formation. Figure 15 c) shows a substantial overlap overheating of S3 when compared to S1 and S2. This can also contribute to the formation of thicker IMC layers.

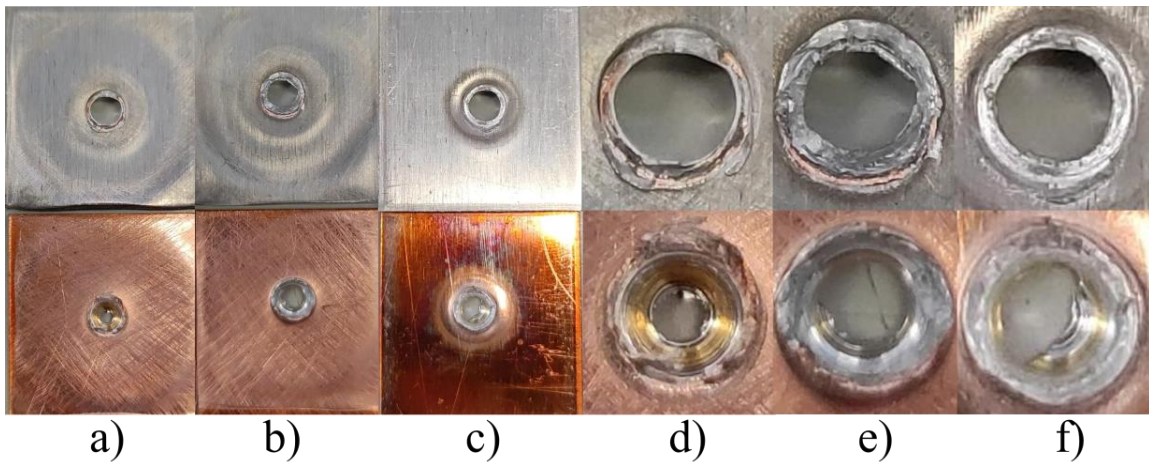


Figure 15 - Failure surface of FSSW joints: a) S1, b) S2, c) S3, d) Magnification of S1 failure surface, e) Magnification of S2 failure surface and f) Magnification of S3 failure surface.

3.2.2 Electrical analysis

For an electrical analysis of the welded joints, a heat gun was used to heat up the interface to the maximum busbar service temperature of 105 °C. Then, as the joint cooldown was happening, a 10 A current is applied during 2 s. To measure the voltage drop and calculate the electrical resistance using Ohm's Law, a voltmeter with probes placed in the substrates 50 mm apart was used, as depicted in Figure 16. A thermal camera captured the decreasing temperature. The results and comparison with the numerical model are showcased in Figure 17, which shows that the results obtained follow the trend described by the numerical model.

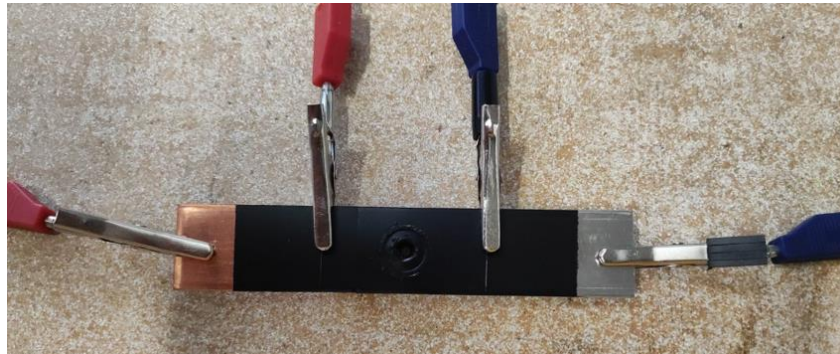


Figure 16 – FSSW Thermal-electrical experimental setup.

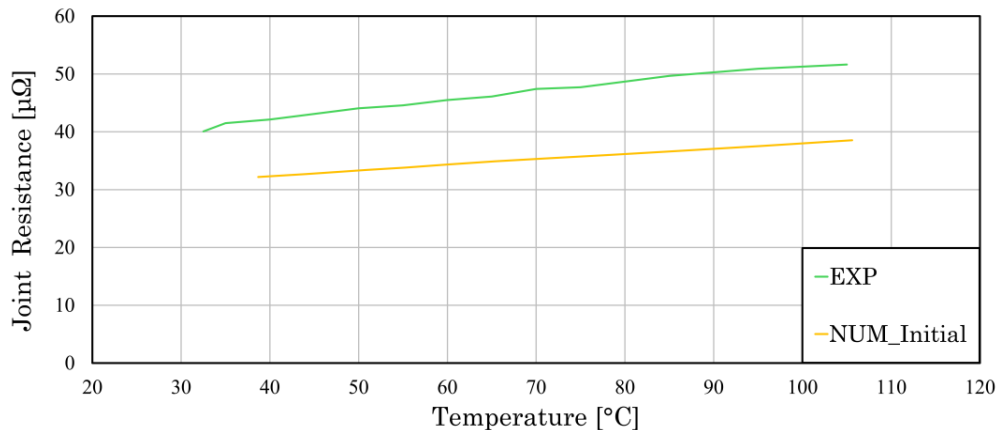


Figure 17 - Evolution of resistance with temperature for experimental and numerical FSSW joints.

3.2.3 Cross section/SEM analysis

For microscopy analysis, specimens were cut in middle across the welded area (for FSW joints) and keyhole area (for FSSW joints) using a *Struers* Accuton-5 machine and a diamond disc. The samples were then ground using a #320 and #800 Silicon Carbide (CSi) emery paper and polished in rotating cloths with 3 and 1 μm diamond in suspension. The SEM analysis was performed at the Material's Centre of the University of Porto (CEMUP), using a high resolution (Schottky) Environmental Scanning Electron Microscope with X-Ray Microanalysis and Electron Backscattered Diffraction analysis (FEI Quanta 400 FEG ESEM / EDAX Genesis X4M). The samples were coated with a thin Carbon (C) film by vapor deposition, using the JEOL JEE – 4X Vacuum Evaporator equipment.

The FSSW joints SEM images are depicted in Figure 18. A poor weld is clearly formed in the 0 mm P.D. specimen (Figure 18 a) and b)), with no mechanical interlock being achieved. However, the 0.5 mm P.D specimen clearly reveals a well-defined wave-like shape hook. This guarantees a high level of mechanical interlock, increasing joint peak loads and load transfer between Al and Cu. Two interface zones identified in Figure 18 c) can be visualized in Figure 18 e) and f). In the hook's right zone, a continuous IMC layer with approximately 3 μm and no visible defects can be observed. Only some contamination seems to be infused inside these layers. The top region of the hook is organized in a chaotic way, as thick IMC layers form a composite-like structure. This zone is expected to be extremely brittle and have a high hardness value. Some voids and Cu particles can be observed in Figure 18 d).

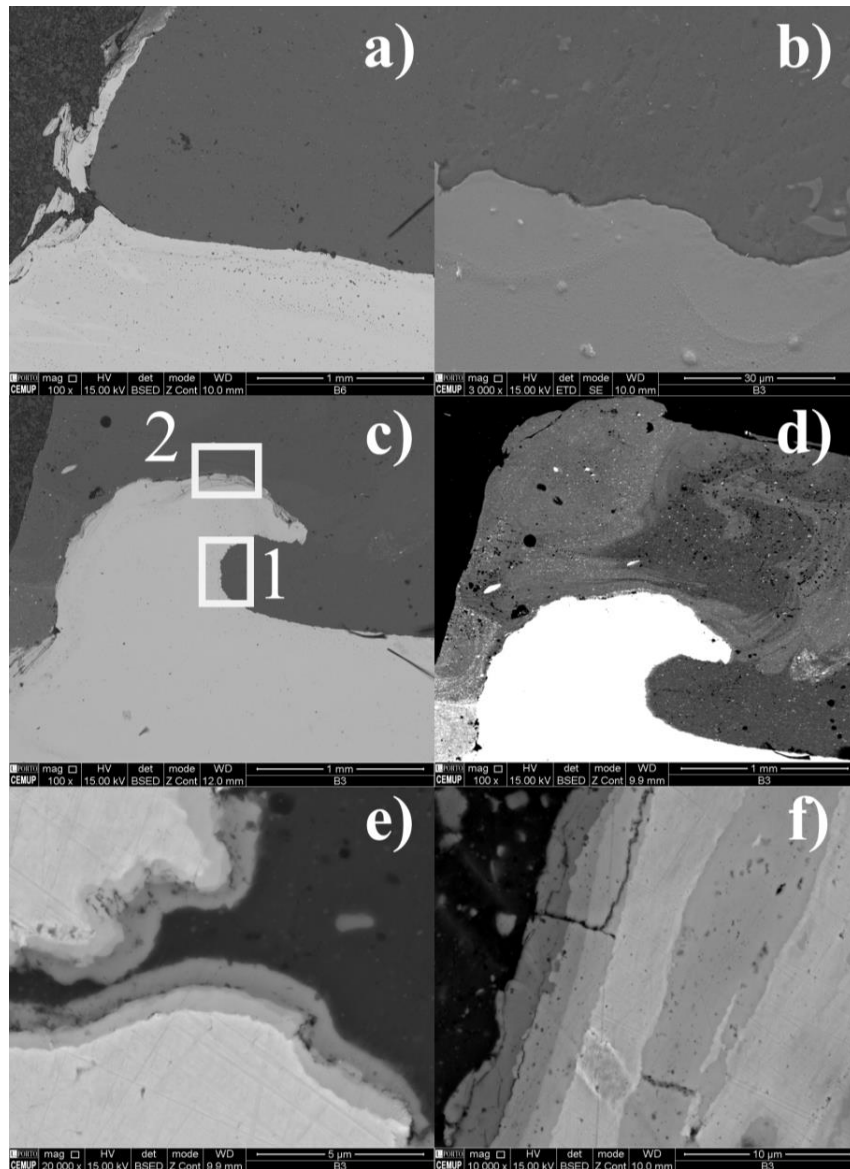


Figure 18 - FSSW SEM images: a) Joint with no plunge depth at 100x; b) 3000x magnification of Al and Cu interface of specimen in a); c) Joint with 0.5 mm plunge depth at 100x; d) Backscatter image of joint; e) 20000x magnified image of location 1 in c); f) 10000x magnification of location 2 in c).

4. Model adjustment

To better replicate the common hook shape that is found in Al/Cu FSSW lap joints, the interface layer geometry was adjusted. Most specifically, a simplified hook with 0.5 mm of height and an interface maximum diameter of 6 mm was introduced. Two simulations were ran, one with the hook (see Figure 19 a) and b)) and another one without a hook (see Figure 19 c)).

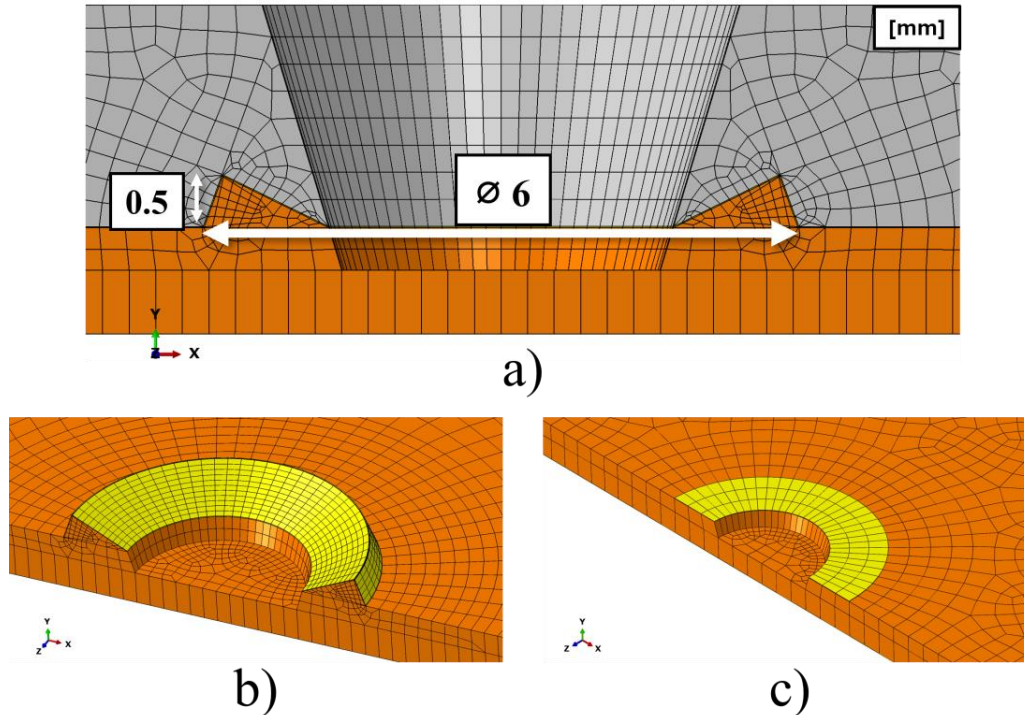


Figure 19 - Interface layer adjustments: a) Hook dimensions, b) Hook area representation and c) Interface area without hook.

The initial interface area assumed for the SLJ made by FSW model had 250 mm². However, after joint production and testing, it became clear that the SLJ interface's area had 125 mm², so this area adjustment was made. The BJ's area had an identical value to the initial analysis.

For thermal-electrical analysis, as seen in Figure 15, the FSSW joint overlap is composed of a compressed or force fitted area, and a smaller ring of welded area. With this in mind, it was decided that the joint interface layer in the numerical model would be divided accordingly, through the use of a force fitted area with the base materials average properties, and the welded area with the 1000 multiplication factor, as shown in Figure 20.

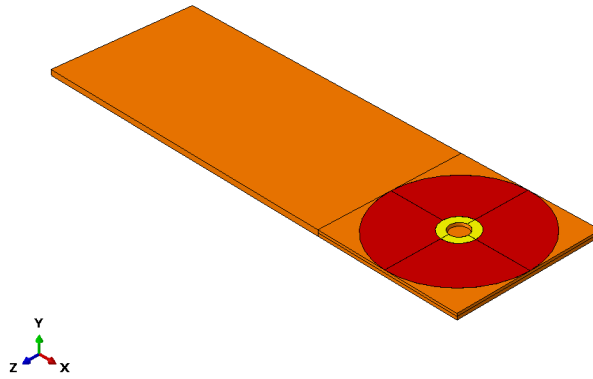


Figure 20 - FSSW SLJ overlap area adjustment: compressed area (red) with BM average properties, and welded area (yellow) with multiplication factor.

Comparing the simulations of the adjusted FSSW tensile models with the experimental results and the initial simulations, as depicted in Figure 21, it can be concluded that the adjusted models resemble more accurately the experimental curves of the tested specimens. At 125 MPa of UTS, the interface layer in the model with the hook displays an identical behaviour to S2, whereas the adjusted model with no hook at 150 MPa and the model with hook at 100 MPa approximate the S3 curve. The presence of a hook in the model severely affects the strength of the interface layer and therefore the behaviour of the joint. It can also be concluded that the initial numerical approach with a larger interface area exceeds the performance of the experimental tests. Therefore, considering an interface layer with the area of the tool shoulder was shown to be incorrect assumption.

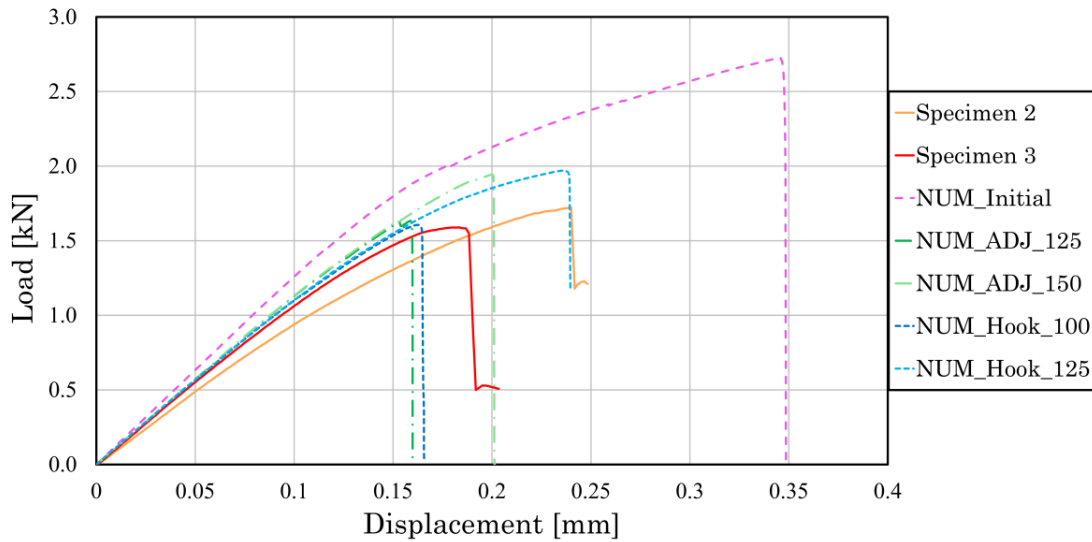


Figure 21 - Comparison of FSSW numerical and experimental curves.

For the FSW joints, their adjustment was a bit more complicated. The main focus of the work regards the peak load achieved in the numerical model. Due to the complexity of the joints failure mechanism and simplifications made, the experimental displacement could not be replicated in the numerical model. A correction factor was applied to the numerical displacement to compensate the compliance. However, a simple study of the IMC layer and its geometry allows a rather accurate peak load

prediction, which is extremely useful for the purposes of designing a joint. Figure 22 - Comparison of FSW BJ numerical and experimental curves. Figure 22 and Figure 23 show the adjustments made to the numerical model of the BJ and SLJ, respectively.

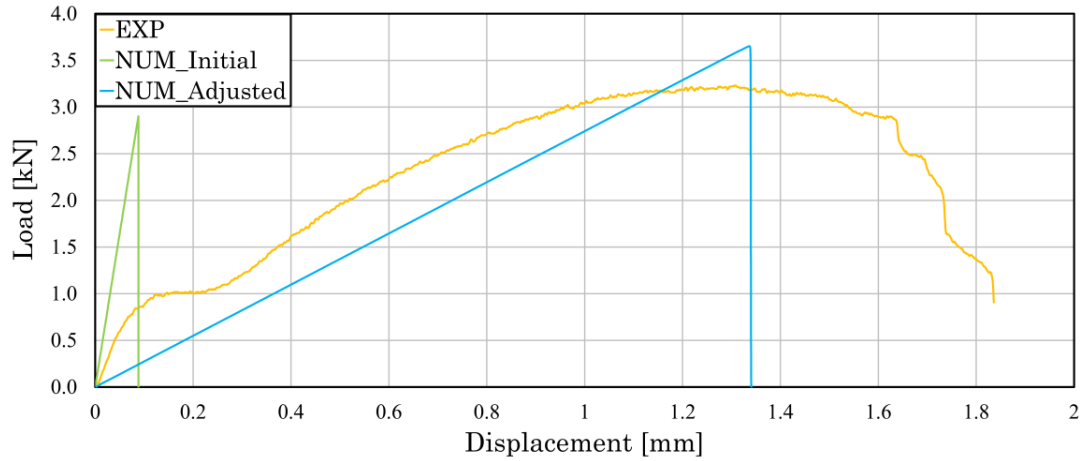


Figure 22 - Comparison of FSW BJ numerical and experimental curves.

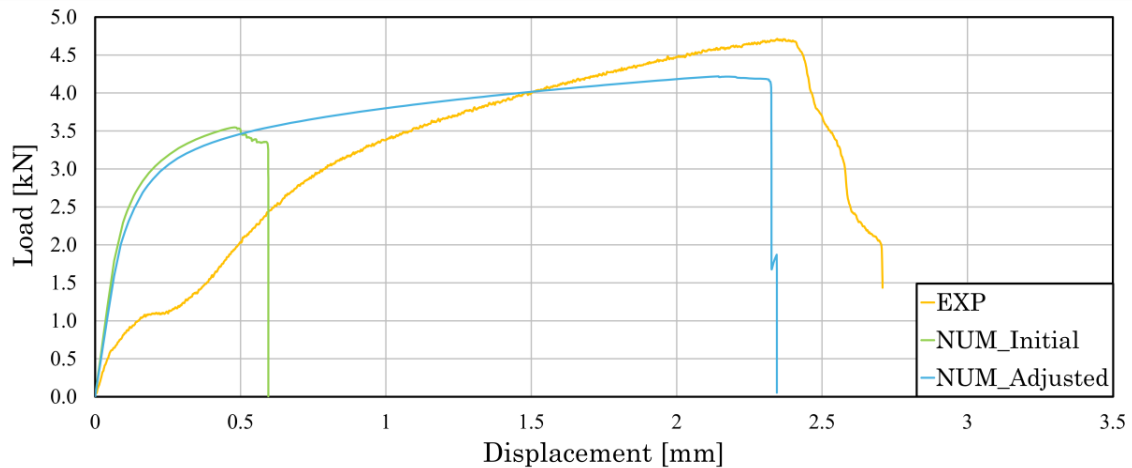


Figure 23 - Comparison of FSW SLJ numerical and experimental curves.

Additionally, three curves can be compared for the thermal-electrical analysis: the initial numerical approach with an interface layer with 80% of overlap area and a 1000 multiplication factor applied to it, the adjusted numerical approach with the force fitted area (average electrical conductivity of BM) and the experimental results. These are all depicted in Figure 24. As it can be seen, the slopes of the numerical and experimental curves are very identical, which leads to the conclusion that the experimental measurements have an offset error. Furthermore, there are external factors that contribute to the increase of the experimental joint resistance, unlike the perfect scenario of a numerical model, such as the heating of the probes which increases the voltage measured and therefore the resistance, or the experimental current value, which only rose up to 9.74 A instead of the intended 10 A.

Also, the difference between the initial and adjusted approach of the model is almost non-existent, so the differentiation between the force fitted area and the welded area is not that significant. This can

be due to the formation of Cu-rich IMCs in the welded area which results in better electrical conductivity.

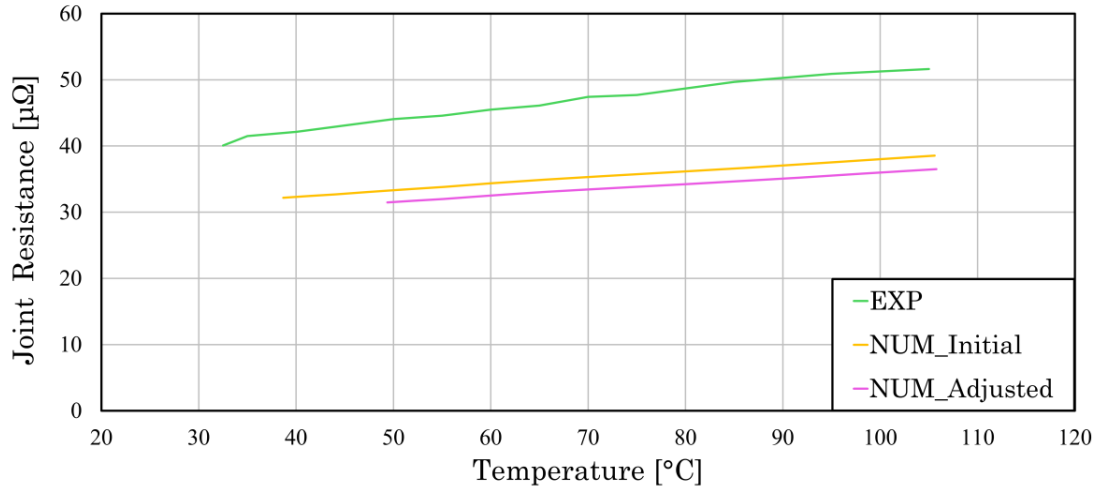


Figure 24 - Evolution of joint resistance with temperature for experimental and numerical approaches.

5. Conclusions

Throughout the development of a numerical model that reproduces FSW and FSSW joints behaviour in butt and lap configurations, the following conclusions could be drawn:

- Cohesive zone modelling can serve as a viable method for modelling the behaviour of joints created using FSW and FSSW. Cohesive elements are able to reproduce the failure of the IMC layer and thus reproduce the failure process of the joint.
- Regarding the mechanical properties of the interface layer, it was shown that a reduction of the interface layer in the FSSW model, with or without adding a hook, much more resembles the behaviour of the experimental specimens. An IMC layer UTS between 100 and 125 MPa was identified as having a level of strength that replicates experimental values. When it comes to FSW, SLJ was adjusted to a UTS of 75 MPa along with a G_{1c} of 1 N/mm and G_{2c} of 2.5 N/mm. The BJ was adjusted to a 150 MPa UTS and a G_{1c} of 1 N/mm.
- As for the electrical properties of the FSSW interface layer, it can be concluded that the assumption of an interface layer with 10 μm and 80% of the overlap area can successfully predict the evolution of joint resistance with temperature. Furthermore, the division of the overlap into a welded area and a compressed area reduces the joint resistance of the model 2 $\mu\Omega$ when comparing to the initial analysis. The difference in values does not justify the interface layer adjustment. An offset between experimental and numerical results is visible due to the probes resistance and other external factors.

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Appendix B

Paper B - A critical comparison between 3 variants of friction stir welding for joining Al to Cu

A critical comparison between 3 variants of friction stir welding for joining Al to Cu

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Abstract: In modern electrical vehicles, electrical power transmission is achieved through the use of aluminium and copper busbar systems, which requires the use of effective and efficient joining processes. This paper aims to understand how three variants of FSW Al-Cu joints (SLJ by FSSW, SLJ and Butt Joint by FSW) perform mechanically and electrically under conditions that replicate busbar applications. A comparison between the three variants was also made, as well as comparison between different welding parameters sets. Specimens joined by both processes were made using a CNC machine and a FSW Machine at 800, 950-1000 and 1100-1200 rpm. For mechanical analysis, quasi-static tensile tests were made, along with Scanning Electron Microscopy (SEM) that allows a close understanding of the interface layer and interaction between the base materials, X-Ray Diffraction (XRD) phase analysis and Vickers micro hardness measurements. Thermal-electrical analysis was achieved through electrical conduction tests. A big difference was revealed in peak loads and displacements between FSW joints and FSSW, with the FSW specimens performing better mechanically. Electrically, the FSSW joints were shown to be better at conducting power, since they provided a better degree of contact between the two metals.

Keywords: FSW, FSSW, interface, IMC, Butt joint, SLJ, Electrical resistance

1. Introduction

Friction Stir Welding (FSW) is a process that started being developed in 1991 by the Welding Institute (TWI) [1]. It stands out as a revolutionary joining process that differentiates itself from common welding techniques, as it joins materials without reaching their melting points. It is also referred to as solid-state welding. The process consists of a cylindrical, non-consumable rotating tool that generates frictional heat when in contact with the materials to join, plasticizing the materials and achieving a metallurgic bond inside the Stirred Zone (SZ). It offers low distortion welds, excellent mechanical properties and is extremely well suited for welding dissimilar materials, as well as joining workpieces with different thicknesses. It does not require any filler material, does not produce dangerous emissions and consumes less energy when compared to the more traditional welding processes, such as arc welding.

One of the main variants of FSW is Friction Stir Spot Welding (FSSW), proposed by Mazda Motor Company of Japan [2, 3]. The main difference regards the existence of no tool path in the welded area, as the tool only penetrates and dwells in the joint. No tool tilt angle and transverse movement makes the heat distribution and material flow different from FSW [4]. Figure 1 shows the appearance of FSW and FSSW joints. Also, a lower heat input from FSSW will result in a slower growth of intermetallic compounds (IMCs) when joining dissimilar materials [5]. When automating manufacturing processes, energetic and time efficiency is key to competitiveness, and this is especially true for companies working in the automotive and electronic equipment sectors, where the use of FSSW can translate into significant gains in the process efficiency.

A busbar is a metallic strip used in electrical applications, such as electrical vehicles (EVs), to distribute the electric power from the battery cells to panel boards and all other EV equipment that requires electrical power [6]. These busbars are normally made of copper (Cu), which has a significant mechanical strength, high thermal and electrical conductivity, and good corrosion resistance [7,8]. However, Cu is rather expensive, and its high density reflects on higher EV weight, increasing energy consumption. Aluminium (Al), on the other hand, is cheaper than Cu, has a high strength-to-weight ratio, good electrical conductivity and excellent corrosion resistance [9], making it an ideal material to combine with Cu in busbar systems. By studying the behaviour of joined Al and Cu for busbar applications, efficient power transmission can be achieved using a localized application of Cu and important weight and price reduction with the use of Al in less critical areas, leading to optimal EV performance. Furthermore, such approach has no need of external fasteners, such as rivets or bolted connections, further reducing weight.

The process of using FSSW to join Al to Cu is still an important investigation theme, as it presents many challenges. The large difference in melting points poses a significant problem. Then, the heat generated by the tool's friction, though much lower than conventional joining methods, contributes to the formation of IMC layers which drastically decrease the joint's ductility and strength [10]. Some common IMCs found in these joint interfaces consist of Al_4Cu_9 , $AlCu$, Al_2Cu and $AlCu_3$ [11]. Various IMC combinations can form, depending on the base materials composition as well as their welding conditions, such as the tool rotation speed and the dwell time [12]. It can be assumed that a continuous 0.5 to 4 μm IMC layer in Al to Cu joints is required to achieve a defect free and sound weld [13,14].

This paper seeks to further the understanding of the mechanical and electrical behaviour of FSW and FSSW joints, doing so by comparing specimens produced by both joining techniques, with different sets of welding parameters. The tensile strength, electrical resistance, microstructure and hardness of the three configurations is analysed and compared. This work supports the design of improved joints for busbar applications as it provides a better understanding of the effects of process parameters on joint quality and electrical characteristics. The IMC layer's effect on the electrical and mechanical performance was quantified and compared.

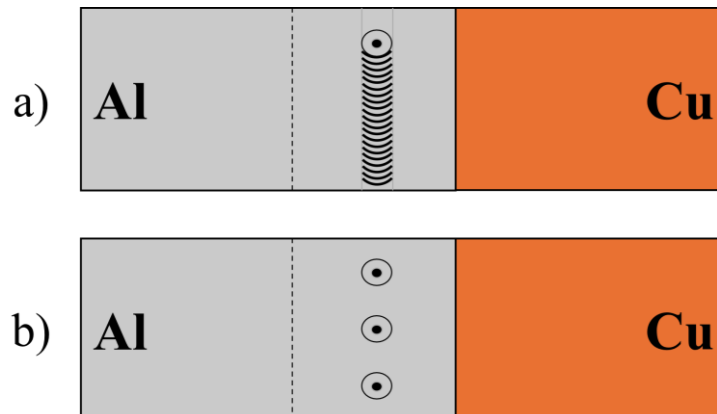


Figure 1 - Top view of an Al-Cu Single Lap Joint: a) welded by FSW, b) welded by FSSW.

2. Experimental details

2.1 Materials

The Al substrate materials chosen were AA6082-T4 and AA6061-T6, two 6XXX series Al alloys that have significantly better mechanical properties than the 1XXX series, for example, without compromising its electrical properties. These were chosen due to material availability and due to their very similar electrical behaviour. As for the Cu substrate, a pure copper with a high level of purity was chosen (Cu ETP R240). The mechanical and electrical properties of these materials are depicted in Table 1.

Table 1 - Mechanical and electrical properties of the base materials used.

	Cu ETP R240	AA6061-T6	AA6082-T4
Young's modulus [GPa]	127	70	70
Poisson's ratio	0.34	0.33	0.33
Density [g/cm ³]	8.96	2.7	2.7
Elongation at fracture [%]	15	3.4-20	6.3-18
Electrical conductivity [%IACS]	≥98.3	43	42

2.2 FSW process details

Multiple 130x50 mm sheets of AA6061-T6 and Cu were welded in single lap (75x25 mm) and butt (100x25 mm) configuration (see Figure 2) using a FSW machine acting in “position control” mode and activated by a 11kW servomotor. For technical facilitation, an Al reinforcement was added to the butt joint while welding. After joining, 25 mm wide specimens were cut in order to perform the tensile testing, as well as electrical analysis. The tool used to perform both configurations is a H13 steel tool heat treated to 42-48 HRC with a flat shoulder and a truncated conical pin, with the geometry depicted in Figure 3 a).

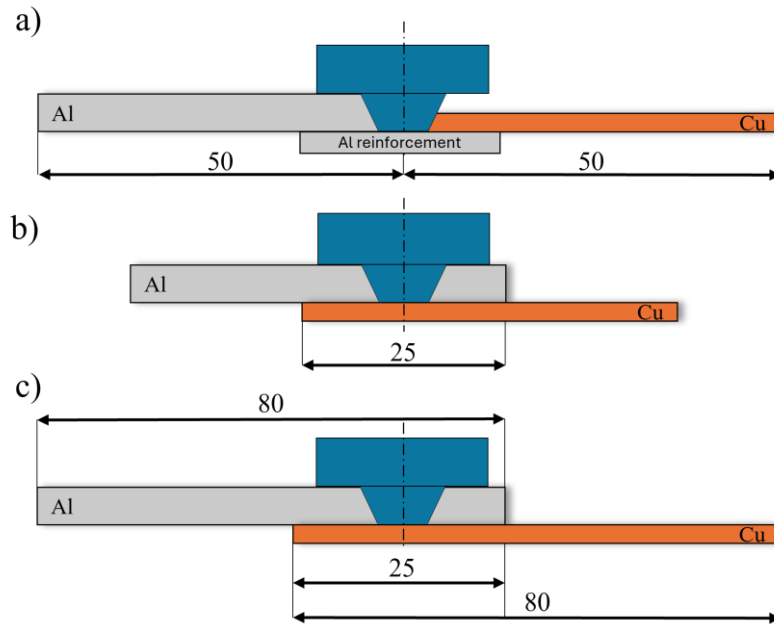


Figure 2 – Dimensions [mm] of: a) FSW butt joint, b) FSW single lap joint, c) FSSW SLJ.

As for the process parameters, the fixed ones include a plunge depth (P.D) of 0.05-0.1 mm, a 30 s dwelling time, a 300 s plunging time, a 2.5° tool tilt angle with respect to the weld direction and a welding speed of 40-60 mm/min. The variable process parameters are the tool's spindle speed (800, 950 and 1100 rpm) and the tool rotation direction (clockwise and counterclockwise), which determines the advancing side (AS) and the retreating side (RS) of the butt and lap joints. A butt joint sheet and the cut specimens are depicted in Figure 4.

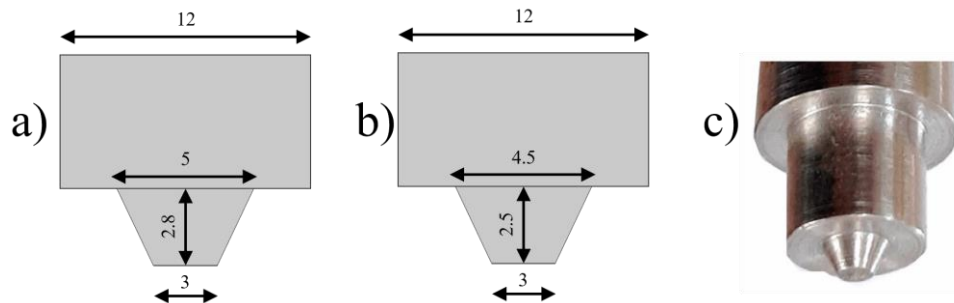


Figure 3 - Tool geometries [mm] used for: a) FSW single lap and butt joint, b) FSSW single lap joint. c) FSW tool representation.

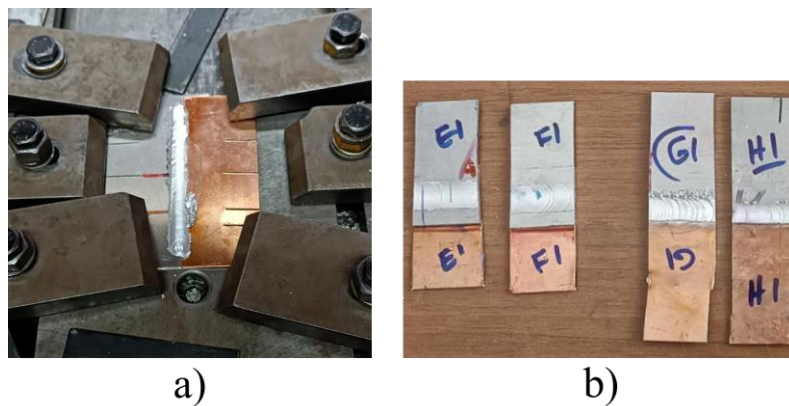


Figure 4 - a) Joined Al and Cu sheets in butt configuration, b) SLJ (left) and Butt joint (right) specimens.

2.3 FSSW process details

For friction stir spot welding of single lap Al/Cu joints, a HAAS MiniMill CNC machine was used along with a H13 steel tool which has a concave shoulder and a truncated conical pin. The tool's geometries are represented in Figure 3 c). As the supplied material came in pre-cut form, a special setup had to be designed to support the welding procedure. The purpose of the setup is to clamp and lock the base materials when they are subjected to the intense pressure and friction of the tool as it penetrates the top substrate, preventing the joint from bending and sliding out of place. The setup consists of a top and bottom machined steel plates that are bolted together to the CNC machine table through six bolts and T-nuts. Two 26 mm central holes allow the tool to reach the top substrate. Four holes along both plate centres lodge guiding pins that help position the joint in the setup. The setup and joint assembly are depicted in Figure 5.

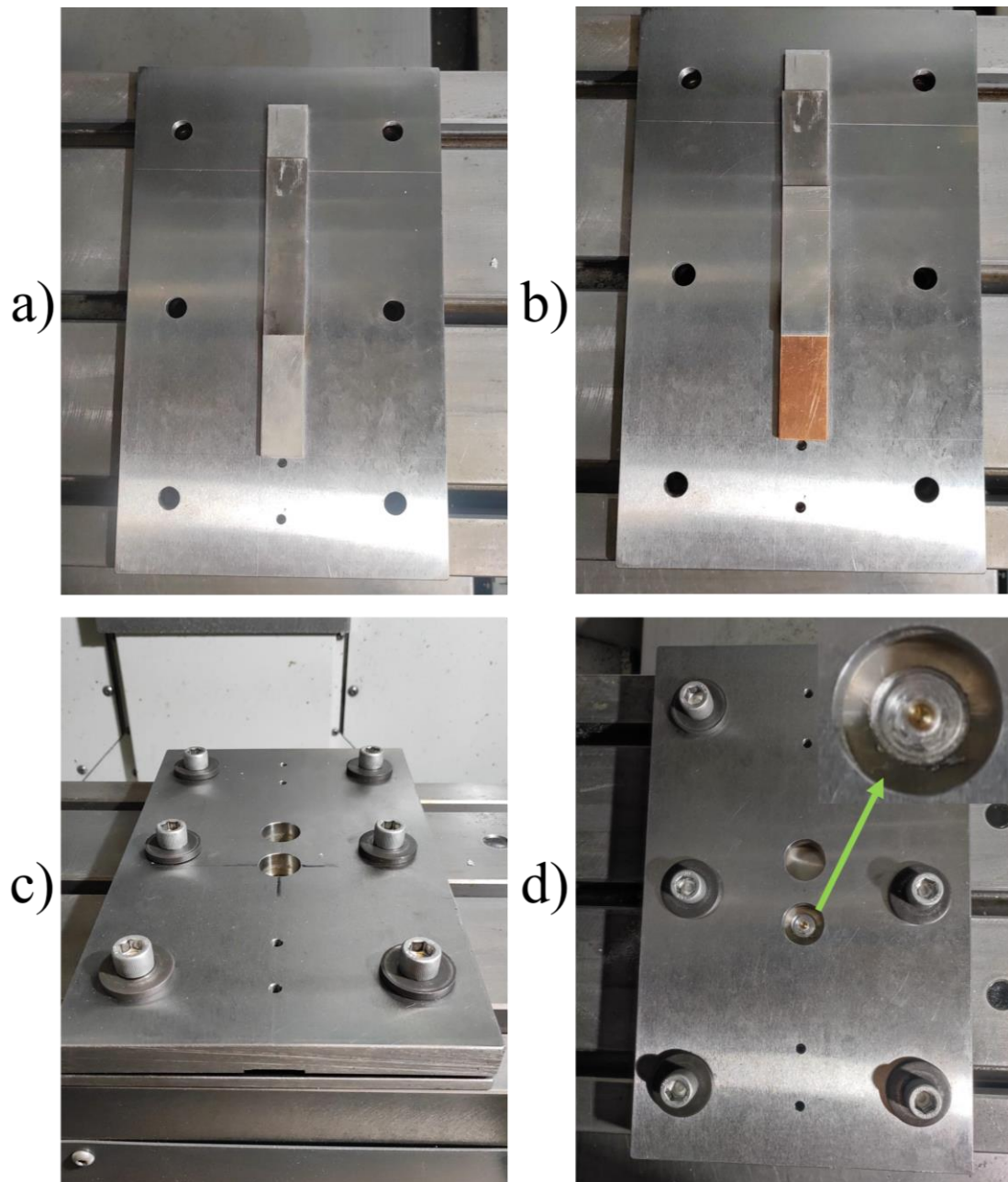


Figure 5 - FSSW setup and joint assembly: a) setup's bottom plate with two back-up steel plates, b) Al and Cu substrates placed on top of the back-up plates and aligned, c) top plate encloses the SLJ and the setup is tightened and locked with M12 bolts and T-nuts, d) Top view of the setup after spot welding is achieved.

Three tool spindle speeds were chosen for comparison purposes, which include 800, 1000 and 1200 rpm. As the dwelling time of the tool was kept constant at 60 seconds, a second variable for investigation consisted of the tool's plunge depth, at 0, 0.25 and 0.5 mm beyond shoulder contact with the top substrate. A higher plunge depth can lead to more intense material heating and subsequent mixing, but it can also foster the IMC layer formation in the interface. In light of this compromise, plunge depth was chosen as a main parameter to study. An example of a SLJ created by FSSW can be visualized in Figure 6.

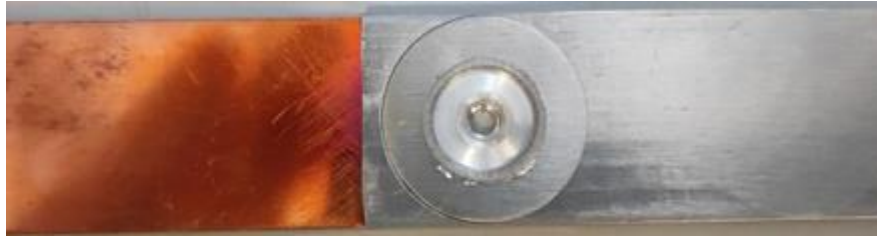


Figure 6 - Example of a 1000 rpm FSSW joint.

3. Results and discussion

3.1 Tensile testing

The FSSW tensile tests were carried out in an INSTRON 3367 universal test machine (Norwood, MA, USA) with a 30 kN load cell and 1 mm/min speed for quasi-static tensile testing (see FSSW tensile testing example in Figure 7) . Figure 8 and Figure 9 show the joints peak loads for the three studied configurations.

For FSSW, the 1000 rpm sample with 0.25 mm plunge depth seems to achieve the highest peak load, followed by the 800 rpm samples and lastly the 1200 rpm samples. The poor performance seen in the 1200 rpm samples can be justified by the excessive heat generation occurring in the interface, caused by the tool's high rotation speed, which stimulates the formation of IMCs and leads to a larger IMC layer thickness, decreasing peak load. The higher rotation can also mean a large turbulent flow in the stirred zone, which does not enable continuous IMC layers to form in the interface, and instead discontinuous zones with micro-cracks. The variation of the plunge depth appears to have a severe effect on joint peak load. Thus, 800 and 1000 rpm samples clearly have enhanced performance for intermediate (0.25mm) plunge depths. The use of limited or inexistent plunging is not able to provide sufficient material mixing and mechanical bonding, but excessive plunging depth leads to an eventual overheating of the area to be joined, increasing IMC presence and strength degradation.

SLJs made by FSW show a clear difference in the peak load values regarding the material on the AS. For 800 rpm, the difference is not notable, as this low rotation speed should not provide the sufficient heat for Al to behave distinctly from Cu when the tool rotation direction is changed. However, for 950 and 1100 rpm, the values drastically changed when the AS is on the Cu side versus when it is on the Al side. This is justified by the tool rotation direction: when Al is on the AS (tool rotation is CC) a hook is found on the RS, pointing to the Cu substrate. The load transfer flows through the Al substrate and, if no major defects are found in the interface layer, the mechanical performance is remarkable. However, when Cu is on the AS, this hook points to the Al substrate. When the loads flow through Al, they encounter the hook first instead of the interface layer. As this hook zone is prone to defects like kissing bonds, cracks and voids, all of which decrease substantially the peak loads and joint performance.

BJs show an intermediate mechanical performance when comparing to SLJ by FSSW and SLJ by FSSW. The small welded area between Al and Cu do not allow the joint to have an identical performance to the SLJ by FSW, for example.



Figure 7 - FSSW tensile testing.

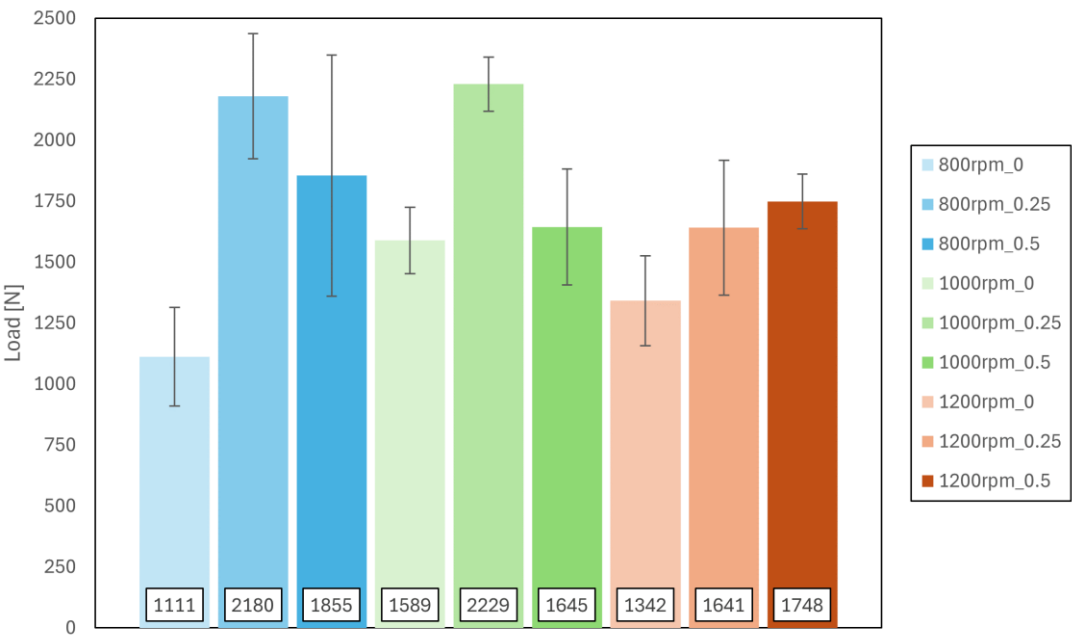


Figure 8 - Maximum load per FSSW parameter set (rotation speed [rpm] and plunge depth [mm]).

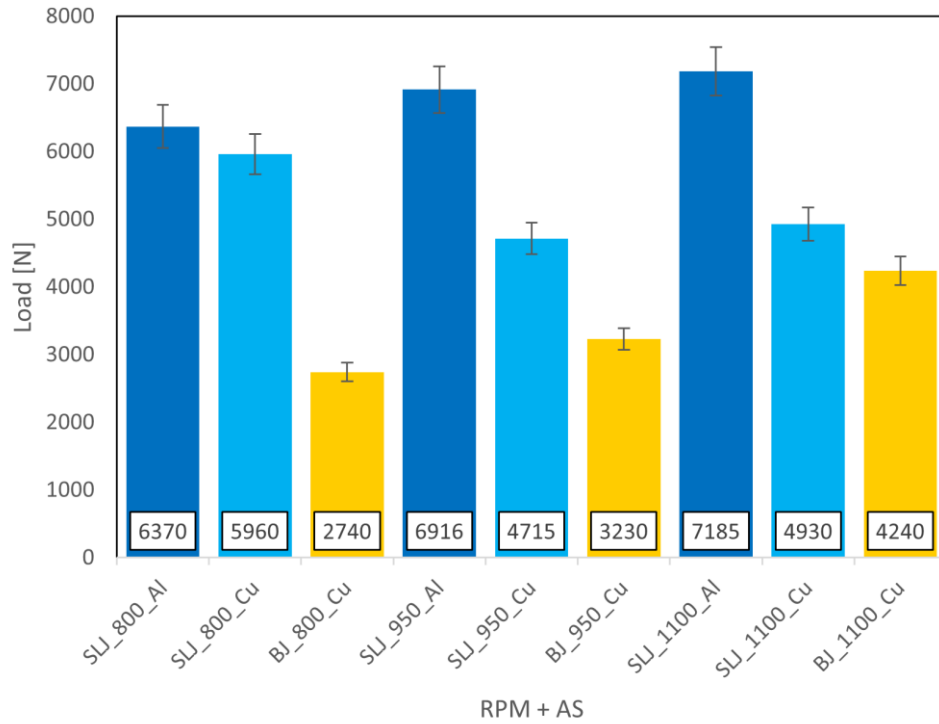


Figure 9 - Peak loads for joints made by FSW. SLJ – Single Lap Joint; BJ – Butt Joint.

Most of the 0 mm P.D FSSW joints had lack of penetration due to the low to non-existent plunge depth, not providing sufficient heat for a sound bonding to be formed. For deeper penetrations, bonding was consistently achieved. However, excessive penetration may lead to an abnormal heat input, resulting in thick IMC formation and therefore a decrease of the peak load. The failure mode was consistently divided between interfacial failure and ductile failure in Al's Heat Affected Zone (HAZ). Figure 10 reveals the fractured welded areas of 1000 rpm FSSW joints.

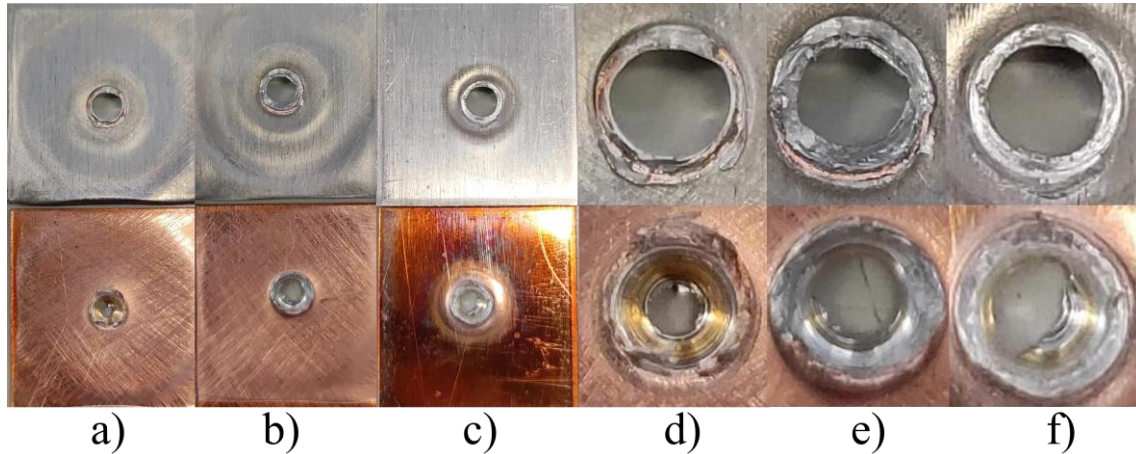


Figure 10 - Fracture surface of 1000 rpm specimens.

FSW joints also had a similar fracture to the presented FSSW joints. Most of the SLJ fracture is interfacial with some ductile damage in the Al top substrate. The BJ however showed no sign of ductile fracture and only achieved interfacial fracture. The observed welded area of SLJ was 125 mm² (5x25 mm) and BJ was 25 mm² (1x25 mm). The fracture surfaces can be seen in Figure 11.

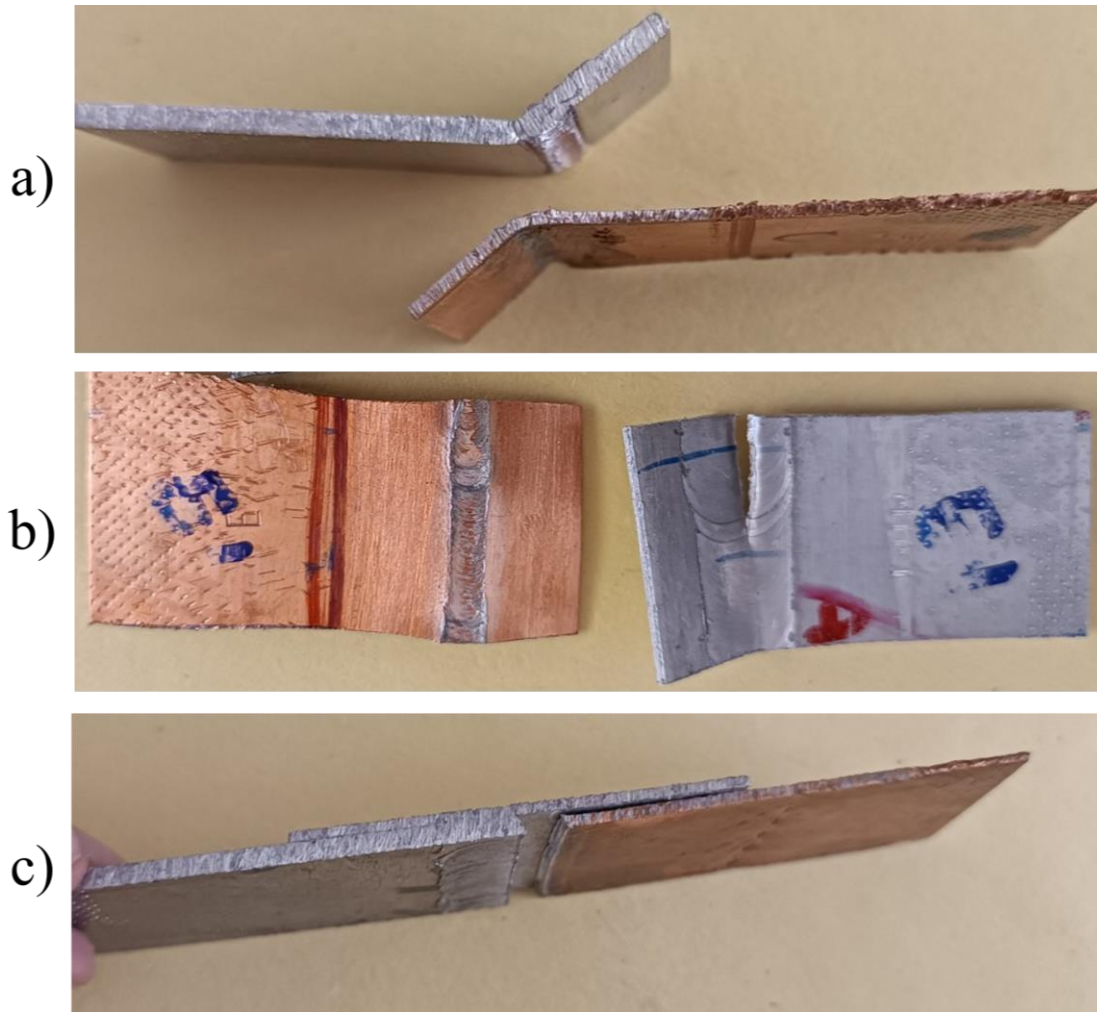


Figure 11 - Fracture surface of: a) SLJ by FSW (side view), b) SLJ by FSW (top view), c) BJ by FSW (side view).

3.2 Microstructure and micro hardness analysis

3.2.1 SEM analysis and micro analysis

Using a Struers Accuton-5 machine and a diamond disc, the specimens were cut halfway across the welded area (for FSW joints) and keyhole area (for FSSW joints) in preparation for microscopic analysis. After that, the samples were ground using Silicon Carbide (CSi) grinds of sizes 320 and 800 and polished in cloths with suspended 3 and 1 μm diamond. Ultimately, 2% Nital was used to etch the samples. The SEM analysis was performed at the Materials Centre of the University of Porto (CEMUP), using a high resolution (Schottky) Environmental Scanning Electron Microscope with X-Ray Micro analysis and Electron Backscattered Diffraction analysis (FEI Quanta 400 FEG ESEM /EDAX Genesis X4M). The samples were coated with a Carbon (C) thin film, by vapor deposition, using the JEOL JEE – 4X Vacuum Evaporator equipment.

The 800 rpm specimen in Figure 12 a) shows an irregular hook as well as a high transfer of Cu particles and Cu IMCs dispersed in the Al matrix. Many cracks are visible in the stir zone, some reaching the hook area. Magnifications on the right side of the hook (Figure 12 b) and c)) confirm the existence of a continuous IMC layer, composed of 3 layers, with a total thickness of 3 μm . However, separation of the IMC layer from the Cu-side is visible through micro cracks. Figure 13 a) and b) depict a 1000 rpm and no P.D applied specimen with an underwhelming mechanical performance and, as expected, no hook was formed, erasing the possibility of a good mechanical

interlock and sound bonding between Al and Cu. However, the 0.5 mm P.D joint seems to achieve a well-defined hook, with a wave-like shape, guaranteeing a high level of mechanical interlock, allowing for enhanced load transfer between Al and Cu. The hook's top region is composed of a composite-like structure, with various thick layers of IMCs, in a chaotic and unorganized manner. Some cracks seem to propagate across and through these layers (see Figure 13 e)). Contamination also is likely to have infiltrated at the tip of the hook. The left and right side of the hook present a continuous IMC layer, with no apparent micro cracks or major defects (Figure 13 f)). The last FSSW specimen analysed has 1200 rpm with 0.25 mm P.D and can be observed in Figure 14. Formation of the hook is clearly visible in Figure 14 a) and d); however, due to the higher rotation speed and an eventual higher plunging speed, parts of the Cu hook got separated and dispersed into the Al matrix. Since these Cu islands are located in the SZ, the intense heat speeds up the interaction between Al and Cu, resulting in Cu and IMC islands, as observed in Figure 14 b) and e). The IMC layers shown in Figure 14 c) and f) are discontinuous, seem to be shattered through micro cracks, have separation between layers and do not exhibit constant thickness. This all contributes to a poor mechanical performance.

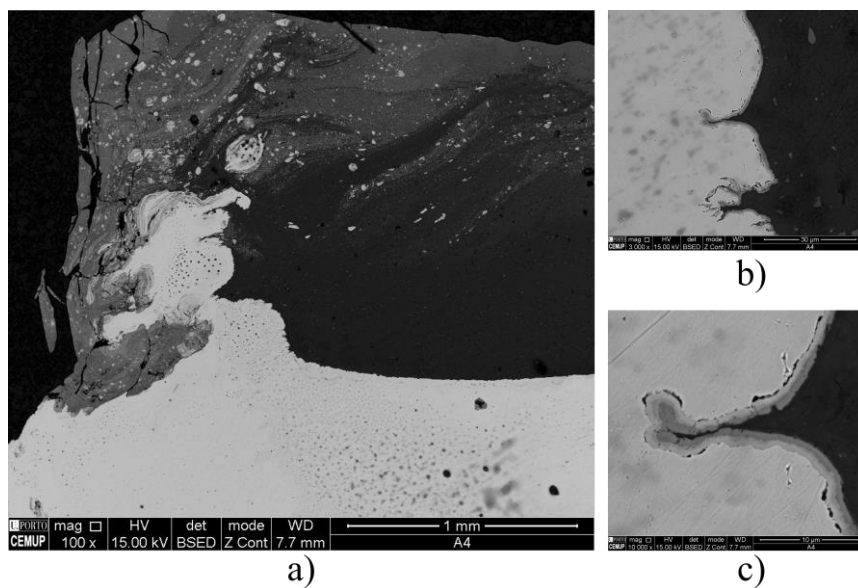


Figure 12 - SEM images of FSSW 800 rpm joint with 0.5 mm of P.D.: a) Right side of the cross section; b) 3000x magnification of the hook's right side; c) 10000x magnification of b).

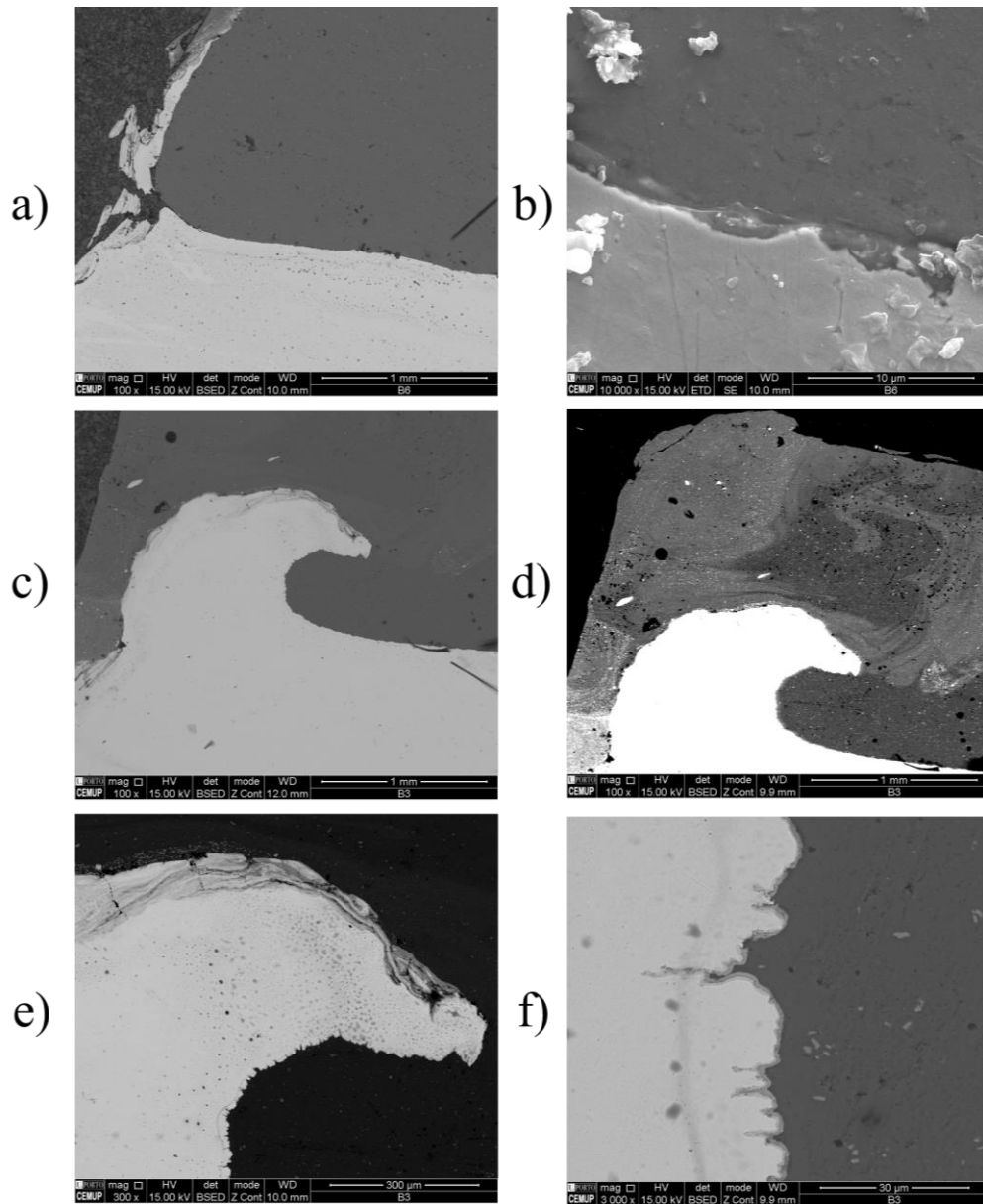


Figure 13 - SEM images of FSSW 1000 rpm joints: a) 0 mm P.D specimen; b) Magnification of Al-Cu interface shown in a); c) 0.5 mm P.D specimen; d) Backscatter image of c); e) Magnification of the hook region; f) Magnification of hook's right side .

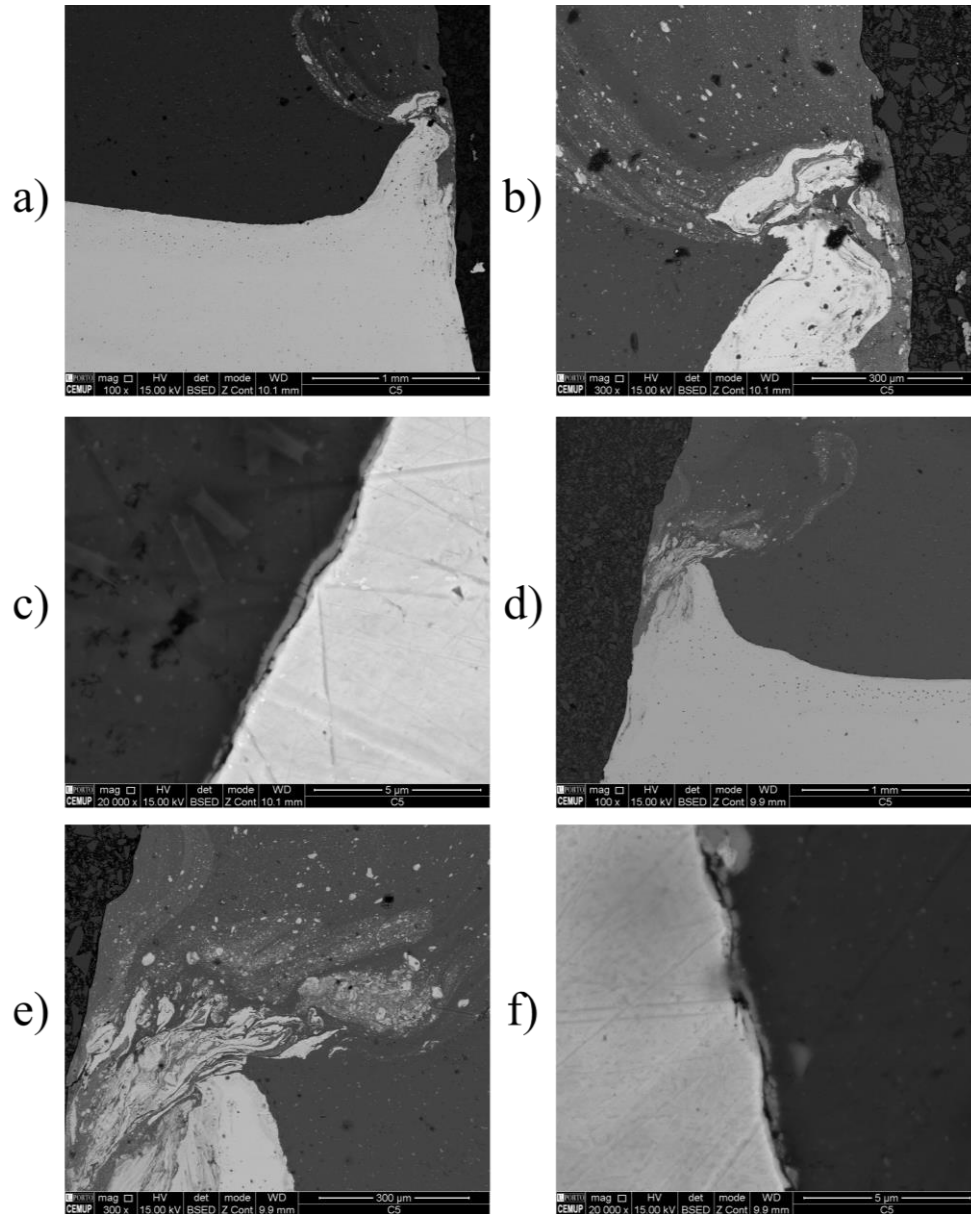


Figure 14 - SEM images of FSSW 1200 rpm joint with 0.25 mm of P.D: a) left side of cross section; b) magnification of a); c) 20000x magnification of left side of hook in a); d) right side of cross section; e) magnification of e); 20000x magnification of right side of hook in d).

As stated before, for the 1200 rpm specimen, a vast amount of Cu and Cu-rich IMC particles seem to have been dispersed in the Al matrix due to violent stirring. A magnification of these particles is showcased in Figure 15. These particles can vary its size, from as little as 1 μm to around 10 μm (Figure 15 b)).

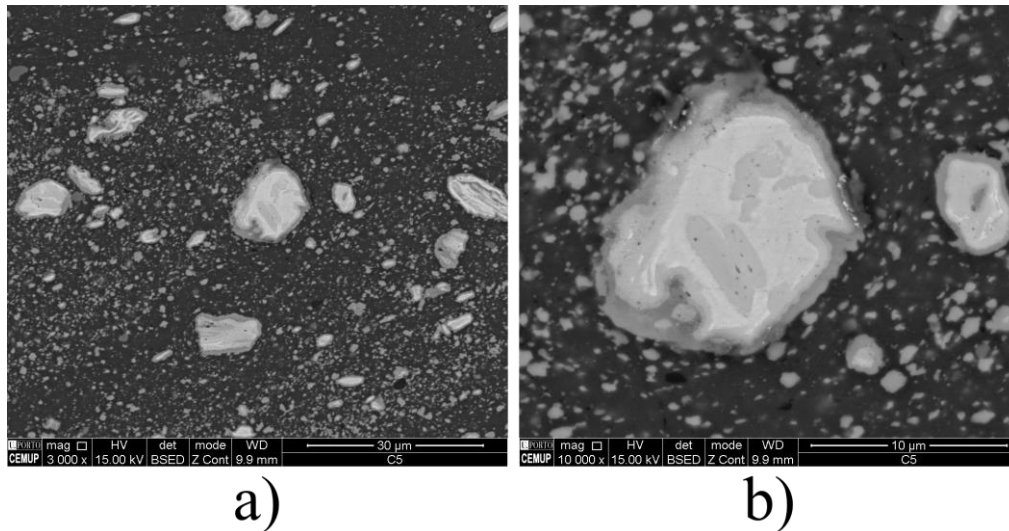


Figure 15 - IMC particles dispersed in the 1200 rpm specimen Al matrix.

Figure 16 showcases magnifications of the hook interface regions for 800 and 1000 rpm FSSW specimens with 0.5 mm of plunge depth. In Figure 16 a), micro cracks can be seen between the IMC layer and Cu, causing separation. The IMC layer seems continuous and of constant thickness with 3 μm , a value within the typical IMC layer thicknesses [14,15]. In these three layers, the composition is all mostly Cu, followed by Al, which indicates these are Cu-rich IMC layers. The presence of Cu-rich IMCs is important for a beneficial thermal-electrical performance. The magnification of the right hook of the 1000 rpm specimens can be seen in Figure 16 c), and the absence of micro cracks is clear when comparing with the 800 rpm specimens. Furthermore, Cu remains the major element present in the IMCs. Some contamination is also visible inside the IMCs. Figure 16 c) showcases the top region of the hook of the 1000 rpm specimens. Due to this zone's intense turbulence, micro cracks across and through layers can be identified. Furthermore, a form of composite layer structure seems to have formed in this region: from left to right, after the three Cu-rich IMCs found, it seems Z9 infiltrates the almost pure Cu zones, Z8 and Z10.

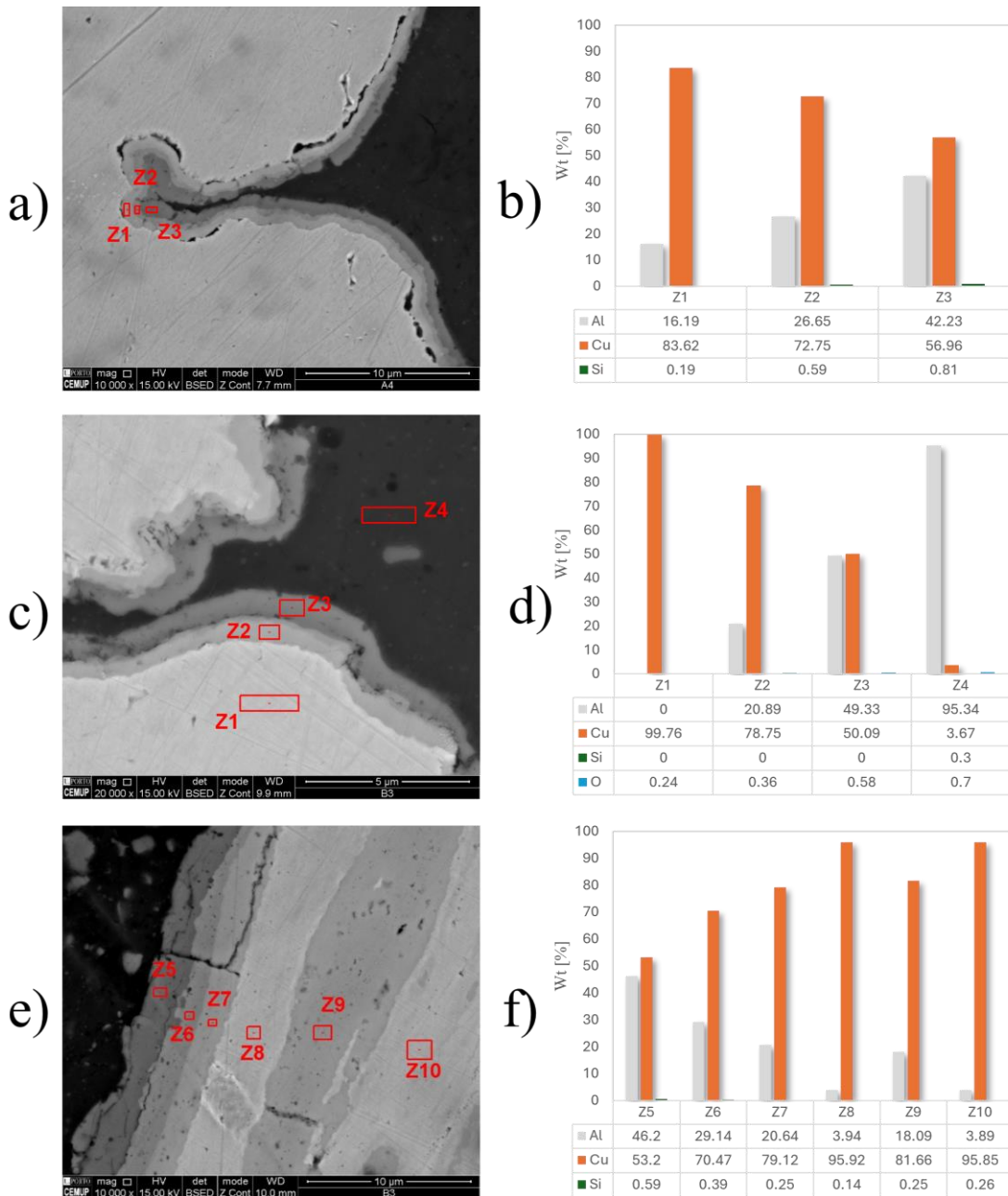


Figure 16 – SEM and EDS analysis of FSSW joints: a) 800 rpm/0.5 mm P.D hook right interface; b) Element weight % of Zones in a); c) 1000 rpm/0.5 mm P.D hook right interface; d) Element weight % of Zones in c); e) 1000 rpm/0.5 mm P.D hook top interface; f) Element weight % of Zones in e).

One possible justification for the extensive presence of IMCs in the Al-Cu interfaces can be due to the long dwelling time applied. Although the study of this parameter was not the focus of this paper, there is evidence that a shorter dwelling time may result in a decrease of IMC presence without compromising the mechanical interlock formed between the materials. Dwell times of 6 s have shown to produce good welds with 2 kN of shear strength, without a strong IMC presence [16].

Figure 17 shows magnifications of a BJ and SLJ created by FSW. The BJ interface (Figure 17 a) and b)) seems to show no significant mechanical interlock. Its interface is continuous and does not present any defects, achieving a sound weld. An absence of defects can also be observed in the SLJ specimen (Figure 17 c) and d)). The presence of a hook in the RS can be observed, as well as small perturbations in the AS.

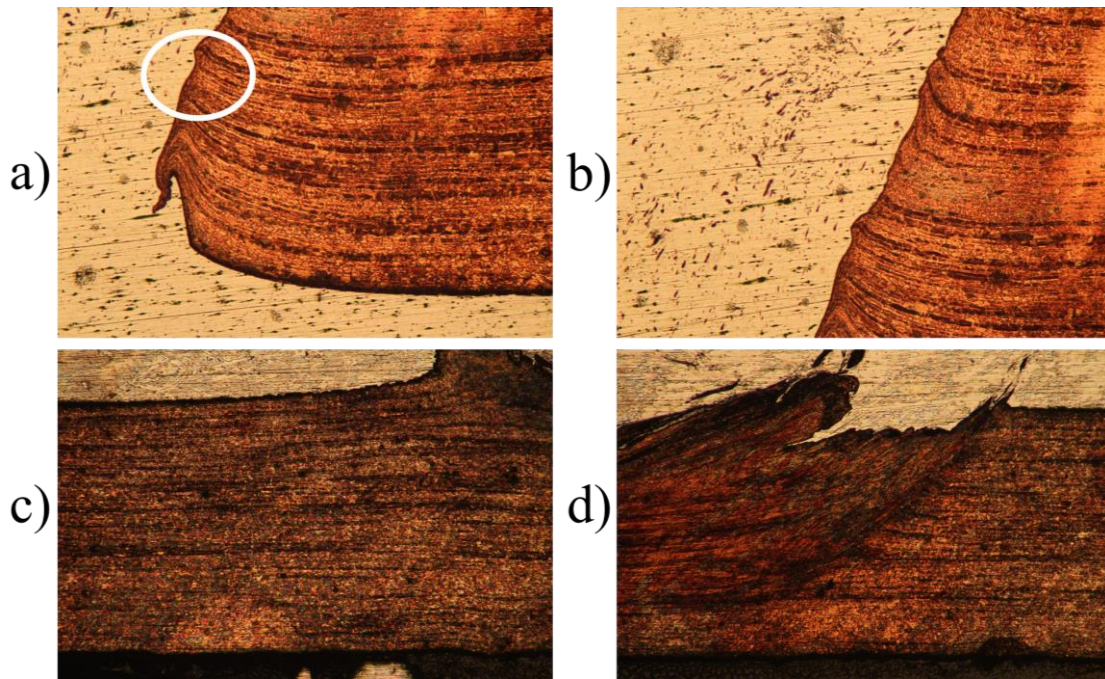


Figure 17 - Interface of a BJ by FSW, b) Magnification of the location encircled in a), c) RS of a SLJ by FSW (Al is the AS), d) AS of a SLJ by FSW (Al is the AS).

3.2.2 Micro hardness measurements

The micro hardness of different locations in the cross section of FSSW joints was measured using a Vickers micro hardness measurement machine, model Shimadzu HMV-G30S, with 15 seconds of indentation and 5 N of load applied. Prior to welded area measurement, the base materials hardness was measured, with Cu having an average of 83 HV and Al 93 HV. These results show us that the high series of the Al alloy can have an identical or superior hardness to Cu. Figure 18 identifies low hardness values on the right side of the 800 rpm joint hook. Due to the complex geometry of the hook's left side, the hardness tends to vary greatly, reaching its peak at the top of the joint (257-341 HV), and fluctuating as it moves down along the hook, ranging from 123 HV to 211 HV. The Cu region had its hardness increased to around 100 HV at the base and at the middle of the hook. Figure 19 shows a 1000 rpm specimen. As it can be seen, the Cu region does not seem to have its hardness affected by the joining process, as the hook region values remain fairly close to the Cu hardness. The Al region seems to increase its hardness values slightly, most likely due to the strong presence of Cu-rich IMCs and Cu particles near the stirred zone and HAZ, respectively. It is on top of the hook, however, that the hardness values skyrocket. The presence of irregular IMC layer structures in this turbulent region increases. This zone is of high Al and Cu interaction. Figure 20 regards the 1200 rpm FSSW specimen. This rotation speed value and long dwelling time allowed the IMCs to not form in continuous lines across the interface, but rather in islands in the Al matrix above the hook and on the left side of the hook. It can be deduced that, on the right side of the hook, no joining is attained and no IMCs are formed, as the hardness is around 70 HV. However, above and left to the hook region, the IMC aggregates result in hardness values of 180 HV up to 518 HV.

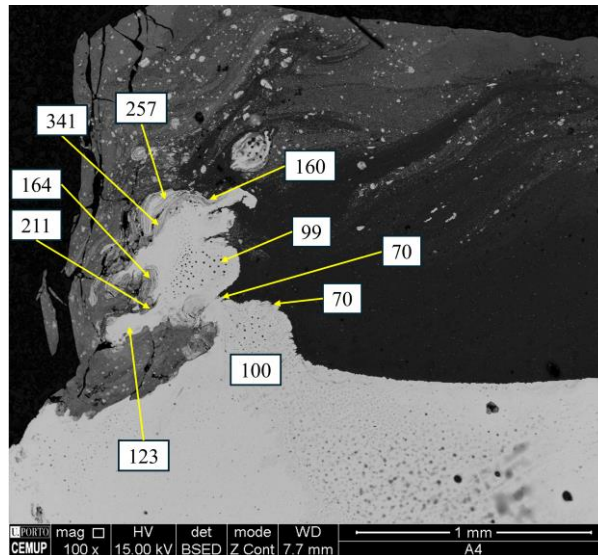


Figure 18 – Micro hardness values map for the 800 rpm FSSW specimen with 0.5 mm of P.D.

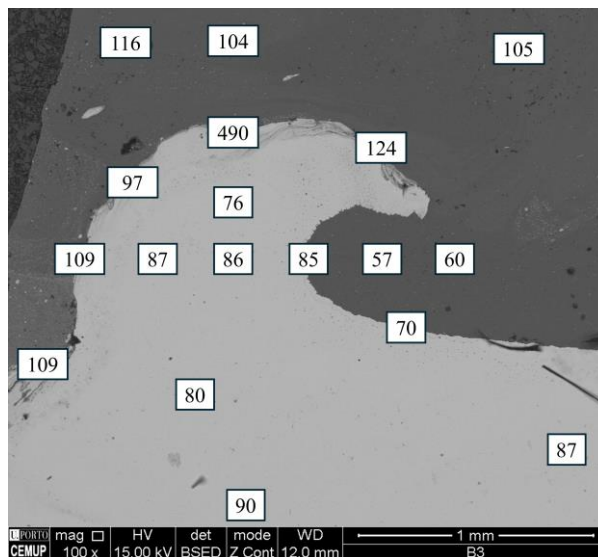


Figure 19 – Micro hardness values map for the 1000 rpm FSSW specimen with 0.5 mm of P.D.

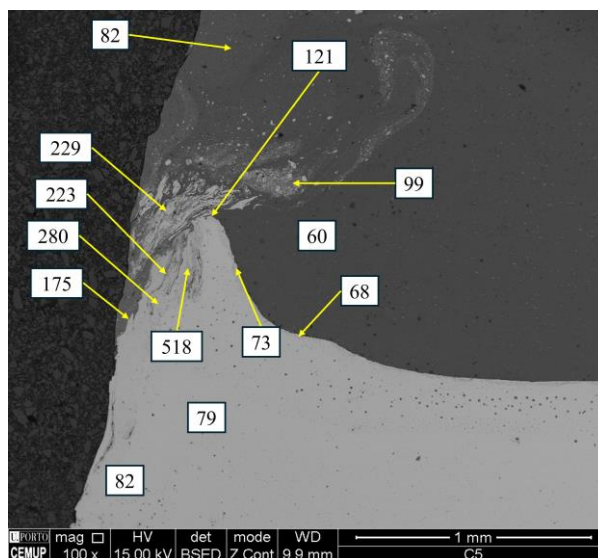


Figure 20 – Micro hardness values map for the 1200 rpm FSSW specimen with 0.25 mm of P.D.

Regarding the FSW joints, the butt joint and the lap joint's longitudinal cross section's hardness was measured. Each measurement is distanced approximately 0.5 mm from each other. Figure 21 depicts the 1100 rpm butt joint measurements, with Al as the AS. It can be seen that hardness values at the weld centre are lower than those found in the stirred zone. Furthermore, the hardness of Al severely drops comparing to the other BM, Cu. The 1100 rpm SLJ measurements are showcased in Figure 22. It can be deduced that, unlike the Al side, the Cu side weld zone's hardness increases.

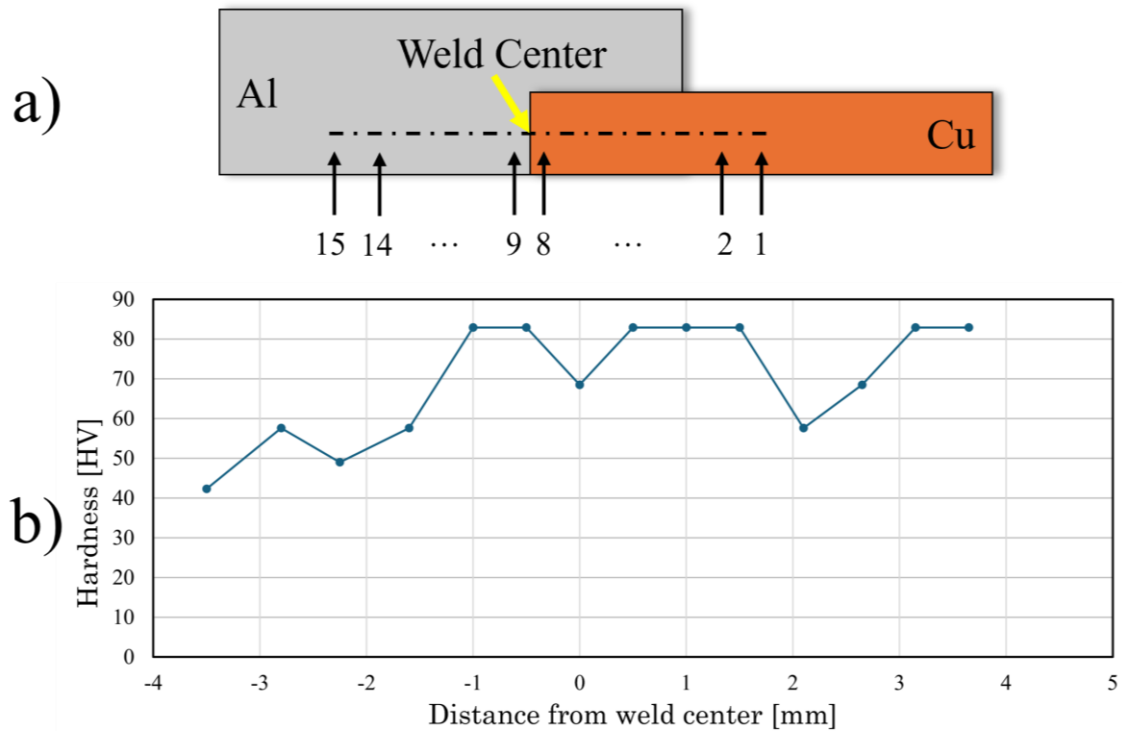


Figure 21 – Micro hardness measurement of FSW butt joint: a) longitudinal cross-section measurement schematic; b) hardness curve.

Figure 22 shows the FSW SLJ measurements. Two sets of measurements were made, one across the Al side, and another across the Cu side. A hardness increase can be seen in the Cu HAZ, caused by grain refinement. This grain refinement also occurs at Al's HAZ along with precipitates dissolving in the Al matrix. These two phenomena balance each other, which leads to the limited change in hardness values across the Al's weld region.

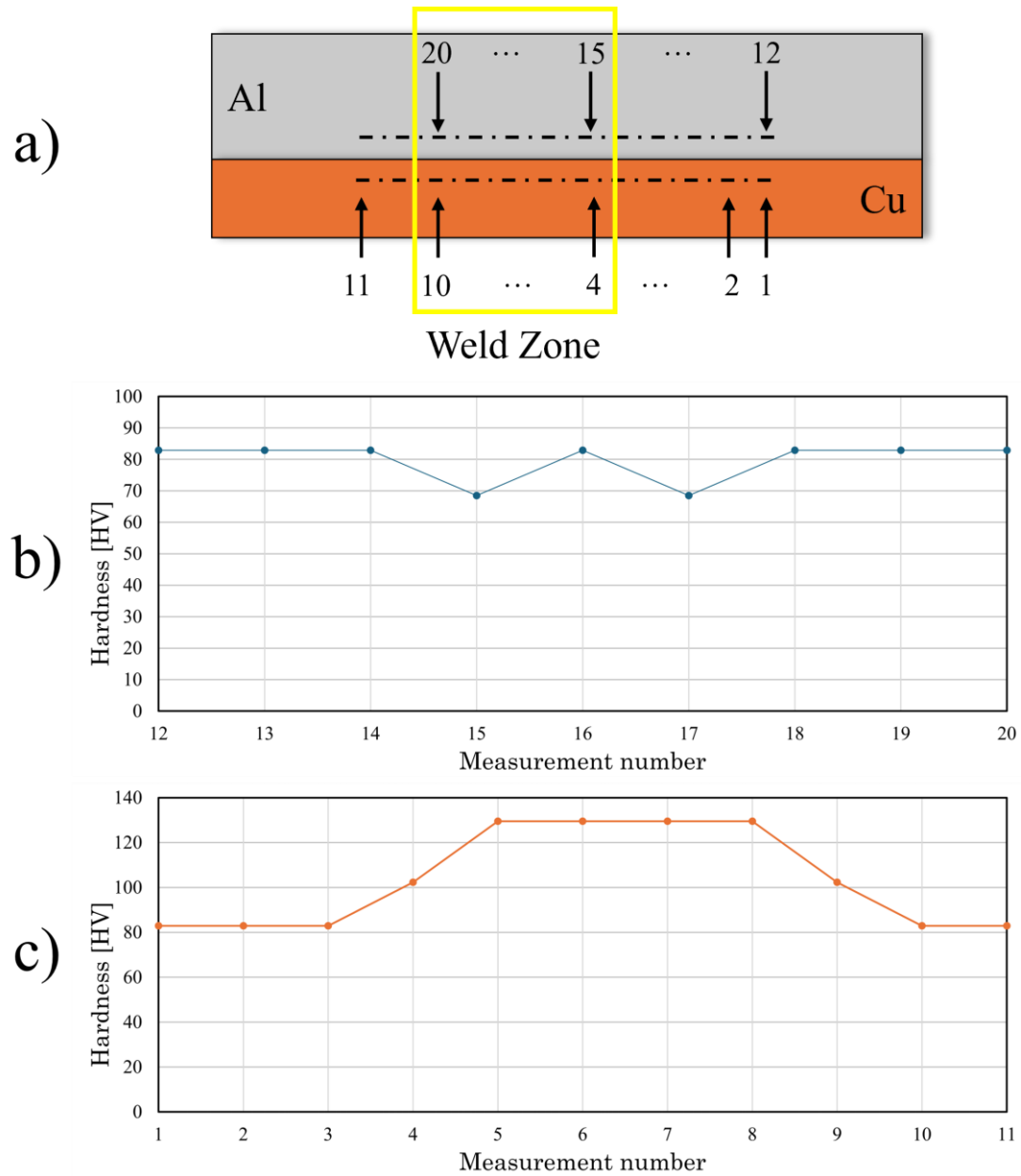


Figure 22 – Micro hardness measurement of FSW SLJ: a) longitudinal cross-section measurement schematic; b) Al hardness values, c) Cu hardness values.

3.3 Electrical resistance measurements

The evolution of electrical resistance with temperature of the FSSW joints can be obtained by subjecting them to a 10 A electrical current induced by a variable power source. A voltmeter measures the voltage drop (V) in the joints, with help from probes that are distanced 50 mm from each other, as demonstrated in Figure 23. The joints are previously heated up to 105°C, the maximum busbar service temperature, with the help of a heat gun. From this point on, as the joint cools down, the temperature is measured with a thermal camera and the electrical resistance is calculated using Ohm's Law.

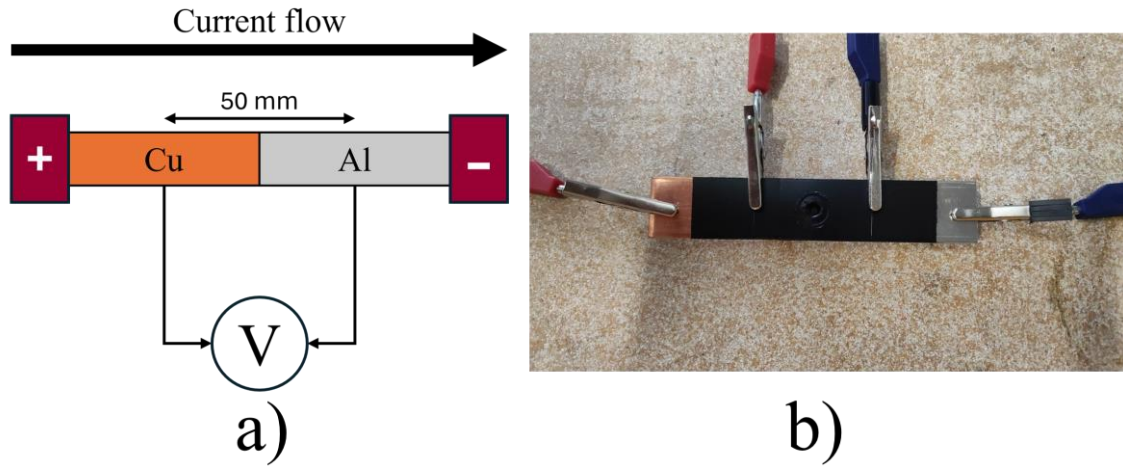


Figure 23 – a) Electrical resistance measurement schematic, b) experimental setup.

From Figure 24 the evolution of the electrical resistance as the joints cool down can be observed. For all specimens, the slope of the curves was identical, following a linear evolution. It is clear that as the tool's rotation speed increases, the resistance decreases. This may be justified by a more violent material mixing inside the stirred zone and around the hook region, creating a more compact bonding. Furthermore, an increased rotation speed may lead to more Cu-rich IMC particles and Cu particles to break apart from the Cu matrix, blending into the Al matrix and therefore increasing the conductivity of the joined area.

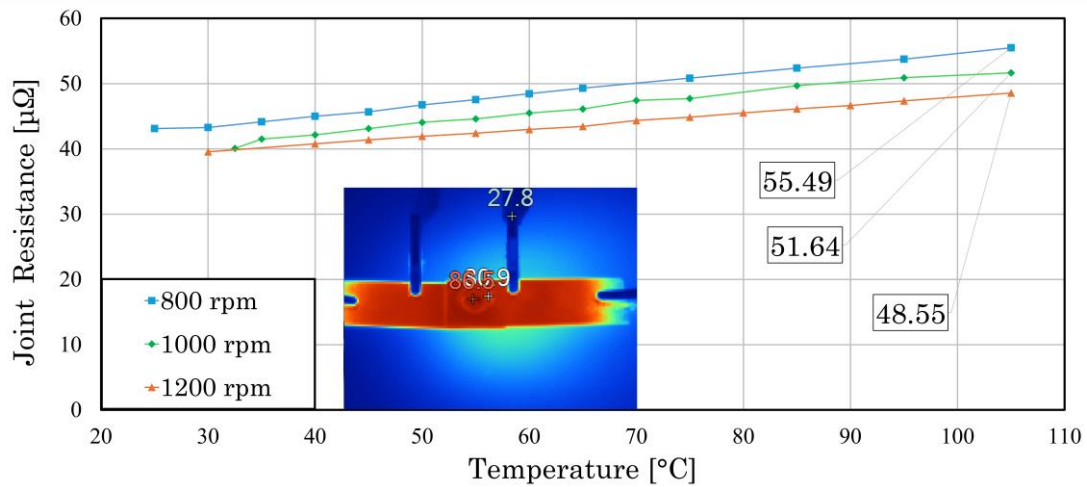


Figure 24 – FSSW joints Electrical Resistance evolution with Temperature.

In the case of the FSW joints, the electrical resistance for both BJ and SLJ reached an almost constant value of 100 $\text{m}\Omega$ (see electrical procedure in Figure 25). Some factors can contribute to this difference between joining processes, such as the use of different equipment for resistance measurement, and external factors such as probe heating procedures. Nonetheless, these values seem clearly superior to the FSSW ones. A possible cause for this difference can be the lack of a force fitted area, which was encountered on FSSW joints (see Figure 10) and greatly enhances substrate contact, and therefore increasing electrical current transmission.

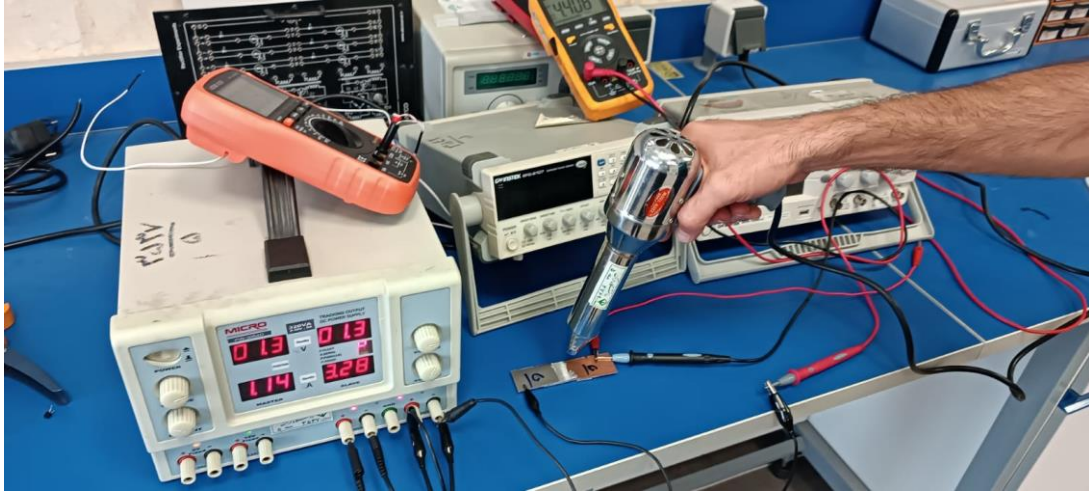


Figure 25 - FSW electrical procedure.

4. Conclusions

Regarding the work presented throughout this paper, the following conclusions can be drawn:

- With a constant dwelling time, FSSW joints have their best mechanical performance when the tool's rotation speed is 1000 rpm. The plunge depth is an important factor as well, as an intermediate value (0.25 mm) performs better than no P.D or excessive P.D. It can also be concluded that the plunge depth contributes to a hook formation, which enhances load transfer and mechanical performance.
- Micro hardness values tend to be substantially higher than the BM across the hook's top region and in the SZ interface of Al/Cu.
- From the SEM analysis it was possible to determine that $< 5 \mu\text{m}$ thick IMC layers are formed across the hook's interface with Al, being continuous for 1000 rpm, but these are discontinuous and with Cu separation for 800 and 1200 rpm. For 1200 rpm, Cu particles get ripped from the Cu matrix and disperse in the Al matrix as Cu-rich IMCs. This can increase conductivity but makes the joints more brittle.
- The increase of the tool's rotation speed was found to decrease the FSSW electrical resistance values, being indicative of a better level of contact between both surfaces.
- In the FSW joints, a higher rotation speed will also benefit the peak load of butt joints. In SLJs with Al as the AS, an increase in rotation speed also means a peak load increase. However, this is not the case when Cu is the AS, as 800 rpm is by far the best parameter. It is also seen that Al in the AS greatly benefits joint performance, as the hook formation tends to happen at the opposite side. This enables a full load transfer to the interface. Common defects in the hook region may degrade and speed up the fracture propagation.
- Micro analysis of FSW surfaces reveals the formation of a sound, defect free interface for BJ, with little to no mechanical interlock. SLJs tends to form hooks along the welded area, although these are prominent on the opposite side of the AS.
- Given the busbar application focused on this work is not for structural use, but rather electrical performance, the mechanical performance is not the main focus and leading variable. However, it can be concluded that almost every FSSW parameter set fell behind any FSW joint performance. A lower welded area teamed up with more accentuated IMC formation causes this configuration to be the least desirable of the three.

- SEM analysis and micro analysis helped reveal a more chaotic mixing of Al and Cu when subjected to FSSW; Cu-rich IMC particles tended to migrate in the Al matrix and create thick IMC layers along the hook's top region. Defects like cracks, discontinuous IMC layers and voids were also found in the FSSW SZ. Comparing to FSW, this process produced an array of defect free joints, with well-defined and continuous interfaces.
- It can be deduced that the welded area of FSSW joints are considerably harder than the FSW welded area. This most likely happens due to concentration of heat generation during FSSW process, as there is no transverse movement; another reason could lie in the excessive dwelling time or even the plunge depth applied.
- Electrically, FSSW joints were shown to be better electrical conductors than FSW joints. The force fitted area generated from the designed FSSW steel setup and tool plunge depth allow a greater area for electrical flow, causing a significant resistance decrease.

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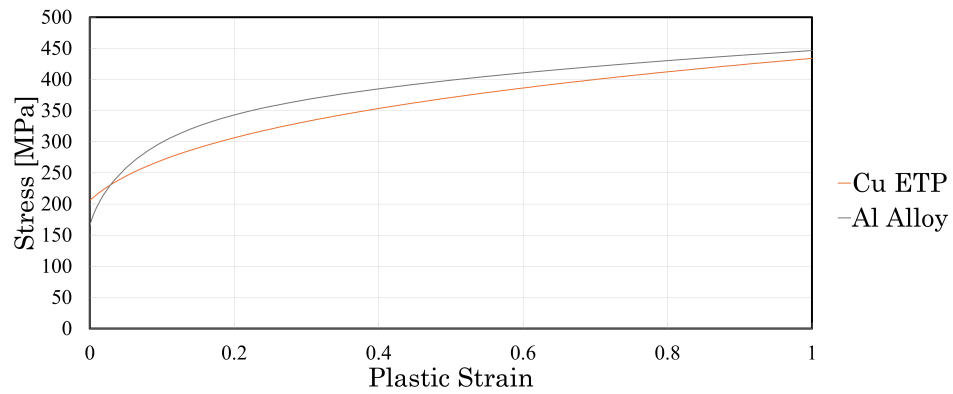
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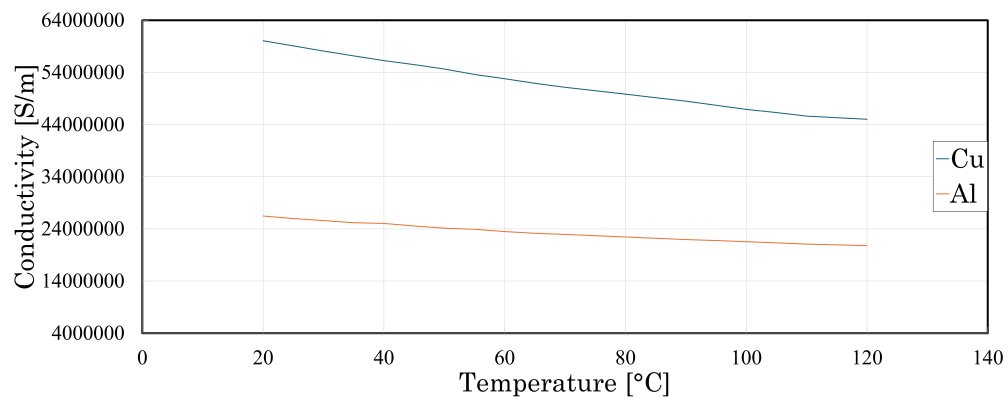
Appendix C

Base material characterization

C.1 Plastic properties for numerical modeling



C.2 Evolution of electrical conductivity with temperature for numerical modeling



Appendix D

Machined setup technical drawings

