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**Fatigue performance of friction stir welded of
aluminium-steel joints used in transportation industries**

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United Nations Sustainable Development Goals

Adopted by all Member States of the United Nations in 2015, the 2030 Agenda for Sustainable Development offers a global solution for peace, and prosperity now and in the future. Central to this agenda are the 17 Sustainable Development Goals (SDGs), which call for collaborative action by all nations, developed and developing. The SDGs aim to end poverty and address other critical challenges through strategies that promote health, education, equality, and economic growth, while also addressing climate change and protecting natural ecosystems such as oceans and forests. The present work is in line with the following SDGs:

- SDG 9: Industry, innovation and infrastructure
- SDG 11: Sustainable cities and communities
- SDG 12: Responsible consumption and production
- SDG 13: Climate action

Table 1 agglomerates the contribution of this study to the identified SDGs.

Table 1: Contribution to the UN Sustainable Development Goals

SDG	Targets	Contribution	Performance Indicators and Metrics
9	9.4; 9.5	This study contributes to the development of advanced solid-state welding technologies applied to dissimilar materials, promoting innovation in materials engineering and optimizing industrial processes with less environmental impact and greater structural efficiency.	Validated FEM models reproducing experimental mechanical behavior; correlation between numerical and experimental results; increase in joint strength and fatigue life due to interface geometry optimization; publication of results in peer-reviewed journals.
11	11.3; 11.6	Supports sustainable mobility and lightweight structures for transportation systems, contributing to safer and energy-efficient vehicles that reduce the environmental impact of urban transport.	Weight reduction in structural components (%); improvement of fatigue durability; alignment with sustainable transport design goals.
12	12.5	Promotes responsible production by using solid-state joining (FSW) that minimizes material waste, eliminates filler materials, and reduces post-processing energy consumption.	Reduction in waste generation (%); decrease in production energy consumption (kWh/unit); recyclability of joined materials (Al-Fe systems).
13	13.1; 13.2	Contributes to climate action by enabling lightweight, low-carbon transportation solutions, and replacing high-emission fusion welding with energy-efficient solid-state technique	CO ₂ equivalent emissions avoided per joint; energy savings compared to conventional welding; life-cycle carbon footprint reduction in transport components.

Resumo

A crescente necessidade de estruturas leves e eficientes tem impulsionado a adoção de juntas dissimilares entre alumínio e aço em setores como o automóvel e o aeroespacial, recorrendo a processos inovadores como a Soldadura por Fricção (FSW). Este trabalho apresenta uma análise integrada experimental e numérica do comportamento mecânico e à fadiga de juntas FSW entre alumínio AA6061-T6 e aço St37, com foco na influência da geometria da interface, nomeadamente com e sem perfil em “S”, na resistência estrutural e nos mecanismos de falha.

Foram realizados ensaios quasi-estáticos e de fadiga que evidenciaram diferenças marcantes entre as duas geometrias. As juntas com perfil em “S” demonstraram maior ductilidade global e falhas nos materiais de base, enquanto as juntas sem perfil em “S” apresentaram ruturas prematuras na camada intermetálica (IMC), revelando a fragilidade dessa região sob carregamento monotónico.

Complementarmente, foi desenvolvido um modelo tridimensional no software Abaqus/Explicit para simular o comportamento mecânico e a propagação de danos nas juntas. Numa fase inicial, o modelo foi implementado ignorando as propriedades coesivas da interface, com o objetivo de validar a geometria e o comportamento global. Os resultados numéricos mostraram boa concordância com os dados experimentais, confirmando o potencial da geometria em “S” na redução das concentrações de tensão e no aumento da vida à fadiga.

Os resultados obtidos demonstram que a geometria da interface e a integridade microestrutural da camada IMC são determinantes para otimizar a resistência mecânica e a durabilidade das juntas FSW em aplicações industriais e automóveis.

Palavras-chave: Soldadura por Fricção e Agitação, Juntas Dissimilares, Alumínio-Aço, Modelação de Zonas Coesivas, Vida em Fadiga, Compostos Intermetálicos, Simulação Numérica, Testes mecânicos.

Abstract

The growing demand for lightweight and efficient structures has encouraged the use of dissimilar aluminum–steel joints in automotive and aerospace applications through advanced joining techniques such as Friction Stir Welding (FSW). This dissertation presents an integrated experimental and numerical study on the mechanical and fatigue behavior of FSW joints between AA6061-T6 aluminum and St37 steel, focusing on the influence of interface geometry, with and without an “S” profile, on structural strength and failure mechanisms.

Quasi-static and fatigue tests revealed clear differences between both configurations. Joints with an “S” profile exhibited higher global ductility and failures mainly in the base materials, while joints without the “S” profile showed premature fracture within the intermetallic compound (IMC) layer, confirming its brittleness under monotonic loading.

A three-dimensional model was developed in Abaqus/Explicit to simulate the mechanical response and damage evolution of the welded joints. In the initial stage, the model was implemented without cohesive properties to validate the geometry and overall mechanical behavior. The numerical predictions correlated well with the experimental data, confirming the effectiveness of the “S” geometry in mitigating stress concentrations and improving fatigue performance.

The results highlight that interface geometry and IMC microstructural integrity are key factors for optimizing the mechanical strength and fatigue durability of dissimilar FSW joints in industrial and automotive applications.

Keywords: Friction Stir Welding, Dissimilar Joints, Aluminum-Steel, Cohesive Zone Modeling, Fatigue Life, Intermetallic Compounds, Numerical Simulation, Mechanical Testing.

*“Doubt is such a strange thing.
There will be times when you succeed and times when you fail.
So, wasting your time doubting if you’ll be successful or not, is pointless.
Just put one foot in front of the other, control what you can control, and then see what the
outcome is.
If you win, great, you’re going to have to wake up the next day and do the journey all over again.
If you lose, sucks, but you’ll have to wake up the next day and do the journey all over again
anyway.”*

Kobe Bryant

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Acronyms and Symbols

List of abbreviations

CCW	Counterclockwise
CTE	Coefficient of thermal expansion
CFRP	Carbon Fiber Reinforced Polymers
CSDMG	Cohesive Damage Variable
CSMAXSCRT	Cohesive Surface Maximum Shear Stress Criterion
CZM	Cohesive Zone Model
EV	Electric Vehicles
FCC	Face-centered cubic
FEM	Finite Element Model
F-SPR	Friction Stir Self-Piercing Riveting
FSW	Friction Stir Welding
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
HAZs	Heated-Affected Zones
HEA	High-Entropy Alloy
IMCs	Intermetallic Compounds
LEFM	Linear Elastic Fracture Mechanics
MMCs	Metal Matrix Composites
RSW	Resistance Spot Welding
SEM	Scanning Electron Microscopy
SSW	Solid-State Welding
SZ	Stir Zone
TMAZ	Thermo-Mechanically Affected Zone
WEDM	Wire Electrical Discharge Machining
XFEM	eXtended Finite Element Method

List of symbols

Al	Aluminum
CO ₂	Carbon Dioxide

Fe	Iron
Hz	Hertz
mm	millimeter
MPa	Mega Pascal
N	Newton
RPM	Revolutions Per Minute
HV	Vickers Hardness
F_n	Axial force
F_x	Transverse force
F_y	Side force
Gc	Fracture energy
T_{ult}	Cohesive strength
ω	Tool rotation speed
μm	Micrometres
E_{IMC}	IMC stiffness
K_{eff}	Initial stiffness
α	Tool tilt angle
Si	Silicon
At. %	Atomic Percentage
Mn	Manganes
Cu	Copper
Zn	Zinc

Chapter 1

Introduction

This chapter introduces the main subject of this dissertation, providing background on the motivation, objectives, applied methodology, and overall structure of the study.

1.1 - Motivation and background

The automotive industry is moving towards lightweight multi-material structures, particularly aluminum and steel joints, to increase fuel efficiency and reduce CO₂ emissions [1]. Although these materials offer high strength-to-weight ratios, their joining presents challenges due to brittle intermetallic compounds (IMCs) that weaken mechanical properties [2]. Advanced solid-state welding techniques such as friction stir welding (FSW) and friction stir self-piercing riveting (F-SPR) minimize IMC formation, improving joint strength, fatigue resistance and manufacturing efficiency, making them crucial to the future of sustainable vehicle design [3]. However, the fatigue performance of these joints remains a critical factor in ensuring their long-term durability and reliability under cyclic loading conditions [2]. Therefore, fatigue testing is essential to assess the structural integrity and service life of aluminum-steel joints, guiding further optimization of welding processes for improved automotive application [3].

1.2 - Objectives

The main objective of this dissertation is to determine the fatigue life of aluminum-steel joints welded by friction stir welding, as well as to assess the influence of interface geometric, specifically, the presence or absence of an 'S-shape' on the mechanical performance and fatigue resistance of the dissimilar joints. A set of specimens manufactured by FSW will be analyzed to evaluate their fatigue performance and mechanical behavior under cyclic loading conditions.

To achieve this, the failure process and failure location will be investigated through microstructural analysis of the welded interface using Microscopy. The study will also include mechanical tests, such as fatigue and static tests, to evaluate the fracture behavior and crack propagation in welded joints.

Additionally, this work aims to develop a simplified numerical model to predict the failure mechanisms of aluminum-to-steel FSW joints. The model will be validated by correlating the experimental quasi-static test results with simulated failure patterns, providing a reliable framework for understanding fracture behavior and optimizing welding parameters in dissimilar joints used in automotive applications.

1.3 - Research methodology

To achieve the intended objectives of this thesis, the following methodology was systematically implemented:

- Conduct a comprehensive literature review focusing on dissimilar aluminum-steel solid-state welding, particularly Friction Stir Welding, its technological challenges, and the resulting formation of intermetallic compounds at the weld interface, which significantly affect joint performance.
- Establish a set of fatigue test parameters based on previous research on solid-state welding (SSW) of aluminum and steel, with emphasis on fatigue performance, to evaluate the durability and failure mechanisms of the FSW joints manufactured in this study.
- Perform a series of experimental tests, including fatigue and static tests, to evaluate the mechanical strength and crack propagation behavior of the welded joints.
- Perform the numerical modeling of the experimental work using a reverse cohesive contact approach to simulate the joint interface between the IMC layer and the aluminum-steel surface, implementing the experimental data to iteratively calibrate and refine the model, in order to obtain a numerical simulation that accurately reproduces the mechanical response and failure behavior observed experimentally.

1.4 - Thesis overview

The thesis is structured as follows:

Chapter 1: Introduction to the dissertation, presenting the research topic and providing an overview of the importance of evaluating the fatigue performance of aluminum-steel joints welded by FSW in the automotive industry. This chapter also defines the research objectives, describes the methodology and establishes the scope of the study in evaluating the mechanical behavior and fatigue resistance of these joints.

Chapter 2: This chapter delves into the fundamentals of Friction Stir Welding, focusing on its application in dissimilar aluminum-steel joints. The main process parameters, rotation speed, feed rate, tool geometry,

and axial force, and their impact on material flow, heat input, and joint quality are analyzed. The control of intermetallic compound formation at the Al–Fe interface is also discussed, given its decisive influence on the mechanical performance of the joint. Finally, essential fatigue testing parameters, such as load ratio, stress levels, and frequency, are presented, laying the technical foundation for subsequent experimental research.

Chapter 3: This chapter details the experimental procedures that will be performed to study the mechanical behavior of dissimilar joints between AA6061-T6 aluminum and St37 steel, joined by the FSW process, with emphasis on the influence of the interface geometry, comparing configurations with and without "S" profile. Quasi-static and fatigue tests will be performed to analyze the structural response under different loading regimes. The fatigue tests will be conducted under controlled conditions of frequency and amplitude of load, allowing to evaluate the durability, the resistance to crack nucleation and propagation, as well as the characteristic failure modes. In addition, post-test inspection techniques will be employed to examine the behavior of the interface region, especially regarding the formation of intermetallic compounds. Finally, the results are critically discussed with the aim of highlighting the impact of the "S" geometry on the stress redistribution, the mitigation of stress concentrations and the fatigue performance of the FSW joints between AA6061-T6 and St37.

Chapter 4: This chapter focuses on the numerical modeling of the interfacial region between the IMC layer and the base materials, aiming to simulate the cohesive zone behavior in dissimilar FSW joints. The model enables the analysis of damage evolution and failure mechanisms along the Al–Fe interface. The numerical results are subsequently compared with the experimental findings from Chapter 3 to validate the proposed model and enhance the understanding of the mechanical response of dissimilar friction stir welded joints.

Finally, **Chapter 5** presents the main conclusions drawn from the experimental and numerical investigation, highlighting the key findings regarding the fatigue performance of aluminum–steel FSW joints. Additionally, it outlines the limitations encountered and proposes potential directions for future research aimed at improving joint design, modeling accuracy, and long-term durability assessment.

Chapter 2

Literature review

2.1 - Aluminum-steel joints in transportation industry

Sustainability has become a central concern in society and the media, gaining increasing attention in scientific research across a variety of fields. In the automotive industry, its importance continues to grow, driven by past corporate controversies and the increasing focus on electric vehicles, lightweight materials and reducing CO₂ emissions as key challenges [4].

The demand for lightweight materials and innovative design solutions has long been a priority in the automotive industry, with increasing use of carbon fiber reinforced polymers (CFRP) and other lightweight composites to improve vehicle performance, dynamics and energy efficiency. Reducing vehicle weight not only improves fuel efficiency, reducing consumption by 6-8% for every 10% mass reduction, but also reduces CO₂ emissions by up to 11 g/km. In electric vehicles (EV), this strategy is even more critical as it can increase driving range by up to 13.7%. The adoption of lightweight materials such as aluminum and high-strength steel also leads to lower production costs and more efficient designs, making weight reduction a key factor for sustainability, performance and energy optimization in modern automotive engineering [5, 6].

Advancements in materials technology have led to the development of high-strength aluminum and magnesium alloys, cost-effective CFRP, and hot-stamped ultra-high-strength martensitic steels, all offering exceptional strength-to-weight ratios. Given their distinct advantages and limitations, these materials can be strategically integrated in different sections of a vehicle to maximize structural integrity and efficiency. While challenges such as corrosion, formability, and production costs are being progressively mitigated, the reliable joining of dissimilar materials remains a critical challenge in automotive manufacturing [2]. Ensuring efficient and durable joint between materials like Aluminum-Steel is essential to fully leverage the benefits of lightweight structures, driving ongoing research in advanced welding and joining techniques.

According to Beygi et al. [7], the development of advanced welding and joining techniques is essential to overcome the limitations of conventional techniques. Fusion welding, though widely used, is not ideal for Aluminum-Steel joints due to brittle IMC formation, which weakens the weld. Laser welding is a promising alternative, but IMC formation remains a challenge. Using high-entropy alloy (HEA) filler metals can reduce Al-Fe IMCs, promoting a more ductile solid solution. Meanwhile, solid-state processes like FSW are preferred for Aluminum-Steel joining, as their lower heat input minimizes IMC formation, enhancing joint strength and durability.

Friction Stir Welding is a cost-effective solution for joining dissimilar materials, eliminating the need for adhesives, rivets, or fasteners. Unlike conventional welding, which can compromise joint properties due to differences in physical, chemical, and mechanical characteristics, FSW operates at lower temperatures, preventing excessive heat-related issues. Its advantages, such as enhanced fatigue and tensile strength, non-consumable tooling, environmental sustainability, and reduced operating costs, have made it a key technique in automotive manufacturing [1].

Alternatives to fusion welding for dissimilar metals encompass Low Dilution Welding and Solid-State Welding, also referred to as Non-Fusion Welding. Moreover, mechanical fastening, riveting, and adhesive bonding are extensively employed joining methodologies, as they mitigate the adverse effects of thermal and electrochemical discrepancies between materials [8].

2.2 - Aluminum and its alloys

Aluminum exhibits better corrosion resistance in comparison to many other materials. The protection against corrosion is granted by a film of oxide, which is formed at the surface of aluminum in oxygen atmospheres. The melting point of aluminum is found dependent on purity. Pure aluminum (99.9%) exhibits 660 °C melting point, but this reduces to 635 °C for 99.5% pure aluminum at atmospheric pressure. Further addition of alloying elements reduces it to 500 °C for some magnesium alloys. Aluminum in its pure form exhibits higher melting point but suffers from poor strength. Attractive properties are obtained by addition of alloying elements. The alloying element enhances many mechanical properties such as strength, hardness, weldability etc...[9].

Pure aluminum alone does not possess sufficient strength for most structural applications. To overcome this drawback, it is commonly alloyed with elements such as copper, manganese, magnesium, zinc, and silicon. By adjusting the type and number of alloying elements, as well as applying suitable heat treatments, a wide range of mechanical properties can be obtained. Because of their face-centered cubic (FCC) crystal structure, aluminum and its alloys generally exhibit good ductility and formability. These alloys are commercially available in both wrought and cast forms. Wrought products are typically manufactured through semi-continuous direct chill casting, followed by processes such as rolling, extrusion, or forging. Cast alloys, on casting or hand, can be produced using techniques such as sand casting, investment casting,

permanent mold casting, or die casting. Wrought aluminum alloys are further categorized into two groups non-heat-treatable alloys or heat-treatable alloys depending on their principal alloying elements [10,11].

Aluminum alloys in conventional metallurgy are generally divided into two main categories: wrought alloys and casting alloys. Their classification into grades depends on the predominant alloying elements. As defined by the Aluminum Association Inc., wrought alloys are identified using a four-digit numbering system (e.g., 1xxx, 2xxx, etc.), whereas casting alloys follow a different scheme, expressed as three digits plus a decimal (e.g., 1xx.x, 2xx.x, etc.) [9].

Casting alloys typically contain higher concentrations of alloying elements, leading to a heterogeneous microstructure characterized by the presence of second-phase particles. These particles act as internal stress concentrators, effectively creating micro-notches within the material. Under cyclic loading, these sites are prone to crack initiation, which significantly limits the ductility and overall mechanical performance of cast components. As a result, cast aluminum alloys generally exhibit lower fatigue strength and reduced elongation compared to their wrought counterparts. In contrast, wrought aluminum alloys benefit from a more uniform microstructure and refined grain structure achieved through thermomechanical processing, resulting in superior strength and fatigue resistance [9].

According to Verma et al. [9] Magnesium-based wrought aluminum alloys, particularly the AA5xxx series, are valued for their good corrosion resistance and weldability. They are commonly applied in marine and offshore structures, storage tanks, cryogenic systems, and pressure vessels, with the 5083 Al-Mg alloy being widely used in welded constructions exposed to seawater and high humidity. And the 6xxx series are heat-treatable aluminum alloys containing magnesium and silicon, offering good strength and weldability. AA6061-T6 is notable for its excellent extrudability, making it suitable for architectural and structural components, and is widely employed in welded structures such as pipelines, marine and truck frames, and railway cars.

2.2.1 - Weldability of aluminum alloys

Welding aluminum and its alloys requires careful control, as fusion welding processes may lead to strength reduction and the formation of defects [12]. Figure 1 shows the main welding processes for aluminum alloys. The most reported processes are GMAW, GTAW, and FSW, while resistance spot welding and laser welding are also mentioned. The choice of process depends on the alloy properties, application requirements, and cost considerations.

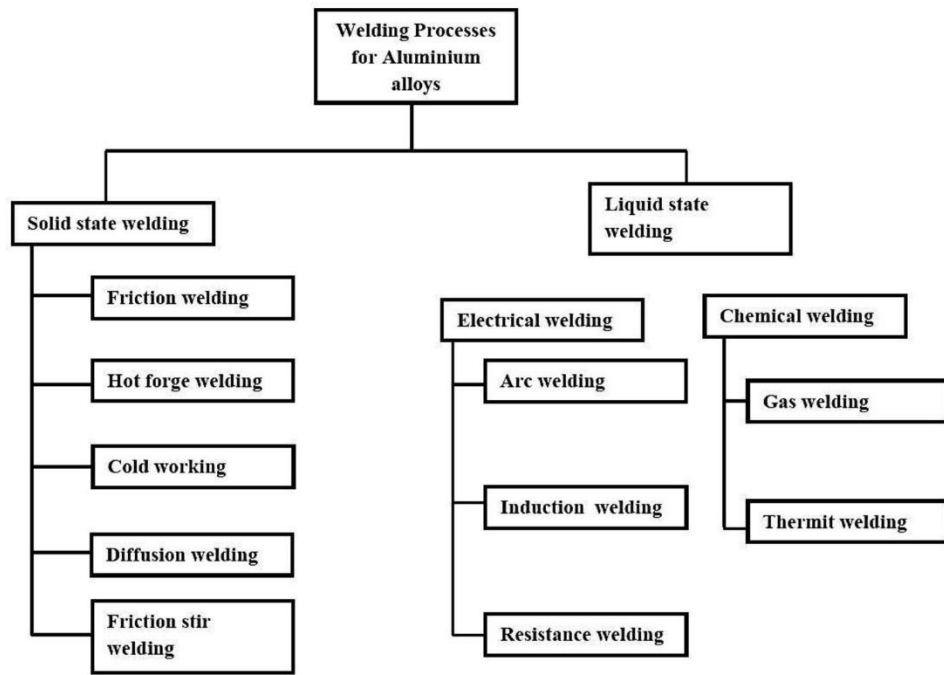


Figure 1: Different welding process used for aluminum alloys [9].

According to Verma et al. [9] and Velu et al. [11], FSW is regarded as the most suitable technique for joining aluminum alloys. As a solid-state welding (SSW) process, it operates below the melting point of the base materials, which minimizes heat input and reduces thermal damage. Unlike fusion welding, SSW generally produces stronger and higher-quality joints because the weld is achieved through plastic deformation of the parent metals. An additional advantage of solid-state welding lies in its ability to join both similar and dissimilar materials under low thermal conditions, thereby limiting distortion, suppressing the formation of brittle intermetallic compounds, and preserving the microstructural integrity of the joint. These benefits make FSW particularly effective in challenging applications such as aluminum–steel joining, where the resulting welds demonstrate superior mechanical performance and enhanced fatigue resistance under cyclic loading.

2.3 - Friction stir welding

Friction stir welding is a high-strain-rate thermo-mechanical welding process in which joining occurs at a heat input below the melting points of the base materials [13]. It delivers welds of superior quality compared to conventional fusion welding methods [14]. Numerous studies have explored its application in joining various aluminum alloys with high-strength steel, demonstrating its effectiveness in producing robust and reliable joints [15].

The FSW process is a solid-state joining technique that provides several advantages over conventional fusion welding methods. It utilizes a rotating tool, typically crafted from durable materials like tungsten carbide or hot-work tool steels, featuring a specially designed shoulder and a pin available in various configurations. The tool generates frictional heat via rotational motion and axial force, necessitating stringent design criteria to endure severe thermomechanical conditions. A qualified FSW tool must retain

structural integrity at elevated temperatures; resist plastic deformation under combined axial, lateral, and torsional stresses during plunging and traversing; maintain mechanical strength to avoid degradation under cyclic loading and efficiently dissipate heat to prevent overheating and preserve joint quality. These requirements ensure consistent material flow, defect-free welds, and extended tool lifespan in high-stress industrial applications [14]. Figure 2 shows the schematic representation of FSW.

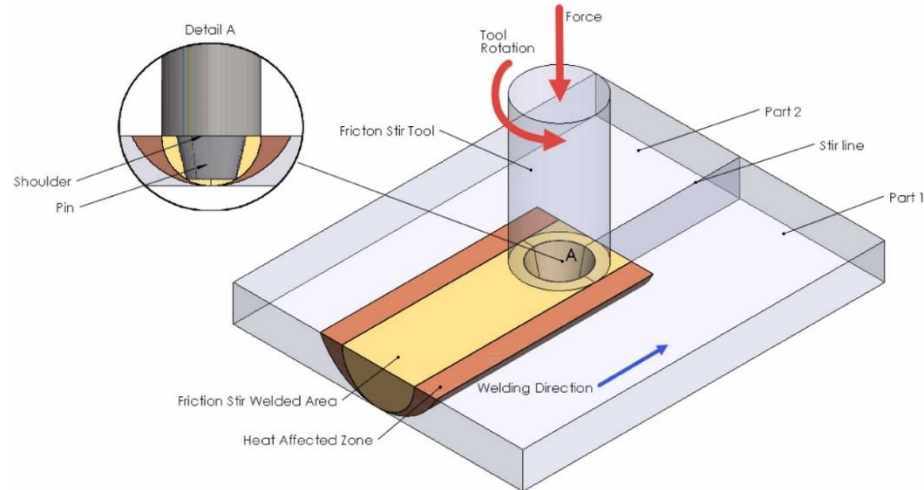


Figure 2: Schematic representation of friction stir welding [14].

2.3.1 - Factors affecting friction stir welding process

Friction stir welding is recognized for delivering joints with superior mechanical performance. In many cases, the strength of FSW joints approaches that of the parent material. This is largely attributed to the refined microstructure developed within the weld zone and to the solid-state nature of the process. Moreover, because fusion is avoided, defects commonly associated with melting and solidification such as porosity or hot cracking are minimized, resulting in improved joint reliability [16].

According to Kilic et al. [14] the mechanical strength of FSW joints is strongly influenced by several factors, such as process parameters, tool geometry, and the properties of the materials being joined. Key variables including welding speed, tool rotation, axial load, plunge depth, and tilt angle directly affect joint performance. Proper adjustment of these parameters makes it possible to achieve welds with tailored strength characteristics. In addition, evaluating the tensile response of FSW joints is essential to ensure the structural reliability of welded components.

2.3.1.1 - Welding parameters

The quality of a friction stir weld is highly dependent on several process parameters that govern heat generation, material flow, and joint consolidation. Proper adjustment of these variables is essential to achieve defect-free welds with the desired mechanical properties. The main parameters are [17]:

- **Tool rotation speed (ω):** rotational velocity of the tool, measured in RPM, which can be applied clockwise or counter-clockwise.

- **Traverse speed (V_x):** linear travel rate of the tool along the joint line, expressed in mm/min or mm/s.
- **Tool tilt angle (θ):** inclination of the tool relative to the workpiece surface, improving material consolidation behind the tool.
- **Axial force (F_n):** downward force applied to maintain tool penetration and forge the material together.
- **Pin plunge depth:** penetration depth of the tool pin into the workpiece, controlling material mixing.
- **Heel plunge depth:** penetration depth of the tool shoulder relative to the plate surface, influencing heat input and joint quality.
- **Friction coefficient:** factor directly affecting heat generation and the plastic flow of material around the tool.

2.3.1.2 - Tool shoulder and pin geometry

The FSW tool is engineered to generate localized heat, facilitate material flow, promote mixing, induce plastic deformation, and apply forging force during welding. Heat initially arises from friction between the tool probe (pin) and the base material during the plunge phase, with additional heat generated by material deformation as the process advances. The tool plunges until the shoulder contacts the workpiece surface, with the shoulder-material interface contributing significantly to heat generation. The shoulder, characterized by its diameter, may adopt flat, concave, convex, or scrolled geometries. The probe (pin), defined by its diameter and insertion depth, features profiles such as flat, tapered, threaded, or fluted to optimize material stirring and bonding. These design elements ensure controlled heat distribution, efficient material flow, and robust solid-state joint formation [18].

Figure 3 illustrates the different shoulder geometries and surface features. Ideal shoulder ends may be flat and smooth or include contours, edges, scrolls, grooves, pits, and concentric circles. In general, three main types of shoulder end surfaces are identified, with the flat end being the simplest form. The figure also summarizes typical external surfaces, bottom-end shapes, and end characteristics. The shoulder is most often cylindrical, although conical designs are occasionally used. Because the plunge depth of the shoulder (about 1–5% of the plate thickness) is relatively small, the external shape—cylindrical or conical—is expected to have little influence on the welding process [19].

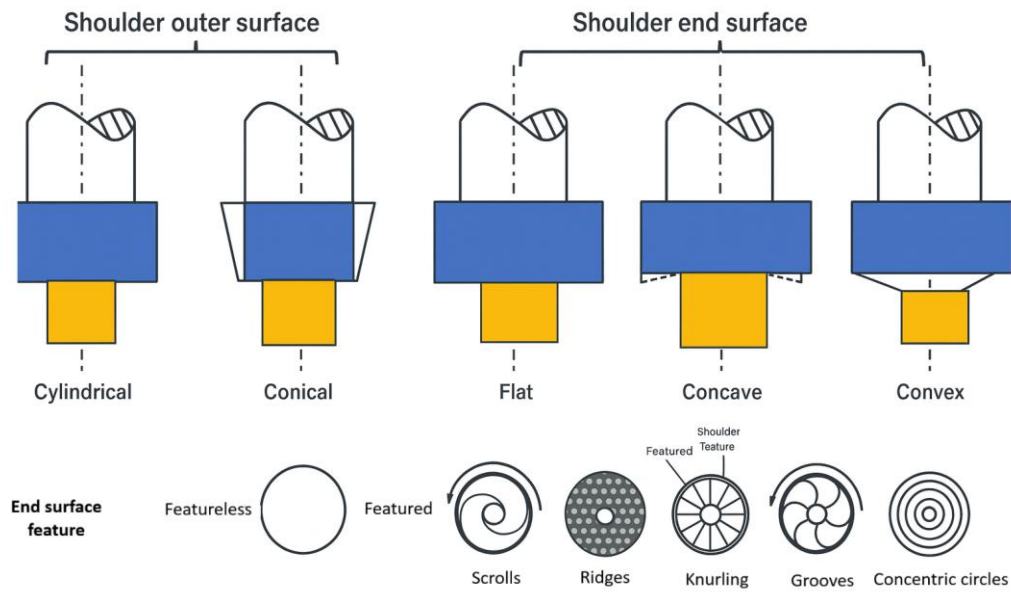


Figure 3: Shoulder shapes and surface characteristics [19].

The tool in FSW is generally constructed from hard, wear-resistant materials like tungsten carbide, tool steel, or ceramics, featuring a cylindrical design with a shoulder at one end and a protruding pin at the other. The shoulder, wider than the pin, applies axial force to the workpieces and confines the softened material during welding. The pin, designed with profiles tailored to the material and welding parameters, includes threaded or fluted sections to enhance material mixing and stirring, as well as a smooth segment to forge a solid-state bond between the joined surfaces. This configuration optimizes heat generation, material flow, and joint integrity [20, 21]. Can be seen in Figure 4 the schematic representation of different pin profiles used in FSW machine.

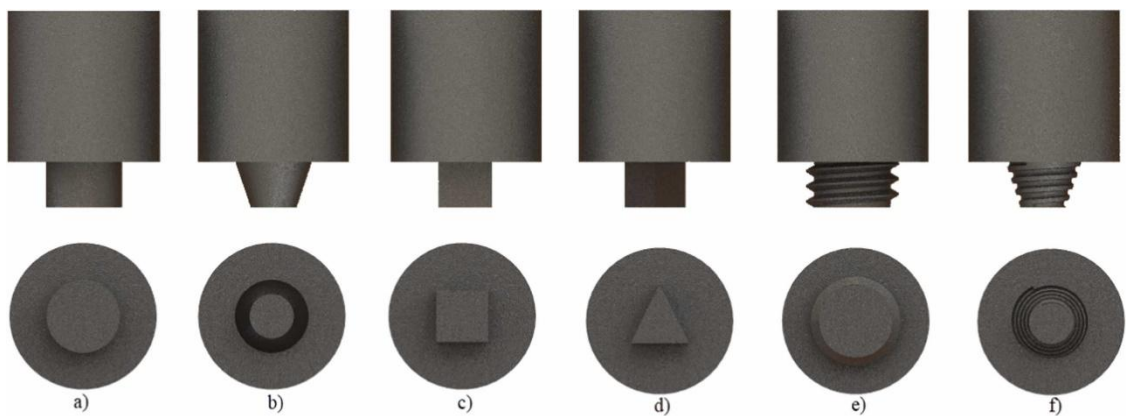


Figure 4: Schematic representation of different pin profiles, a) cylindrical, b) conical, c) square, d) triangular, e) screw, f) conical screw [14]

Several studies have analyzed the impact of tool pin profile on friction stir welding performance. Srinivasa Rao et al. [22] concluded that the conical cylindrical(b) pin profile provides greater tensile strength and minimizes defects such as tunneling. It was identified by Ghiasvand et al. [23] that the combination of

rectangular(c) and triangular(d) profiles improves the quality of the weld due to the greater dynamic/static volume ratio. Elangovan et al. [24] highlights that the square(e) profile of the pin favors the quality of the weld, with better mechanical properties and refined grain structure.

2.3.1.3 - Tool tilt angle

The tilt angle, shown in Figure 5, is a critical parameter in FSW that influences heat input, material flow, and overall joint quality. Adjusting the tilt angle during welding controls these factors: a larger angle increases heat generation and material flow, enhancing mixing, homogenization, and grain structure uniformity, which improves mechanical properties and joint strength. It is advantageous for welding thicker materials or achieving specific weld geometries. However, excessive tilt angles risk defects like tunneling, hooking, thermal distortion, and residual stresses. Conversely, smaller angles reduce heat input and material flow, minimizing defect risks and distortion but may compromise mixing and bonding if too low. Optimizing the tilt angle is essential to balance joint integrity, defect prevention, and thermal management [21].

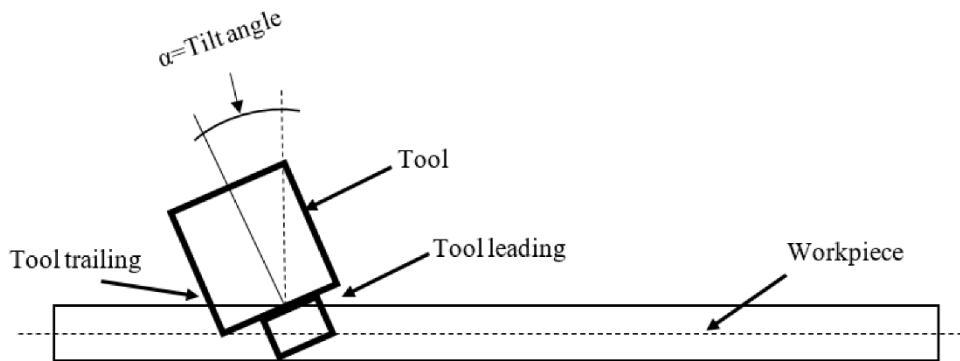


Figure 5: Illustrative cross-sectional view that clearly shows the part and the tool along the longitudinal direction, highlighting the applied tilt angle [25].

2.3.1.4 - Tool rotational speed

The rotational speed of the tool in FSW determines the rate of rotation across the joint, generating frictional heat to soften the metal and enable solid-state welding. This parameter directly affects material flow, defect formation such as voids and final mechanical properties, and must be optimized to balance sufficient heat with flow control and ensure a weld bead free of imperfections [21].

The rotation speed of the tool (rpm) is crucial for the heat input and the behavior of the softened metal: high rotations (“hot weld”) increase the temperature and favor mixing, but can generate flash, porosity and tunnels, in addition to requiring greater force to keep the tool stable and accelerate its wear; on the other hand, low rotations (“cold weld”) can lead to incomplete welding, voids and low coalescence. Therefore, it is essential to balance this parameter to ensure good bead quality without inducing defects [21, 26]. The effect of tool rotational speed on the microstructural evolution of the FSW joint can be observed in Figure 6, which presents the macrostructure and corresponding microstructures of the weld produced at 1200 rpm.

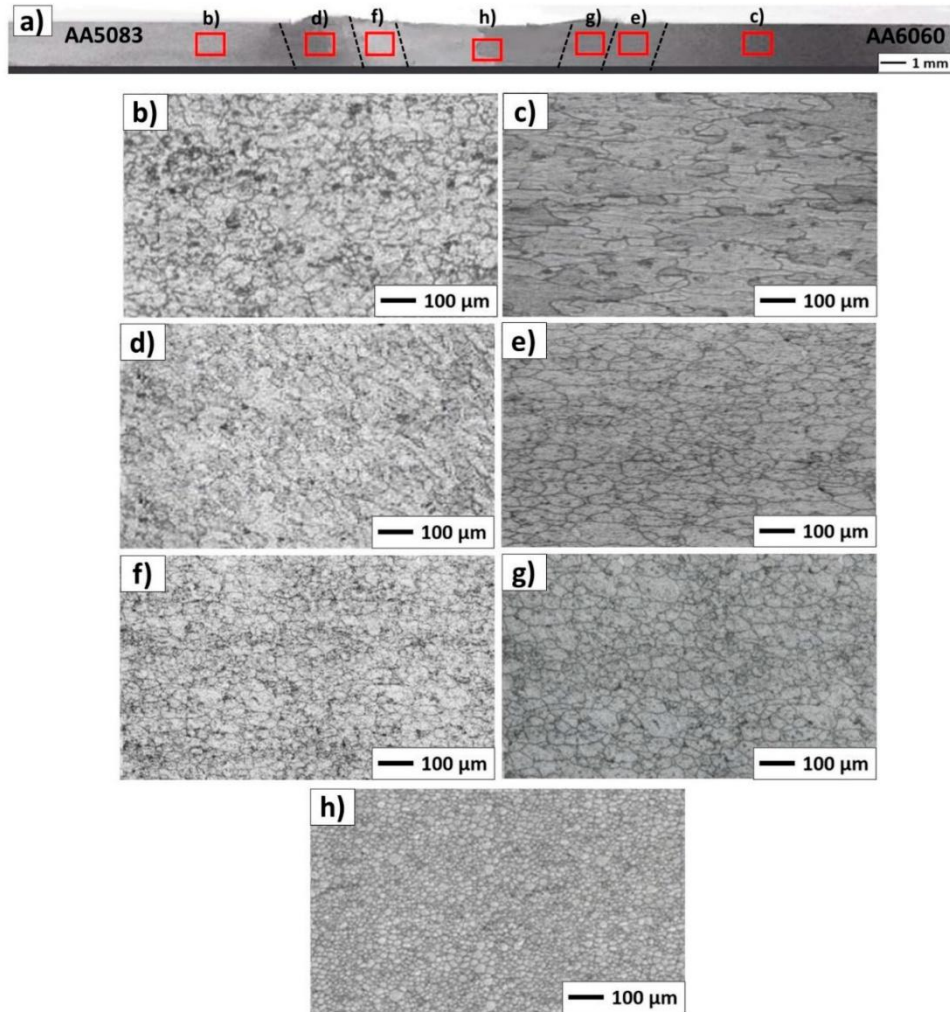


Figure 6: Macrostructure of the weld produced with a tool rotational speed of 1200 rpm (a) and microstructures of base metals AA5083 (b), AA6060 (c), HAZ on AA5083 side (d), HAZ on AA6060 side (e), TMAZ on AA5083 side (f), TMAZ on AA6060 side (g) and the weld nugget (h) [27].

2.3.1.5 - Welding speed

Welding speed is influenced by several factors, including the alloy type, tool rotation rate, penetration depth, and joint configuration. An increase in rotational speed enhances frictional heating, which raises the temperature and promotes more vigorous stirring and mixing of the material. As the tool traverses, the softened material at the leading edge is transported to the trailing edge by the combined effect of tool rotation and forward motion. This displaced material is then compacted and consolidated at the trailing edge under the applied axial force, ensuring joint formation [17].

2.4 - Metallurgical challenges in Al-Steel joining

The use of dissimilar aluminum-steel joints in structures combines economic and functional advantages, such as cost reduction due to the price difference between the materials, lower structural weight due to aluminum's low density, and the achievement of hybrid mechanical properties by combining the lightness of aluminum with the strength of steel [28]. However, this joint presents considerable technical challenges, particularly due to the physical and chemical incompatibility between the metals. Significant differences, such as the approximately 850°C difference in melting points, the distinct formation of oxides, and low mutual solubility, hinder homogeneous fusion. Furthermore, aluminum has a coefficient of thermal expansion and specific heat almost twice as high, a thermal conductivity approximately six times higher, and a significantly lower modulus of elasticity than steel. The electrochemical difference between aluminum and steel is 1.22 volts. The discrepancies in their thermophysical, chemical, and mechanical properties result in significant disadvantages, such as the formation of intermetallic compounds (IMCs), heat-affected zones (HAZs), metallurgical precipitation, bond defects, geometric distortions, and degradation of the joint's mechanical properties [29, 30]. The table 2 shows the comparison of the thermo-mechanical properties of steel and aluminum.

Table 2: Comparison of thermo-mechanical properties of steel and aluminum [31].

Properties	Steel	Aluminum
Melting point (°C)	1425–1540	463–671
Coefficient of thermal expansion (CTE) ($10^{-6} \text{ }^{\circ}\text{C}^{-1}$)	11.3–12.3	21.5–23.8
Conductivity (W/m·K)	45	235
Tensile strength (MPa)	247	90

2.4.1 - Binary phase diagram and Intermetallic Compound Formation

Aluminum and steel have extremely low mutual solubility, which favors the formation of Fe_xAl_y intermetallic compounds during the joining of dissimilar materials. This formation occurs through solid-state reactions between the constituent elements, namely iron (Fe) and aluminum (Al), especially under the thermal and mechanical conditions typical of welding processes. The specific type of intermetallic phase generated depends on the atomic ratio (at. %) between the elements Fe and Al, with different compositional ratios leading to the nucleation of distinct phases, such as FeAl_3 , Fe_2Al_5 , or FeAl , each with specific structural and mechanical characteristics that directly influence the integrity and strength of the joint [29].

According to Ratanathavorn [32] understanding the binary phase equilibria in Al-Fe and Al-Zn systems is fundamental for the development of FSW processes between aluminum alloys and ultra-strong steels. This knowledge is essential because the dissimilar bonding between aluminum and iron tends to promote the formation of atomic bonds at high temperatures, typical of FSW thermal conditions. The low mutual solubility between Al and Fe favors the precipitation of several intermetallic phases in the Al-Fe system, as illustrated in Figure 7. These phases can be classified into iron-rich phases, such as AlFe and AlFe_3 , and aluminum-rich phases, such as Al_2Fe , Al_3Fe_2 , and $\text{Al}_{13}\text{Fe}_4$. Controlling these phases is crucial to ensuring

the mechanical integrity of the joint, since their morphology, thickness, and distribution directly influence the ductility and fatigue strength of the connection. However, it was sad by Li et al. [33] that certain equilibrium phases may not form during the welding process due to extremely slow growth kinetics, rendering them undetectable or metallurgically insignificant under typical processing conditions.

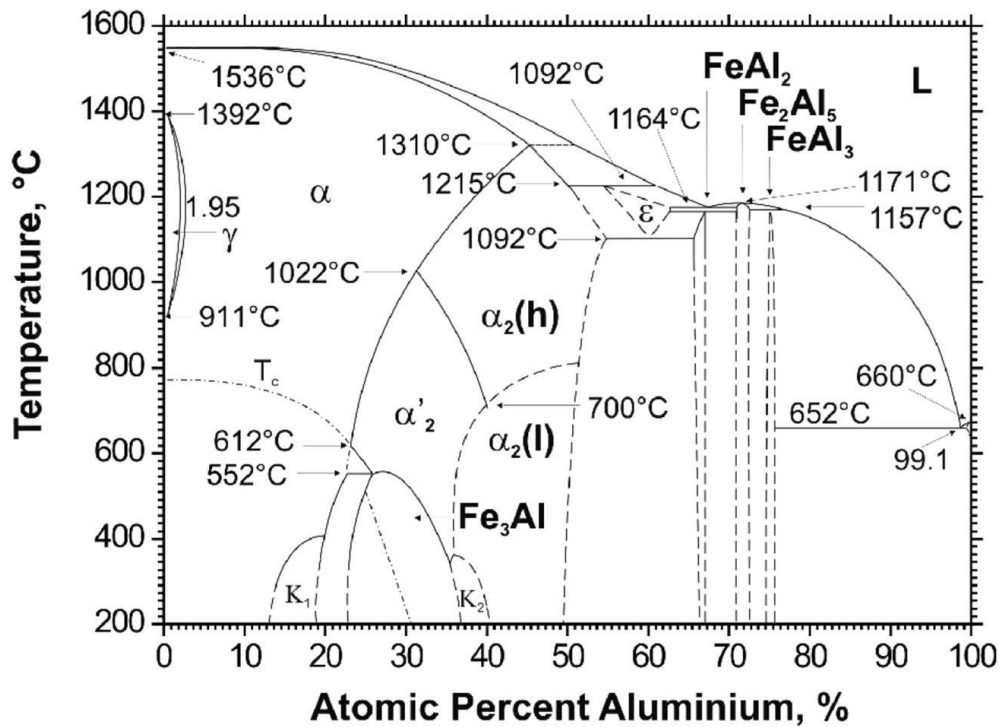


Figure 7: Iron-Aluminum phase diagram[34].

The binary phase diagram between iron (Fe) and aluminum (Al), illustrated in figure 7, allows us to understand the thermodynamic stability of the different phases of intermetallic compounds (IMCs) formed and the reactions between the elements as a function of temperature. The formation of these compounds is governed by parameters such as time, temperature, pressure, and local chemical composition, and is strongly influenced by the conditions of the welding process, such as the thermal and mechanical parameters applied during the joining of the materials [28]. According to Wan et al. [34] the Al-Fe system exhibits low mutual solubility in the solid state, which favors the formation of intermetallic compounds during thermal joining processes. The phase diagram reveals that the predominant phases at the interface are Fe_2Al_5 and FeAl_3 (or $\text{Fe}_4\text{Al}_{13}$), with Fe_2Al_5 being the most common due to its high thermodynamic stability and rapid diffusion of aluminum into iron. These IMCs develop over a wide temperature range, which explains their frequent formation in dissimilar welds. The IMC layer thickness is strongly dependent on the process conditions, especially the exposure time and temperature, as predicted by the phase equilibria. Also, Chen et al. [35] studied the Al-steel interface in resistance spot welding (RSW) and identified Fe_2Al_5 as the dominant intermetallic phase, initially with fine equiaxed grains that evolve to a [001]-oriented columnar morphology with increasing temperature. The growth of the IMC, accentuated above 900°C, leads to layer thickening, compromising the joint toughness: the fracture changes from ductile (in aluminum) to brittle (inside Fe_2Al_5). The toughness drops from 1.07 to 0.35 MPa m^{1/2} when the IMC thickness increases from 3 to 6.5 μm , with critical degradation starting at 4 μm , due to columnar

growth, increased crystallographic texture, and the disappearance of ductile phases. It is concluded that strict control of the Fe_2Al_5 thickness is essential for the mechanical integrity of the joint.

2.4.2 - Residual Stresses

According to Brust et al. [36], residual stress is defined as any stress present in a continuous body after all external loads have been removed. In the case of welded joints, these stresses arise due to thermal stresses caused by the non-uniform temperature distribution during welding, followed by plastic deformation. The resulting distortions observed in the structure are, therefore, a direct consequence of residual stresses.

During friction stir welding, the welded part is subjected to complex thermal variations due to the heat generated by friction and severe plastic deformation. Because the temperature distribution throughout the body is not uniform, thermal stresses arise that, in many regions, exceed the material's elastic limit, resulting in plastic deformations. As an immediate outcome of the uneven heat distribution and cooling during the FSW process, welded materials generate complicated residual stresses. The ability of structures to support loads is reduced by these stresses. The high stresses in the area around the weld joint may also make brittle fractures and fatigue failures more likely [37].

In addition to the thermal effects, the mechanical stirring action, particularly the shear force and axial pressure exerted by the tool, causes severe plastic deformation. When adjacent regions experience different plastic strains, strain incompatibilities occur, leading to residual stresses once the material solidifies [38].

Several process parameters critically influence the magnitude and distribution of residual stresses:

- **Tool rotation and traverse speed:** Higher traverse speeds reduce heat input, increasing thermal gradients and generating higher tensile residual stresses [38].
- **Material properties:** In dissimilar joints (e.g., aluminum–steel), differences in thermal conductivity, coefficient of thermal expansion, and stiffness lead to mismatched contraction behavior, amplifying residual stress near the interface [39].
- **Clamping and boundary conditions:** Rigid clamping systems restrict thermal expansion and contraction, resulting in higher longitudinal tensile residual stresses along the weld line [38].

Typically, the stir zone (SZ) exhibits longitudinal tensile residual stresses, while the heat-affected zone (HAZ) or outer regions may experience compressive residual stresses, depending on process conditions and joint geometry [38].

2.5 - Fatigue behavior of welded joints

Fatigue can be defined as the process that leads a structure to failure due to the accumulation of damage caused by cyclic stresses, which can lead to catastrophic failure, even when the structure is stressed significantly below the static resistance limits [40]. According to Braun et al. [41] The fatigue behavior of engineering components develops through distinct stages. For practical purposes, this process is generally grouped into three main phases: crack initiation, stable crack growth under fatigue, and unstable crack extension leading to failure. These stages are often analyzed separately as can be seen in Figure 8. The initiation stage is considered complete once a microcrack forms with dimensions comparable to the material's microstructure, such as the grain size. The second stage is characterized by a gradual and stable propagation of the crack, largely controlled by the applied cyclic stresses. The final stage corresponds to rapid and unstable crack growth as the component approaches its ultimate load capacity.

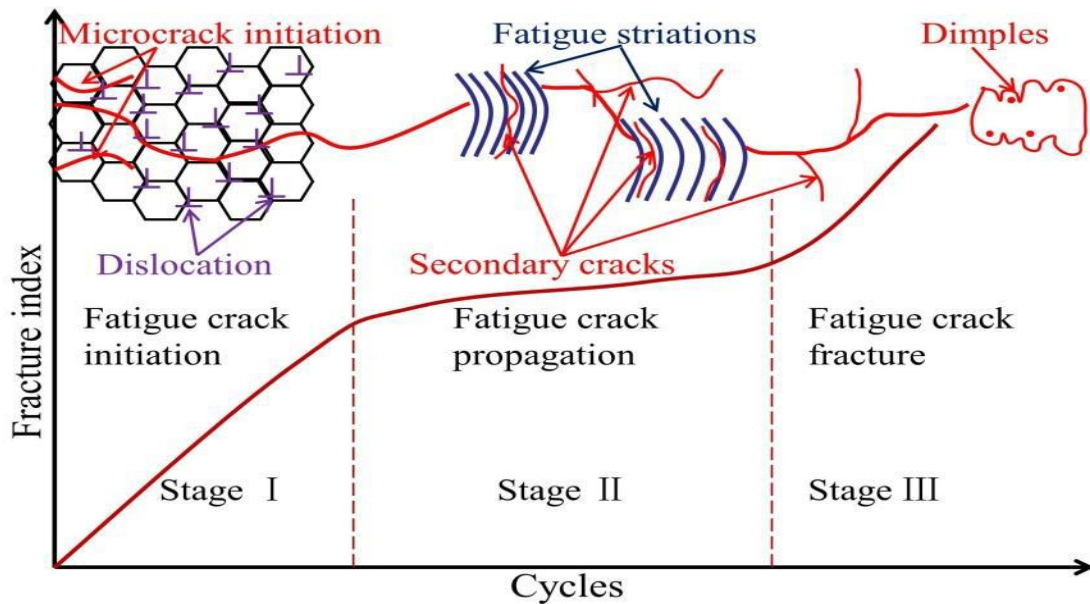


Figure 8: Three stages of fatigue failure [42]

The fatigue behavior of welded joints is a critical concern in components exposed to cyclic loading. Residual stresses typically develop due to thermal effects and plastic deformation during welding. In contrast, FSW joints demonstrate superior fatigue resistance, largely owing to their refined microstructure and the absence of fusion-related defects [14].

2.5.1 - Introduction to the phenomenon of fatigue in joints

Fatigue is a progressive degradation process that occurs in materials subjected to cyclic loading, resulting in the accumulation of microstructural damage that can lead to the formation (nucleation) and growth (propagation) of cracks, eventually culminating in structural failure. In the case of welded joints, this phenomenon is especially critical due to the presence of several factors intrinsic to the welding process, which favor the occurrence of fatigue:

- **Geometric discontinuity:** The welding process introduces discontinuities in the joint geometry, such as weld toe, incomplete penetration and lack of fusion. These irregularities act as local stress concentrators, becoming preferred sites for crack nucleation under cyclic loading [43].
- **Microstructural changes:** During the welding process, the thermal heating and cooling cycles result in the formation of different zones with distinct microstructural characteristics: the base metal (parent metal), the HAZ and the fusion zone (fusion zone). In the specific case of FSW, the latter is known as the nugget zone. Each of these regions presents significant differences in terms of microstructure, hardness and mechanical properties, which directly influence the joint behavior under structural stresses [43].
- **Residual stress:** The welding process induces residual stresses in the material, and it is common for tensile stresses to be present on the surface adjacent to the welded region. These stresses act as pre-existing internal loads and can alter the effective stress ratio (local stress ratio) during the application of cyclic loads, negatively influencing the fatigue resistance of the joint [44].
- **Defects and roughness:** The presence of imperfections such as inclusions, porosity, lack of fusion and inadequate joint finishing have a significant impact on reducing fatigue life, acting as preferential sites for crack nucleation.

In highly critical structures, such as bridges, vehicles and aeronautical components, fatigue in welded joints is one of the main causes of structural failures. In view of this, recent studies have revisited and improved the methods for assessing the fatigue life of these joints, encompassing probabilistic, experimental, numerical and, more recently, machine learning-based techniques, aiming at greater accuracy and reliability in performance predictions

2.5.2 - Parameters governing fatigue failure

2.5.2.1 - Geometry

Fatigue behavior is strongly affected by the geometry of a structure, including its dimensions, the location of cracks, and overall complexity. Stress concentrations typically arise from abrupt geometric transitions, which act as critical points for crack initiation. To improve fatigue life, such discontinuities should be minimized during the design stage [45].

According to Rajaganesan [45], the fatigue strength of welded joints is strongly affected by the thickness of the welded section. This observation is consistent with the experimental results of T. R. Gurney (1968), who showed that increasing thickness reduces fatigue strength due to higher residual stresses induced by welding. To address this effect, Gurney [46] proposed a thickness correction factor shown in equation, which quantifies the reduction in fatigue performance for thicker plates as:

$$\Delta\sigma_t = \Delta\sigma_{nom,HSS} \left(\frac{t_{ref}}{t} \right)^n \quad (1)$$

where $\Delta\sigma_{nom,HSS}$ is the fatigue strength from nominal stress or hot spot method, t_{ref} is the reference thickness, and n is the thickness exponent.

2.5.2.2 - Effect of stress amplitude

In fatigue testing, the term fatigue cycle denotes the smallest repeating segment of a stress–time or strain–time waveform and is commonly referred to as a stress, load, or strain cycle [47]. According to Mohammed [48], identifying the characteristics of a load cycle requires the evaluation of several key parameters, as illustrated in Figure 9. These include the maximum stress (σ_{max}), minimum stress (σ_{min}), mean or steady stress (σ_m), stress amplitude (also known as alternating stress, σ_a), stress range (σ_r), stress ratio (R), and amplitude ratio (A). The amplitude ratio is determined by equation (2):

$$A = \frac{\sigma_a}{\sigma_m} = \frac{\sigma_{max} - \sigma_{min}}{\sigma_{max} + \sigma_{min}} = \frac{1-R}{1+R} \quad (2)$$

Where σ_a is the Stress Amplitude. which is calculated by equation (3):

$$\sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2} \quad (3)$$

And σ_m is Mean stress which is calculated by equation (4):

$$\sigma_m = \frac{\sigma_{max} + \sigma_{min}}{2} \quad (4)$$

The stress range (σ_r), which the algebraic difference between maximum and minimum stress in one cycle is calculated by equation (5):

$$\sigma_r = \sigma_{max} - \sigma_{min} \quad (5)$$

and the ratio of the minimum stress to the maximum stress, is calculated by equation (6):

$$R = \frac{\sigma_{min}}{\sigma_{max}} \quad (6)$$

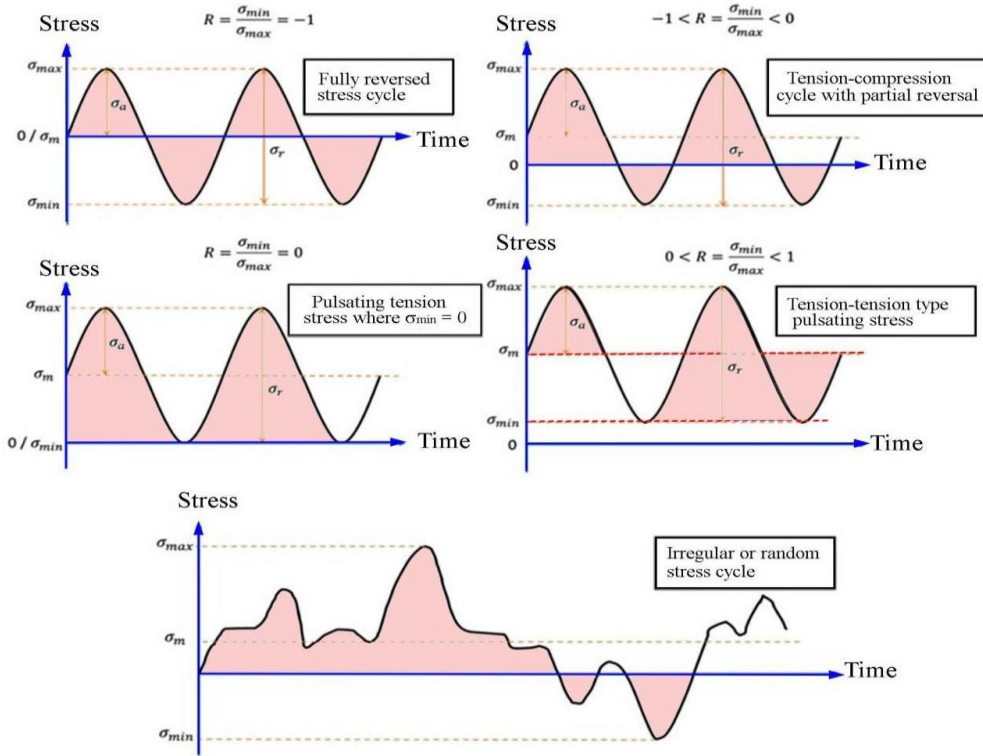


Figure 9: Illustration of common stress cycle configurations encountered in fatigue testing[49]

According to Mohammed [48], the time-dependent stress cycles illustrated in Figure 9 are representative of the fatigue behavior observed in materials under cyclic loading. The figure shows sinusoidal stress variations with different stress ratios, which are commonly found in rotating and reciprocating components of machinery. However, in practice, fatigue loading often involves complex, irregular, or random stress cycles. For instance, an airplane wing encountering turbulent flight conditions may be subjected to unpredictable overloads, resulting in non-uniform stress fluctuations. Similarly, intermittently operated machinery can experience random stress patterns due to transient vibrations during startup and shutdown phases. To analyze fatigue design, it is necessary to simplify the random stress cycle. This is usually achieved by dividing the actual stress cycle into several simplified sinusoidal variations, ensuring that each set contains the same number of oscillations with similar mean stress and stress amplitude.

The type of stress in a fatigue stress cycle can be tensile, compressive, shear, or torsional, resulting from axial, flexural, shearing, or torsional loading, or a combination of these. As stated in the *ASTM Manual of Fatigue Testing* [ASTM STP 91A], more than thirty different fatigue testing machines have been developed, varying according to the type of load and the method of its application [50]. Therefore, to fully define a stress condition, it is necessary to specify not only the degree of stress variation but also the nature of the stress. Three fundamental factors related to the stress cycle are essential for fatigue failure to occur. [49] These are:

1. A sufficiently high maximum tensile stress, σ_{max} , in the applied stress cycle.
2. A high stress amplitude, σ_a , in the applied stress cycle; and
3. A sufficiently large number of load cycles (oscillations) in the applied stress cycle.

According to Mohammed [48] fatigue cycles can be classified into two primary categories:

1. High-cycle fatigue, also called “stress-controlled fatigue,” involves conducting fatigue tests using a prescribed cycle of fixed load or stress limits. This type of fatigue generally occurs with high-stress cycle numbers, ($<10^4$ cycles).
2. Low-cycle fatigue, termed “strain-controlled fatigue,” involves conducting fatigue tests using a prescribed set of elastic and plastic strain limits within each cycle. This type of fatigue usually occurs at low numbers of stress cycles ($< 10^3$ cycles).
3. Ultra-low cycle fatigue. This section highlights the unique characteristics of ULCF, such as its occurrence under large cyclic loads leading to complete ductile fracture and the distinct mechanisms involved, which are different from those in HCF and LCF.
4. Ultra-high cycle fatigue (UHCF) refers to fatigue failure occurring beyond 10^7 to 10^9 cycles, typically under very low stress amplitudes and high-frequency loading. Unlike conventional fatigue, UHCF is governed by microstructural features, surface conditions, and environmental effects, with failure initiated by microcracks, grain boundary cracking, or surface defects that slowly propagate over millions of cycles before leading to catastrophic failure.

High-cycle fatigue is of major engineering importance, as it accounts for the majority of in-service fatigue failures, typically occurring beyond 10^4 cycles. Smooth, carefully prepared specimen surfaces are critical to minimize stress concentrations and tensile residual stresses that can accelerate crack initiation. Despite being a leading cause of safety-critical failures in industries like aerospace and automotive, fatigue behavior remains under-prioritized due to the complexity, lengthy duration, and resource-intensive nature of testing, which demands a large number of precisely prepared specimens [48].

In addition to primary stress parameters, fatigue failure in dissimilar Al–steel joints are strongly influenced by interfacial and environmental factors. The formation of brittle intermetallic compounds (IMCs), such as Fe_2Al_5 and FeAl_3 at the interface acts as a primary site for crack initiation, with their thickness, morphology, and continuity directly affecting fatigue resistance. Stress concentrations, residual stresses from thermal mismatch, and mechanical property differences further promote localized damage. Galvanic corrosion, driven by the electrochemical potential between aluminum and steel, accelerates crack growth in corrosive environments. Additionally, microstructural heterogeneity, interfacial defects, and temperature fluctuations contribute to degradation by enhancing residual stresses and IMC growth. These combined effects must be carefully managed to ensure durable joint performance under cyclic loading.

Table 3 summarizes the fatigue stress ratio (R) and amplitude ratio (A) corresponding to different loading conditions. Lerch and Halford [51] investigated how the control mode (stress- vs. strain-controlled) and stress ratio influence the fatigue behavior of metal matrix composites (MMCs) under two distinct conditions: $R = 0$ (tension-only loading) and $R = -1$ (fully reversed cyclic loading). Their findings indicate that the loading regime significantly affects the dominant damage mechanism. Under $R = 0$, transverse fiber cracking prevails, with minimal matrix cracking observed. In contrast, under $R = -1$ (tension-compression), fiber cracking is less prevalent, while the matrix sustains extensive damage. Notably,

consistent results were observed regardless of whether stress or strain was controlled, suggesting that the damage evolution is primarily governed by the load ratio rather than the control method.

Table 3: The values corresponding to the fatigue stress ratio (R) and amplitude ratio (A) associated with the fatigue loading modes. Adapted from [48].

R values	Amplitude ratio (A)	Mode of fatigue loading
$R = -1$	∞	Completely reversed stress (tension compression)
$-1 < R < 0$	> 1	Tension-compression fatigue
$R = 0$	1	Zero-tension load
$0 < R < 1$	< 1	Tension-tension
$R = 1$	0	Static

2.5.2.3 - The S-N diagram and fatigue properties

According to Bhaduri [49] engineering fatigue data under stress-controlled conditions are typically presented using the S-N diagram, also known as the Wöhler diagram. This plot represents the relationship between the applied stress amplitude S and the number of cycles to failure N , particularly for high-cycle fatigue regimes usually exceeding 10^4 cycles. The S-N curve exhibits significant curvature across most of its range, especially at lower stress levels, because the rate of increase in fatigue life slows down progressively as the stress level decreases. However, when the number of cycles N is plotted on a logarithmic scale, the initial portion of the curve often becomes nearly linear. As a result, S-N diagrams are almost always displayed with a logarithmic scale for N . The data used to construct these curves are typically derived from standardized rotating bending fatigue tests conducted at constant stress amplitude. Schematic representations of typical S-N curves for ferrous and non-ferrous metals obtained from such tests are shown in Figure 10.

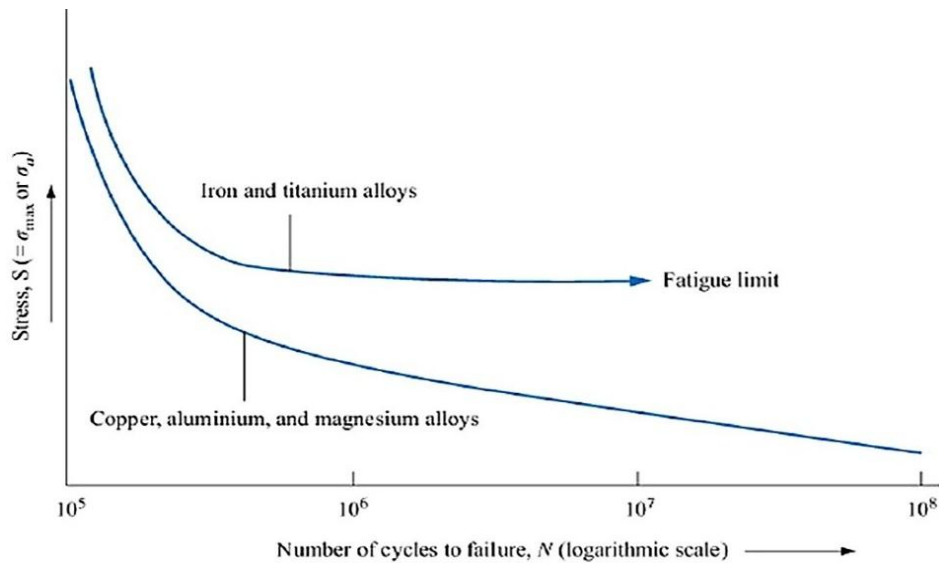


Figure 10: Typical schematic S-N curves from ferrous and non-ferrous metals [49].

The figure shows the S–N curve, also known as the Wöhler curve, establishes the relationship between the applied stress and the number of cycles to failure under cyclic loading. For ferrous metals, such as iron and titanium alloys, a fatigue limit (or endurance limit) is observed, identified by the horizontal section of the curve at high cycle values. This limit corresponds to a critical stress, generally much lower than the yield stress, below which fatigue failure is not expected, regardless of the number of cycles. In contrast, non-ferrous metals, such as aluminum, copper, and magnesium, do not exhibit this behaviour. Their S–N curves do not stabilize, maintaining a downward trend as the number of cycles increases, demonstrating the absence of a safe stress limit [48]. This difference is crucial in structural dimensioning, as it implies different design criteria: while in ferrous materials it is possible to define an operating stress below which the fatigue life is theoretically infinite, in non-ferrous materials a finite service life must always be considered, adjusted to the service conditions.

2.5.3 - Fracture fatigue mechanism

Understanding the fracture mechanism in fatigue necessitates understanding the development of fatigue fracture. Fatigue fractures occur when stress is applied, removed, and reapplied cyclically. This repetitive process can continue for millions of cycles until the fatigue fracture reaches a critical point, leading to material failure [48]. The fatigue process, from crack nucleation to final fracture, can be divided into three distinct stages [49]:

- Crack initiation: This occurs during the early phase of fatigue and typically begins at heterogeneous nucleation sites, such as pre-existing flaws (e.g., inclusions, voids) or microstructural defects generated during cyclic deformation. These sites are regions of localized stress concentration where dislocation slip is initiated.
- Stage I crack growth (also known as slip-band crack growth): In this stage, the crack propagates along crystallographic slip planes regions of high shear stress under the influence of cyclic loading. The crack growth direction is generally oblique to the applied tensile axis and is governed by the material's crystal structure.
- Stage II crack growth (also referred to as crack growth on planes of high tensile stress): This is the dominant phase of crack propagation, where the crack advances primarily in a direction normal to the maximum applied tensile stress. The crack front becomes more stable and less influenced by crystallography, transitioning into a macroscopic mode of failure.
- Ultimate ductile failure: This final stage occurs when the crack has grown to a critical length, reducing the remaining cross-sectional area to a point where it can no longer support the applied load. This leads to rapid, catastrophic failure under plastic deformation.

The relative contribution of each stage to the total fatigue life depends on the material properties and loading conditions. In high-stress, low-cycle fatigue, Stage II crack growth dominates due to the limited number of cycles and higher strain amplitudes. Conversely, in low-stress, high-cycle fatigue, Stage I crack growth often accounts for a significant portion of the total life. In some cases, particularly with sharply notched materials or under high tensile stresses, Stage I may be negligible, and crack initiation can occur almost immediately after loading.

2.5.3.1 - Crack nucleation

Crack nucleation represents the initial phase of the fatigue process and is defined as the emergence of microscopic discontinuities in the material subjected to repetitive cyclic loading. This phenomenon occurs mainly in locations where there are stress concentrations, microstructural defects or geometric irregularities [40]. In welded joints, these critical sites are often located at the weld toe, joint root and HAZ, due to the microstructural heterogeneity and high residual stresses generated during the welding process [52].

During fatigue, metals undergo deformation by slipping on the same atomic planes and the same crystallographic directions. Under fatigue loading, cyclic slip bands form within the first few thousand cycles due to the accumulation of slip lines. These bands generate surface extrusions and intrusions microscopic ridges and grooves that act as stress concentrators and promote crack initiation [48]. Zhang et al. [53] demonstrated that these slip bands play a critical role in both initiating and propagating fatigue cracks, as shown in Figure 11 for a nickel-based superalloy tested to failure.

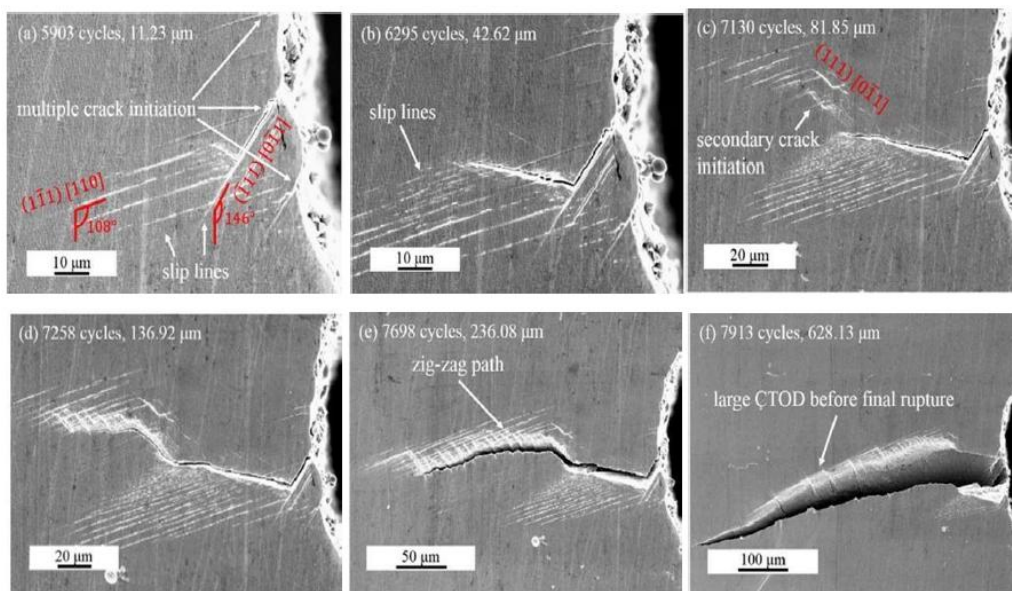


Figure 11: Scanning electron microscopy images of fatigue-crack initiation and growth in nickel-based superalloys [53].

Studies on fatigue crack nucleation have evolved significantly over the last fifty years, driven by the use of high-resolution experimental techniques, especially electron microscopy, which have deepened the understanding of nucleation sites and the morphology of small cracks. Already in the 1960s, the emergence

of Linear Elastic Fracture Mechanics (LEFM) allowed a more consistent description of the propagation kinetics of long cracks [54].

2.5.3.2 - Crack growth and its propagation

This stage can be separated into two phases: the first involves crack growth, where the crack begins to propagate along slip planes at a very slow rate, typically on the order of nanometers per cycle [48]. Once initiated, fatigue cracks tend to advance along slip planes, typically aligning with persistent slip bands at an angle of about 45° to the main tensile stress axis. In this stage, the crack growth rate is extremely slow, usually in the nanometer range per cycle, and the fracture surface formed is almost featureless. In polycrystalline materials, Stage I cracks generally extend only a few grain diameters before transitioning into Stage II growth [49].

When a Stage I crack reaches a critical length where the stress field at the crack tip dominates, the process transitions to Stage II. In this phase, cracks propagate perpendicularly to the applied tensile stress, and the growth rate becomes significantly higher on the order of microns per cycle, compared to nanometers in Stage I. This stage marks the development of macro-cracks, whose growth remains stable until a critical size is reached, beyond which propagation becomes unstable and eventually leads to final fracture. The rate of crack extension is strongly governed by the stress range (σ_r) in each cycle as well as the material's mechanical properties, particularly in the thickness region. A characteristic feature of Stage II is the formation of fatigue striations microscopic ripples representing the incremental crack growth per stress or strain cycle, which are not visible to the naked eye but can be detected under magnification [45], [49]. The schematic representation in Figure 12 illustrates the mechanism of fatigue crack propagation described above. It shows the sequence of events occurring at the crack tip during cyclic loading, including the opening and closing of the crack, plastic deformation, and the progressive increase in crack length by a characteristic striation spacing in each cycle.

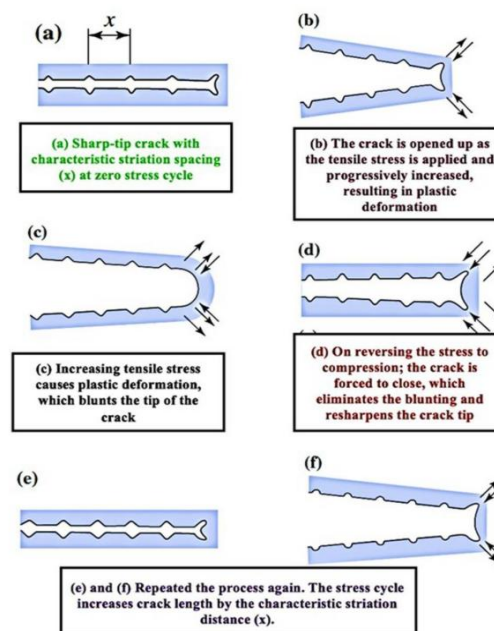


Figure 12: The stages of fatigue crack propagation [48], [49].

2.5.3.3 - Fatigue failure

In this stage, fatigue failure occurs if the crack formed during the second phase of growth and propagation continues to extend under sufficient energy. The final failure mode is a catastrophic fracture, which may present as ductile, brittle, or a combination of both, depending on factors such as material type, thickness, applied stress, and temperature. Fatigue fractures are often unexpected, occurring suddenly without prior warning. Typically, fatigue-induced failures exhibit smooth fracture surfaces with little or no signs of plastic deformation [48].

2.6 - Cohesive zone modeling

Given the extremely thin nature of the IMC layer, especially when compared to the scale of traditional weld samples, it was not feasible to model the IMC layer explicitly in the numerical simulation. Instead, a cohesive zone model (CZM) was adopted to capture the separation behaviour at the aluminum-steel interface. This approach has proven effective in simulating interfacial delamination and predicting weld failure in dissimilar material joints. To account for the mechanical influence of the IMC layer, cohesive contact behaviour was defined between the aluminum and steel surfaces using a traction-separation law. According to Cho et al. [55], this cohesive contact formulation shown in Figure 13, combined with a penalty-based method to enforce constraints in both normal and tangential directions, allows for an accurate representation of interface behaviour. The method provides insight into the mechanical response of the joint while avoiding the computational complexity of directly modelling the ultra-thin IMC layer.

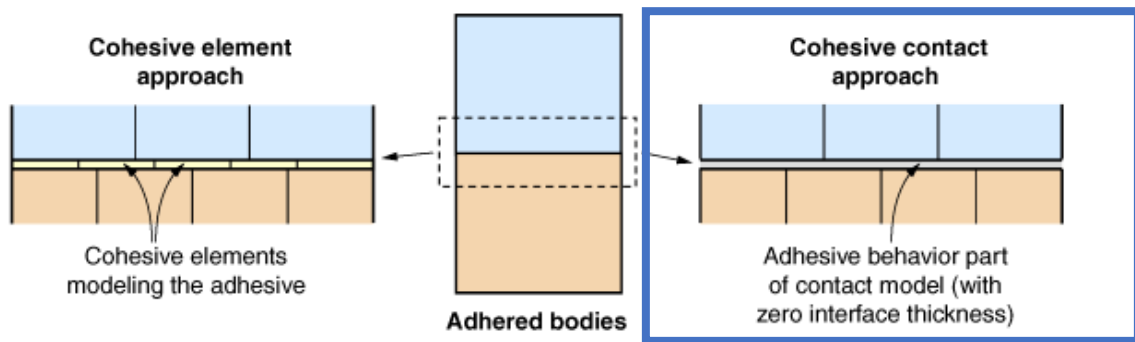


Figure 13: Use of cohesive contact approach due to complex geometry

The behavior of the interface is governed by a traction-separation law, which defines how the interfacial traction develops in response to the relative displacement (or separation) between connected nodes. Although various forms of this law have been proposed, their overall mechanical response tends to be comparable when they share the same cohesive strength (σ_m) and fracture energy (G_c) [56]. In this work, a stress-based criterion was used to determine the onset of damage, followed by a bi-linear law to model damage progression (as illustrated in Figure 14). This combination allows for a realistic representation of interface degradation and failure under loading.

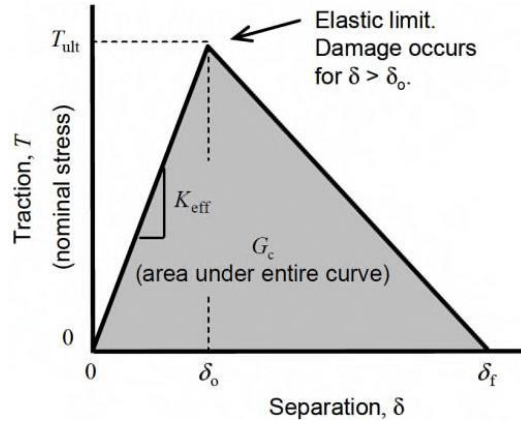


Figure 14: Bilinear traction-separation law diagram.

To characterize the traction-separation behavior, three key parameters need to be defined: the initial stiffness (k), the cohesive strength (T_{ult}), and the fracture energy (G_c). The initial stiffness, which corresponds to the initial slope of the traction-separation curve, is derived from the elastic properties of the IMC and its thickness. Specifically, it can be calculated by equation (7) using the elastic modulus of the IMC (E) and its thickness (t), establishing a direct link between the material's mechanical behavior and the interface response in the model.

$$K = \frac{E_{IMC}}{t} \quad (7)$$

Determining accurate values for cohesive strength and fracture energy is a key challenge, particularly due to the limited availability of experimental data on the mechanical behaviour of the IMC layer. In the absence of comprehensive direct measurements, these parameters are typically estimated by combining experimental results with inverse modelling techniques [55].

While it is common to assume uniform cohesive properties along the weld interface for simplification, the reality is more complex. The IMC layer often exhibits variations in phase composition, thickness, and microstructure across the joint, meaning that a single set of cohesive parameters may not fully capture its heterogeneous mechanical response. To address this, reference values from the literature were used to inform the model. Based on the work of Mitra [57], a maximum cohesive strength of 600 MPa was adopted, representing the typical strength of the IMC layer in similar Al-steel joints. The fracture energy (G_c) was estimated at 0.123 N/mm. Additionally, the elastic stiffness of the IMC layer was set to 261 GPa, consistent with reported values for intermetallic phases formed in such dissimilar metal welds. Together, these parameters provide a realistic approximation of the IMC's mechanical behaviour within the cohesive zone framework.

Chapter 3

Experimental work

3.1 - Joint manufacturing

In the scope of this dissertation, dissimilar butt joints between AA6061-T6 aluminum and St37 steel were fabricated using the FSW process. The joints were produced using base plates with different dimensions. Both the aluminum alloy and the steel substrate had a length of 50 mm, while the widths were 5 mm for aluminum and 2 mm for steel, and the thickness was 5 mm for both materials. These dimensions were selected to simulate realistic industrial joining conditions and to evaluate the influence of material asymmetry on the thermo-mechanical behavior of the process. The main mechanical, physical and chemical properties of the base materials relevant to this study are summarized in Table 4.

Table 4: Properties of St37 carbon steel and 6061-T6 Aluminum [58].

St37 Carbon Steel	AA6061-T6 Aluminum	
Tensile strength - 370 MPa Yielding strength - 200 MPa Vickers hardness - 120 HV	Tensile strength - 241 MPa Yielding strength – 145 MPa Vickers hardness - 75 HV	
Chemical composition:	Chemical composition:	
Fe: 99.43 – 99.75% C: 0.08% Mn: 0.25 – 0.4% S: 0.05% P: 0.04%	Al: 98.56%-98.6% Si: 0.4%-0.8% Fe: 0.70% max Cu:0.15- 0.40% Mn: 0.15% max	Mg: 0.8-1.20% Zn: 0.25% max Ti: 0.15% max Cr: 0.04 - 0.35 Others: 0.15%

To ensure the production of reliable dissimilar joints with the intended thickness configuration, a custom FSW clamping jig was employed. The setup consisted of aluminum support plates of 1 mm and 2 mm

thickness, positioned respectively below and above the St37 steel substrate, to compensate for thickness mismatch and eliminate gaps between the specimen, the welding table, and the tool shoulder, as illustrated in Figure 15.

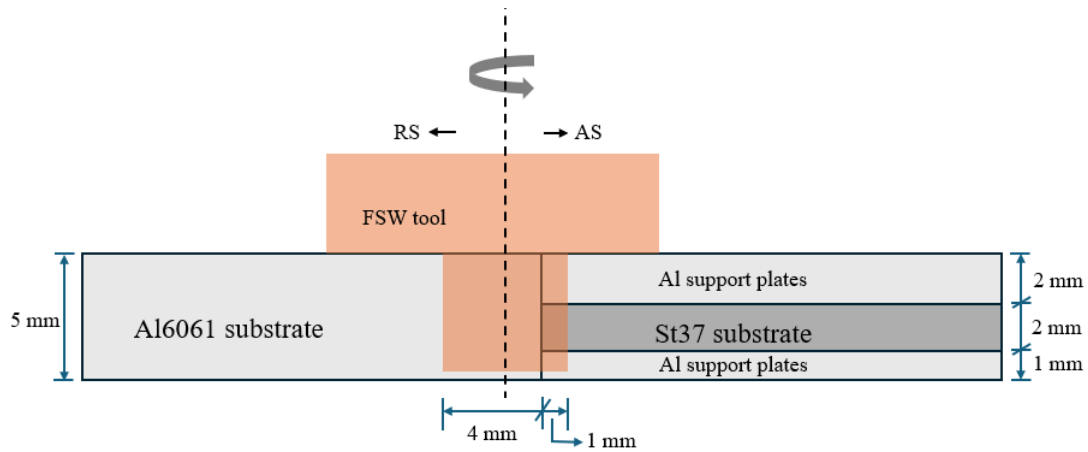


Figure 15: Schematic representation of the FSW mount apparatus used to manufacture the Al-steel joints.

The FSW tool pin was positioned with an offset toward the retreating side (RS), penetrating 4 mm into the AA6061-T6 substrate and 1 mm into the St37 steel substrate, while maintaining a tool tilt angle (θ) of 2.5° . The H13 steel tool used for welding the dissimilar joints had an 18 mm shoulder diameter, a 5 mm pin diameter, a 4.7 mm pin length, and a 2.5° shoulder concavity. This concavity helped confine the plasticized material, promoting stable flow, proper joint consolidation, uniform heat distribution, and reduced residual stresses, as illustrated in Figure 16. Furthermore, the tool rotation speed (ω) was set to 950 RPM, rotating counterclockwise (CCW), and the traverse speed (V_x) varied between 10 and 20 mm/s, in order to investigate the influence of the welding parameters on the heat generation, material flow, and overall joint quality. Those parameters and specifications of the tools can be seen in Table 5.

Table 5: FSW parameters and tool specifications

FSW parameters	Tool specifications
- Tool rotation speed (ω): 950 RPM, CCW	- Material: H13 tool steel
- Tool traverse speed (V_x): 10-20 mm/s	- Tool shoulder diameter: $\varnothing$ 18 mm
- Tool tilt angle (θ): 2.5°	- Tool shoulder concavity: 2.5°
- Pin plunge depth: 4.7 mm	- Tool pin diameter: $\varnothing$ 5 mm
- Tool offset: 1.5 mm to RS	- Tool pin length: 4.7 mm

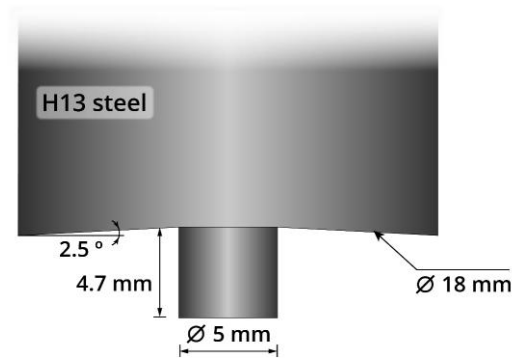


Figure 16. Schematic representation detail of the tool's shoulder and pin, with the respective dimensions.

Upon completion of the welding process, the steel support plates were detached, and the resulting welded joint was precisely sectioned into several specimens using Wire Electrical Discharge Machining (WEDM), ensuring dimensional accuracy and minimal thermal distortion, as shown in Figure 17.

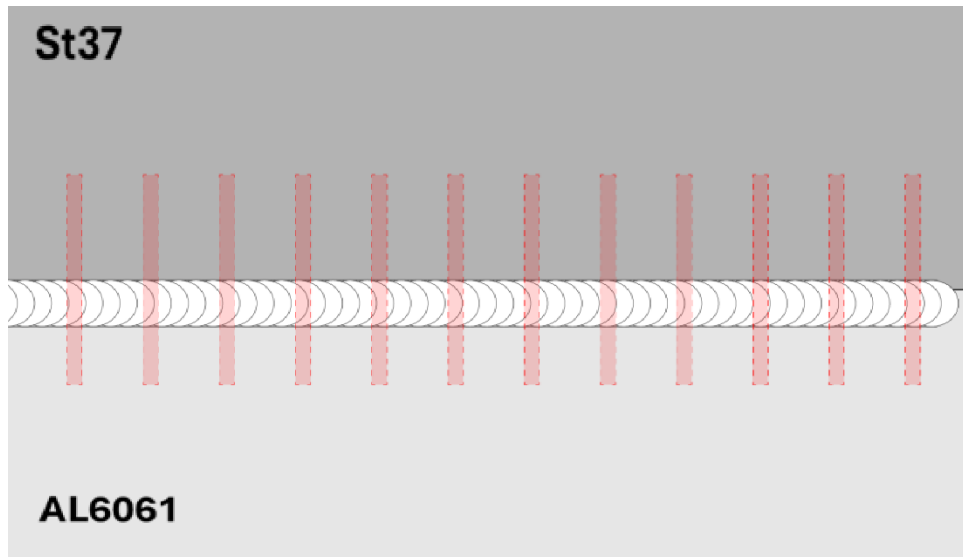


Figure 17: Top view schematic representation of the joint substrate plates after welding, with the WEDM cut specimens, represented in red.

3.2 - Experimental tests

In order to investigate the fatigue behavior of joints formed by friction stir welding, experimental tests were performed involving two types of joint configurations: S-shape and Without S-shape. The main purpose of this study was to understand how joints welded by FSW behave when subjected to cyclic loading, with special attention to the influence of the joint geometry (presence or absence of the "S" profile). The experimental analysis sought to evaluate the effects of these different geometric configurations on fatigue resistance, as well as on crack propagation throughout the load cycles. The joint configurations are illustrated in Figure 18.

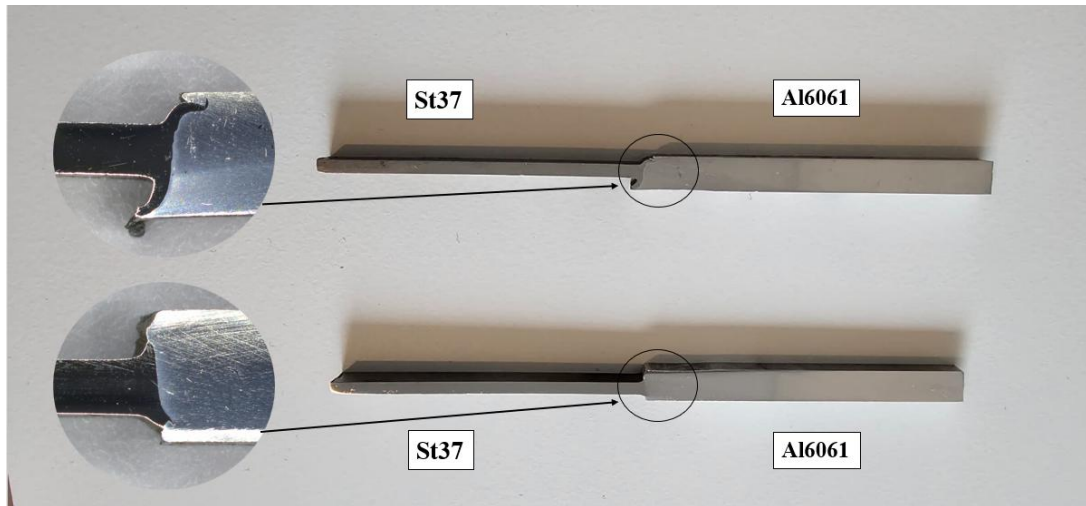


Figure 18: Joint configurations “with S-shape” on top and “without S-shape” on the bottom

Before performing the experimental tests, the joints were subjected to a preliminary polishing process. The main objective of this procedure was to remove the surface oxidation layer present on the joint surfaces, ensuring uniform conditions for subsequent microstructural analysis. In addition, polishing facilitated the obtaining of clear and detailed images through microscopic photography, allowing an accurate evaluation of the microstructural characteristics and phenomena occurring during the tests.



Figure 19: Before (above) and after (below) polishing treatment

3.3 - Microscopy analysis

Before performing the mechanical tests, metallographic samples were extracted from three specimens of each joint geometry, namely “with S-shape” and “without S-shape” profile, in order to enable a comparative analysis of the interfacial quality. The observations were carried out using a high-resolution optical microscope, following a conventional metallographic preparation procedure with the purpose of evaluating the microstructural integrity of the weld interface.

The main objective of this analysis was to characterize the IMC layer formed between aluminum and steel, identifying possible discontinuities, thickness variations, and defects related to the FSW process. In

addition, the investigation focused on detecting irregularities in the base materials (substrates), such as inclusions, voids, lack of bonding, or incomplete metallurgical joining. This preliminary step was essential to assess the initial metallurgical quality of the joints and to correlate microstructural imperfections with the subsequent mechanical performance observed in tensile and fatigue tests, thereby providing a deeper understanding of the influence of joint geometry on IMC formation and behavior. Figures 20 and 21, shows the results of this analysis.

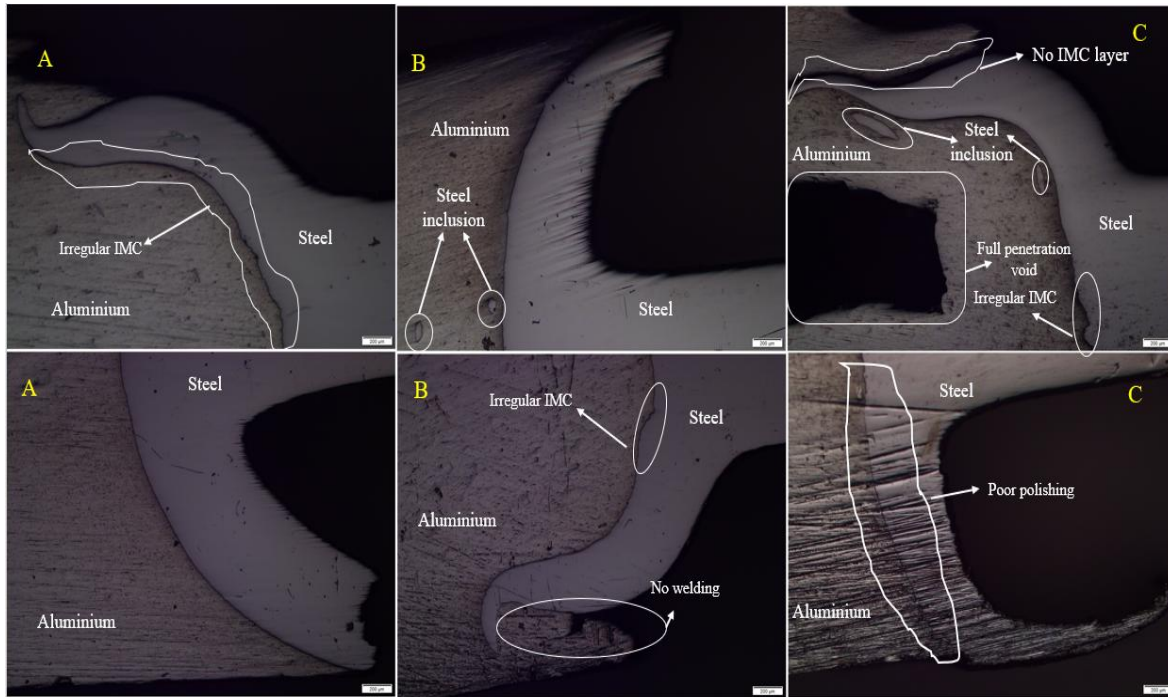


Figure 20: Microstructural characterization of interfacial defects in “with S-shape” joints (Samples A, B, and C)

The metallographic analysis of the three samples in Figure 20 (A, B, and C) reveals a combination of interfacial and structural defects typical of Aluminum–Steel joints produced by FSW, which are expected to strongly influence the mechanical behaviour in subsequent quasi-static tensile and fatigue tests. In sample A, an irregular and thick IMC layer with a wavy morphology and variable thickness was observed, resulting from excessive heat input and prolonged dwell time, which promoted uneven diffusion between aluminum and iron, leading to the formation of brittle intermetallic phases such as Fe_2Al_3 and FeAl_3 . Although these phases provide metallurgical bonding, they are hard and brittle, acting as stress concentrators and favouring premature interfacial fracture. Samples B and C exhibited steel inclusions within the aluminum matrix, caused by mechanical dragging of steel fragments by the tool due to excessive penetration, improper axial force, or an unbalanced rotation-to-traverse ratio. These inclusions represent metallurgical discontinuities that serve as crack initiation sites under cyclic loading, thus reducing fatigue resistance.

Additionally, regions with incomplete metallurgical bonding (no welding / no IMC layer) were detected, associated with insufficient heat generation and limited plastic flow, resulting in weak adhesion and localized adhesive failure. Sample C also exhibited a full penetration void, indicating poor material consolidation and deficient plastic flow during the FSW process, which reduces the effective load-bearing cross-section and can lead to catastrophic failure under tensile loading. The combined presence of these

defects, irregular IMC layers, steel inclusions, voids, and lack of bonding, demonstrates thermal and mechanical non-uniformity during processing, which directly affects the ductility, ultimate strength, and fatigue life of the joints. Consequently, in the quasi-static tests, a reduction in maximum load and total deformation before fracture is expected, while in the fatigue tests, premature crack initiation at the interface and a significant decrease in the number of cycles to failure are anticipated when compared with defect-free joints.

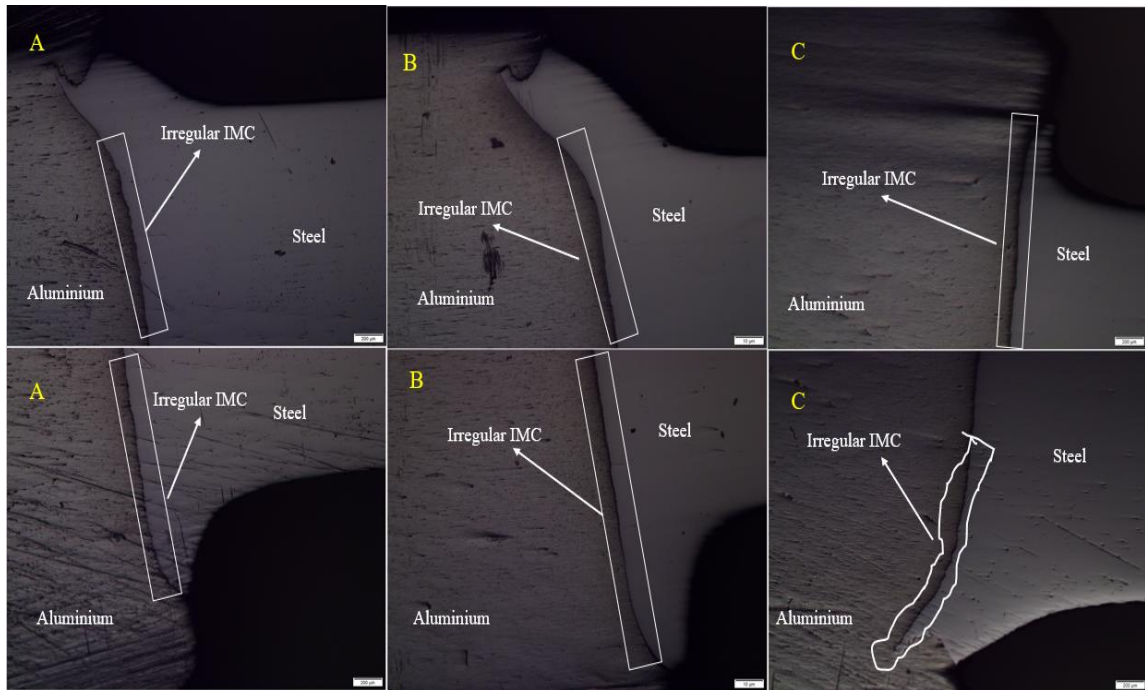


Figure 21: Microstructural characterization of interfacial defects in “without S-shape” joints (Samples A, B, and C)

In all samples (A, B, and C), the IMC layer appears continuous but with variable thickness and wavy contours, indicating uneven diffusion between aluminum and steel. The irregularity is less pronounced than in some regions of the “with S-shape” joints, yet it still reveals thermal instability and local variations in heat transfer during the welding process. The layer thickness is not homogeneous, some regions show localized thickening, while others are extremely thin suggesting heterogeneous plastic flow and heat input under tool action.

In the “with S-shape” joints, the intermetallic layer was thicker and more discontinuous, with areas showing no IMC, steel inclusions, and even full penetration voids, revealing a more complex thermo-mechanical behaviour. Conversely, in the “without S-shape” joints, the interface appears more linear and stable, and the IMC formation is more uniform and continuous, indicating a longer diffusion period and lower material turbulence. However, this apparent uniformity can be detrimental to mechanical performance: a continuous and thick IMC layer acts as a brittle barrier between aluminum and steel, reducing ductility and fatigue resistance, whereas the “S” geometry promotes better mechanical interlocking and greater energy absorption before fracture, despite having localized discontinuities.

3.4 - Tensile testing

Quasi-static tensile tests were performed to mechanically characterize welded joints manufactured with two different geometries: “with S-shape” and “without S-shape”. These tests allowed obtaining load–displacement curves for both types of joints, enabling direct comparison of results and correlation between the mechanical performance of the joint and the presence or absence of the "S" geometric profile.

To perform the tests, a universal testing machine from INSTRON® (Norwood, Massachusetts, USA), model 3367 showed in figure 22, was used, operating under controlled conditions of ambient temperature and humidity. The loading rate adopted was 1 mm/min, as recommended for quasi-static tests. The load was applied in the longitudinal direction of the test specimens, with the joint interface positioned frontally in relation to the testing machine. In addition, the tests were filmed using a macro mode camera, focusing on the joint interface region, to capture in detail the behavior during deformation and the failure mode of the specimens. The load–displacement curves were timed and synchronized with the recorded videos, ensuring a joint analysis between the global mechanical behavior and the local phenomena observed during the failure process. The recordings were conducted until the complete separation of the halves of the test specimens.

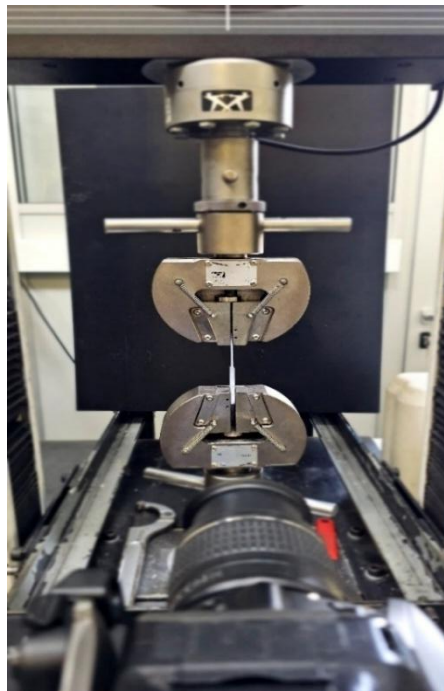


Figure 22: Tensile test setup

3.5 - Microhardness analysis

Hardness is defined as the capability of a metal to resist permanent deformation under an applied load. In materials that exhibit heterogeneity, fine microstructures, or multiple phases, conventional macro-hardness testing often produces large scatter in the results and cannot distinguish the contribution of individual phases. In such cases, micro-hardness testing is more suitable. This method involves pressing a small indenter, typically of the Vickers or Knoop type, into the material surface using relatively low forces. The

resulting impressions are extremely small and require optical microscopy for measurement. Microhardness testing allows the evaluation of specific microstructural constituents and is especially useful for characterizing sharp hardness gradients, for example those found in weld regions [59].

Hardness testing is a standard method for assessing the mechanical performance of FSW joints. Measuring hardness across the weld zone, heat-affected zone, and base material provides insight into microstructural modifications and their impact on mechanical behavior. Microhardness measurements, in particular, enables a more precise evaluation of local hardness variations, making it possible to identify how process parameters influence the weld microstructure [14]. Figure 23 shows the schematic representation of the microhardness lines measurements.

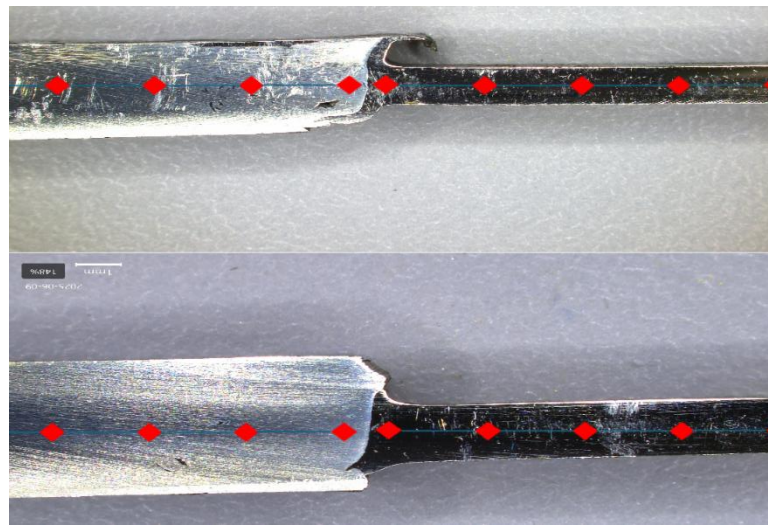


Figure 23: Schematic representation of the microhardness lines measurements

The figure 24 shows the control panel of the Vickers microhardness tester used to measure the hardness distribution across the weld nugget and interface regions of the FSW joints. The test was conducted under a load of 2.0 kgf (≈ 19.61 N) with a dwell time of 15 s, as displayed on the equipment screen. These parameters were selected to ensure adequate indentation depth while avoiding excessive plastic deformation in the heat-affected zones (HAZ) and the intermetallic compound (IMC) layer. This procedure ensured consistent and comparable results between the aluminum and steel sides, allowing for an accurate evaluation of the hardness profile along the joint.



Figure 24: Control panel of the Vickers microhardness tester showing the test parameters used.

3.6 - Fatigue test

After performing the quasi-static tensile tests, fatigue tests were conducted to evaluate the cyclic behavior and service life of the welded joints, considering the influence of the interface geometry ("S" and without "S") on mechanical performance. The fatigue tests were performed on an Instron 8801 servo-hydraulic machine (figure 25), equipped with a high-precision load cell and dynamic force control system.

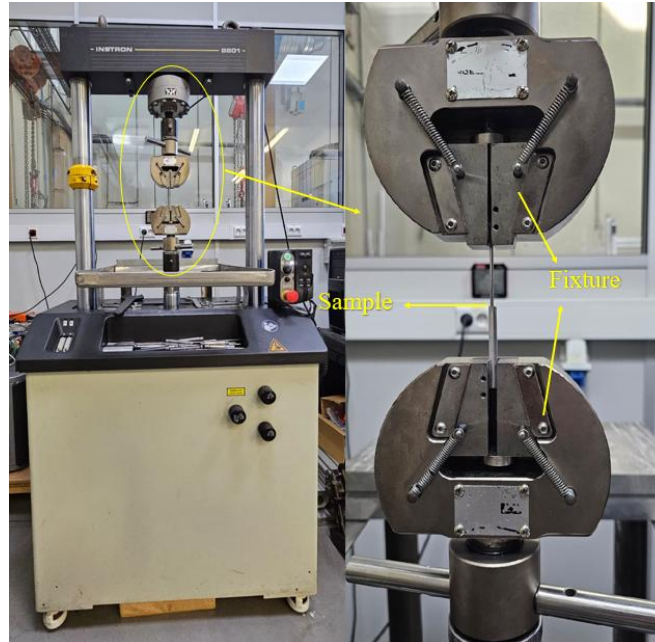


Figure 25: Experimental Setup for fatigue test using the INSTRON 8801 machine

To minimize bending and ensure a predominantly axial load state, the specimens were rigidly aligned along the load application axis using specially designed fixtures. The tests were performed under load control, with a stress ratio $R = 0.1$ (minimum stress equal to 10% of the maximum stress) and a sinusoidal frequency

of 10 Hz, in accordance with ASTM E466 – Standard Practice for Conducting Force-Controlled Constant-Amplitude Axial Fatigue Tests of Metallic Materials.

The applied load amplitude was defined based on 60% of the average maximum loads obtained in the quasi-static tests, to reproduce a realistic service stress regime without exceeding the local elastic limit of the joints. During the tests, axial displacements and the evolution of cyclic stiffness were monitored until complete failure or interruption due to deformation stabilization occurred, allowing the determination of the number of cycles to fracture (N_f).

3.7 - Experimental results

3.7.1 - Load vs. Displacement results

Tensile tests are essential to understand the mechanical behavior of joints under monotonic loading, allowing a correlation to be established between the tensile strength of these joints and the changes in their structural characteristics resulting from the geometry adopted. These tests provide valuable information on the global performance of the joints, as well as local details related to the failure process, especially in relation to the different geometric configurations.

In this section, the results of tensile tests performed on specimens with two different geometries will be presented and discussed: “with S-shape” and “without S-shape”. For each geometry, four specimens were tested for S-shape (with "S" profile) and three for Without S-shape, ensuring a robust and reliable analysis of the data obtained. The results will be supported by images and frames extracted from the videos recorded during the tests, in addition to photographs of the specimens after failure, which will provide additional insights into the failure mode and the distribution of damage at the joint interface.

Finally, a comparative summary of the tests will be carried out, aiming to establish a clear correlation between the different joint geometries and the impact of these configurations on the mechanical performance and degradation observed in the test specimens. This integrated approach will allow a systematic evaluation of the effects of geometry on the tensile strength and failure behavior of welded joints.

S-shape (“S” profile)

Initially, tests were performed on four joints with S-shape configuration, aiming to evaluate the mechanical behavior and the failure location. The results obtained showed consistent patterns between the different tests, as shown in figure 26. In Tests 1 and 3, it was observed that the tensile strength values were very close, with the rupture location occurring in the base material (steel). On the other hand, in Tests 2 and 4, the results also showed good agreement with each other, but the failure was detected in the region of the metallic composite interface and on the base material (aluminum), unlike the other two tests. The following are graphs and detailed images of each test, providing visual evidence of the specific failure locations. This

information is crucial to understand the differences in the mechanical performance of the joints under monotonic loading and to identify how the joint geometry and microstructural characteristics influence the failure mode.

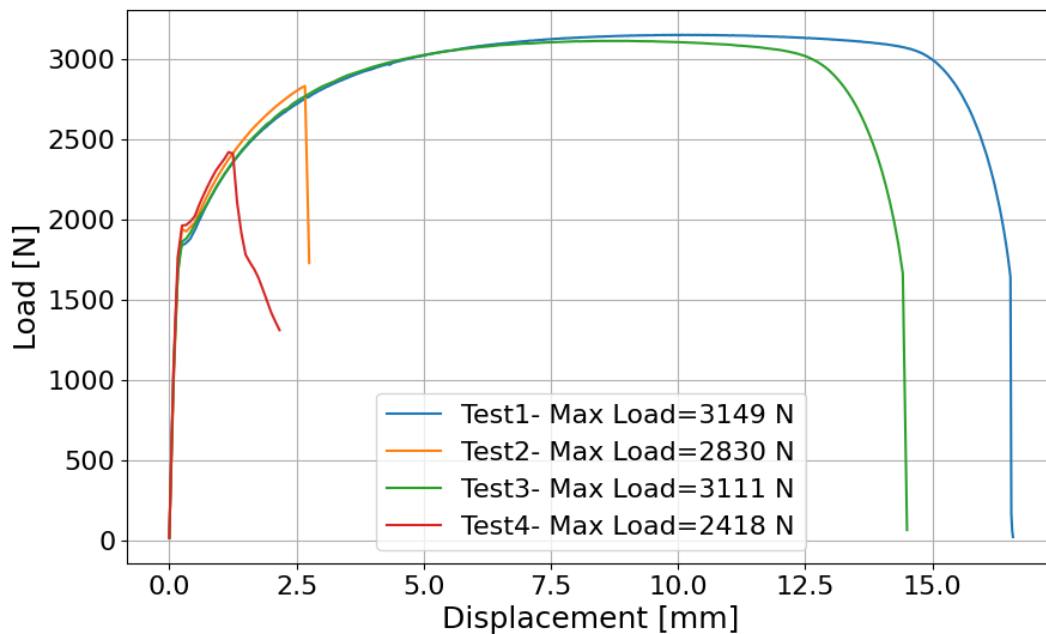


Figure 26: Load vs. Displacement curve of the “with S-shape” specimens

The graph in figure 25 shows the load–displacement curves obtained in the tensile tests performed on four welded joints with S-shape configuration, identified as Test 1 (blue), Test 2 (orange), Test 3 (green) and Test 4 (red), where each line represents a different sample subjected to the same type of loading. The maximum load values varied between 3149 N (Test 1) and 2418 N (Test 4), evidencing differences in mechanical performance probably associated with variations in weld quality, stress distribution or microstructural characteristics.

The tensile tests revealed initial elastic behavior followed by plastic response in the welded FSW joints, with greater ductility observed in Tests 1 and 3, whose failures occurred in the steel base material, indicating good joint performance and efficiency of the welding process. Tests 2 and 4 showed early ruptures at the IMC–aluminum interface and in the aluminum substrate, respectively, suggesting brittleness associated with the thickness and quality of the intermetallic compound, as well as possible defects in the base material or microstructural changes in the HAZ. The comparison between the results showed consistent patterns within each group (Tests 1/3 and 2/4), reinforcing the influence of factors related to welding parameters, interface quality and local material properties in defining the failure mode and overall strength of the joints.

These results highlight the critical influence of the microstructure, interface quality and substrate properties (St37 steel and AA6061-T6 aluminum alloy), on the mechanical performance of joints with S-shape geometry. It is clear that the thickness and continuity of the IMC, combined with the homogeneity of the base aluminum and the mechanical characteristics of the steel substrate, are determining factors in ensuring

a connection with high structural strength. Failure modes of S-shaped joints under quasi-static tensile testing are shown in figure 27.

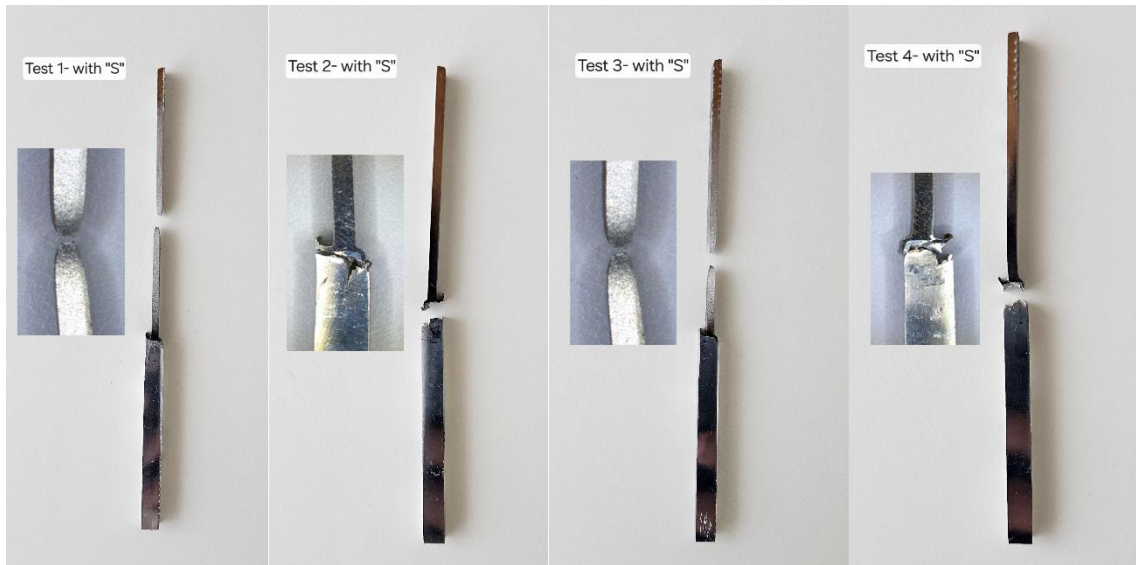


Figure 27: Failure modes of S-shaped joints under quasi-static tensile testing

Without S-shape

After performing the tests on the joints with “S” geometry, similar tests were conducted on the joints without the “S” profile, aiming to evaluate the impact of this geometric configuration on the mechanical behavior of the connections. Three tests were conducted under this condition, and the results showed a high level of consistency, both in terms of the maximum load achieved and the failure locations, which were consistently concentrated in the IMC region as shown in figure 28. In contrast to the results observed in the joints with “S” profile, where the failures occurred predominantly in the base materials (steel or aluminum), all the ruptures in the joints without the “S” profile occurred within the IMC zone, as can be seen in figure 29, evidencing a greater fragility of this region under monotonic loading when the geometry does not promote a more efficient redistribution of the stresses.

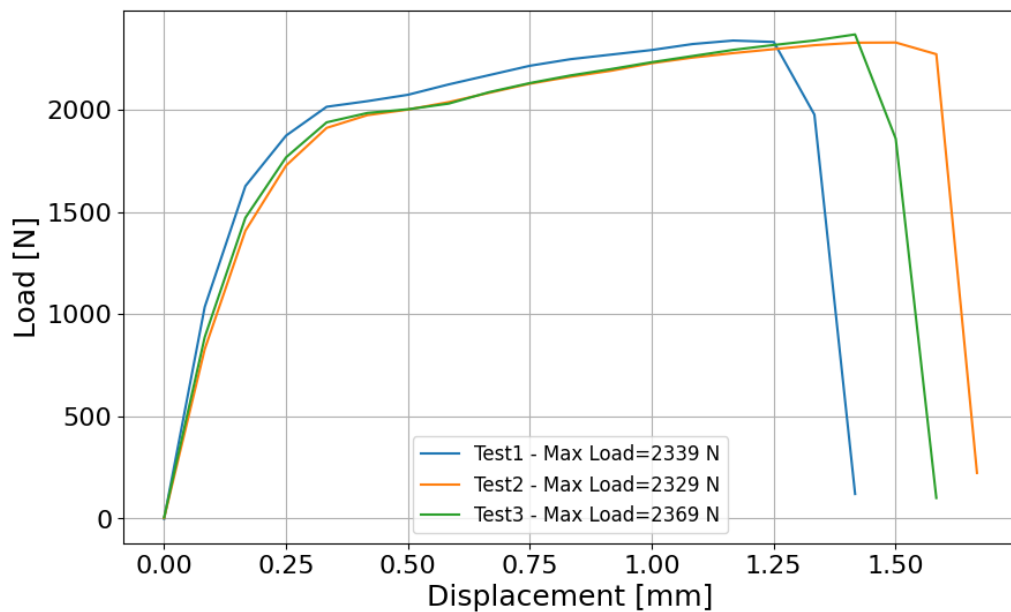


Figure 28: Load vs. Displacement curve of the “without S-shape” specimens

The graph in figure 28 shows the load versus displacement curves obtained in three tensile tests performed on FSW welded joints without "S" geometry. These curves reveal an initially elastic behavior, characterized by a linear relationship between load and displacement. After reaching the elastic limit, the curves enter the plastic region, indicating permanent deformation. The maximum loads recorded in the tests were close (2339 N, 2329 N and 2369 N), suggesting consistency in the manufacturing conditions and properties of the materials used. Failure occurred exclusively in the IMC zone in all tests, resulting in an abrupt and brittle fracture, as evidenced by the sharp decline of the curves after the stress peak.



Figure 29: Tensile test, failure location (IMC) in test 1, 2 and 3- without "S"

Comparison between S-shape and Without S-shape

The FSW welded joints with "S" profile initially showed elastic behavior, followed by a more extensive plastic region, exhibiting greater global ductility (total displacements greater than 10 mm) and a smooth transition from the elastic to the plastic regime, indicating good deformation capacity. The maximum loads varied between 2830 N and 3149 N, with consistent results between Tests 1 and 3, reflecting high tensile strength and adequate control of the welding process. Failure occurred predominantly in the base material (steel or aluminum), suggesting efficient stress redistribution and interface quality. On the other hand, the joints without "S" profile also started with elastic behavior, but presented a limited plastic region, significantly smaller total displacements before failure (less than 1.6 mm), and an abrupt transition to the plastic regime, evidencing interface fragility. The maximum loads were similar (2329 N, 2339 N, 2369 N), although lower than those of the joints with "S" profile, but the difference was more marked in ductility. All failures in the joints without "S" profile occurred exclusively in the IMC zone, indicating local brittleness related to the absence of the "S" geometry, which compromised the uniform distribution of stresses.

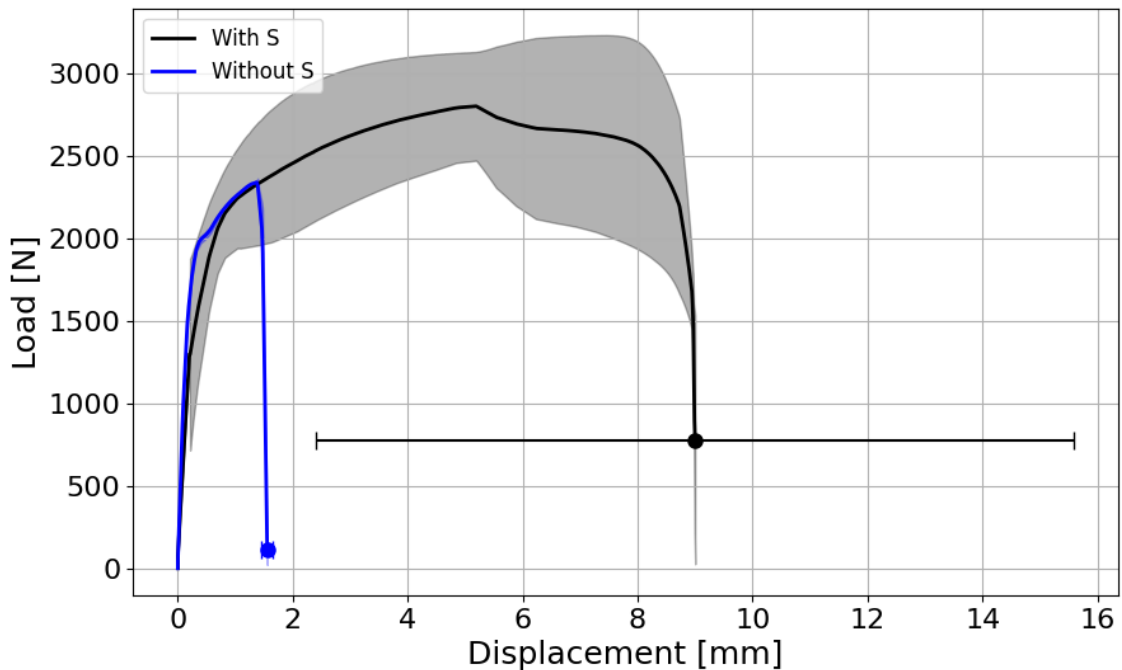


Figure 30: Comparison of Load vs. Displacement curve of the “with S-shape” specimens and of “without S-shape”

The graph presents a comparative analysis of the experimental results, including standard deviation, highlighting greater variability in the data of the joints with an “S” profile, which can be attributed to the intrinsic complexity of this geometry. Conversely, the joints without an “S” profile exhibited lower data dispersion, indicating a more uniform mechanical behavior, despite the brittleness observed in the IMC layer. In the quasi-static tensile tests, these without “S” joints showed premature interfacial fracture, characterized by lower total elongation and a more brittle fracture mode, since the continuous IMC layer restricts plastic deformation.

On the other hand, the joints with an “S” profile demonstrated superior global ductility and more effective stress redistribution, resulting in failures predominantly in the base material and larger displacements

before fracture. Their irregular interface and mixed zones helped to dissipate stresses and delay crack initiation, enhancing static performance. These results emphasize that joint geometry plays a decisive role in optimizing the mechanical response of dissimilar FSW joints, particularly in structural and automotive applications, where ductility and fatigue resistance are critical for ensuring reliability and long-term performance.

3.7.2 - Microhardness result

In this section, the results of the Vickers microhardness measurements are presented for each analysed sample. The hardness profiles were obtained along the midline of the cross-section of the welded joints, covering the entire interface region between the aluminum and steel substrates. The measured values were plotted in a Vickers Hardness (HV) versus Distance (mm) graph to illustrate the variation of hardness across the joint, as shown in Figures 31 and 32.

The negative distance values correspond to the steel side (St37), whereas the positive values represent the aluminum side (AA6061-T6) of the joint. The region around 0 mm indicates the IMC layer and the stir zone (SZ), where significant microstructural changes and hardness gradients are typically observed due to the thermos-mechanical effects of the FSW process.

This analysis provides insight into the microstructural transitions between the base materials, heat-affected zones, and the mixed zone, allowing correlation between hardness distribution and metallurgical phenomena such as plastic deformation, grain refinement, and intermetallic formation.

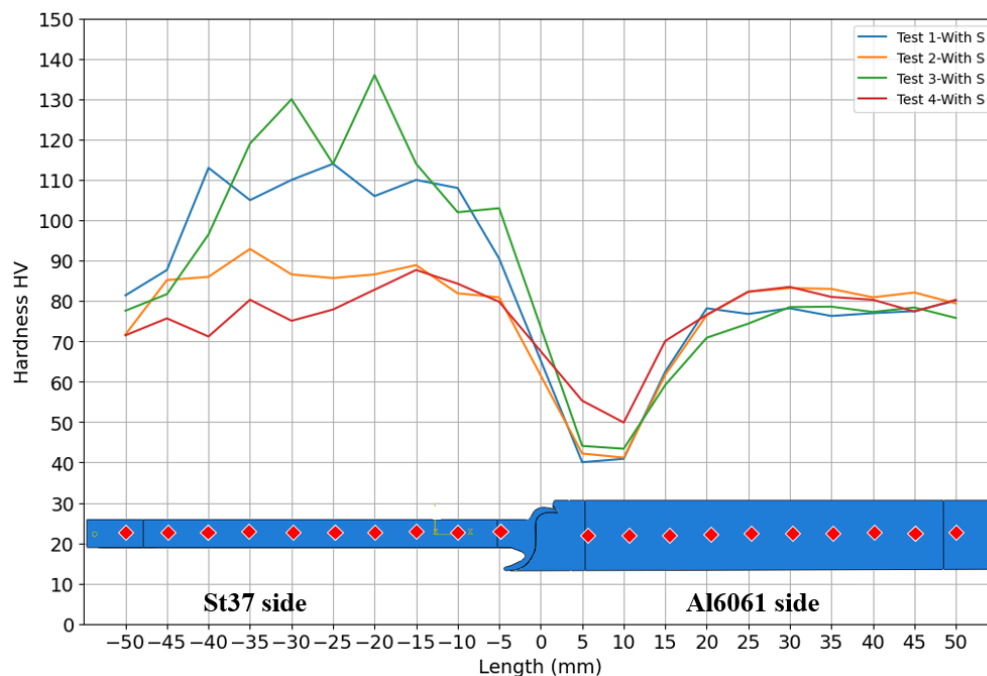


Figure 31: Vickers Microhardness profile across the interface for joints with “S” Geometry

The graph in figure 31 illustrates the Vickers microhardness profiles measured along the cross-sections of the joints with an “S” profile after the quasi-static tensile tests. The results reveal a pronounced hardness gradient between the aluminum and steel sides, with a sharp decrease of approximately 50% in hardness

values within the aluminum region near the Al–Fe IMC interface. This significant drop is primarily attributed to recrystallization and thermal softening phenomena occurring during the FSW process. The intense plastic deformation and elevated temperatures generated beneath the tool shoulder promote grain refinement and recovery in the thermo-mechanically affected zone (TMAZ), followed by partial recrystallization, resulting in a local reduction in hardness.

On the other hand, a significant increase in hardness was observed on the steel side, especially in samples 1 and 3, which is directly related to the strain hardening effect (work hardening) resulting from the severe plastic deformation that occurred during the quasi-static test, precisely in the regions where the material ruptured. This increased hardness results from the accumulation of dislocations and the increased density of crystalline defects in the steel microstructure, a phenomenon typical of areas subjected to high stress and strain gradients during loading to fracture.

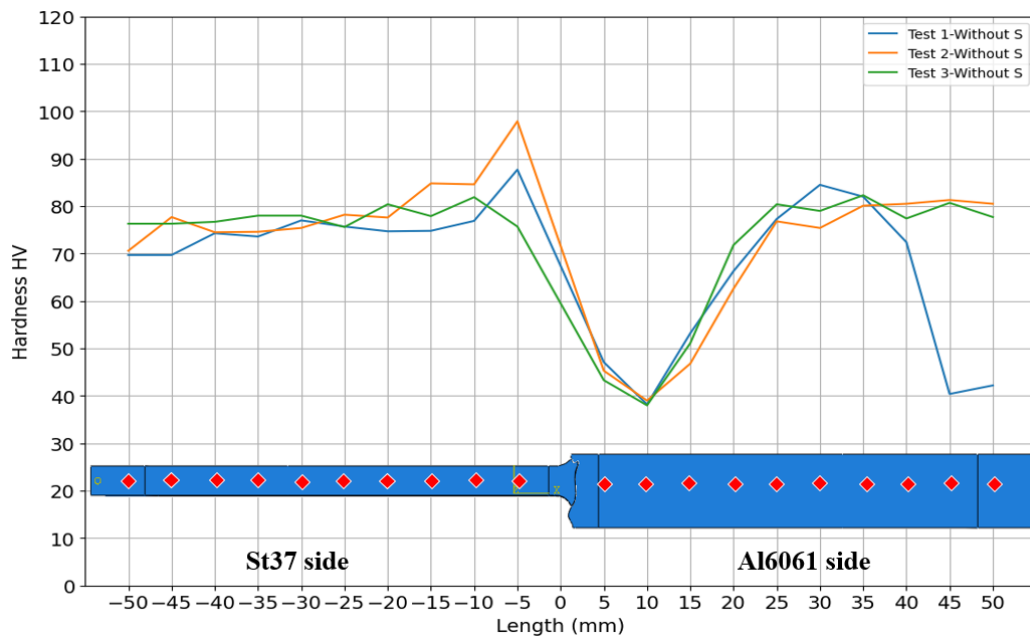


Figure 32: Vickers Microhardness profile across the interface for joints without "S" Geometry

For joints without an "S" geometry, shown in Figure 32, the behavior on the aluminum side is like that observed for joints with an "S" profile. The highest hardness values occur in the regions farthest from the heat-affected zone (HAZ), while there is a sharp reduction, approximately 50%, in the regions close to the interface. This decrease is associated with the thermal effects of the welding process, which promote recrystallization and grain growth, resulting in local softening of the aluminum.

On the steel side, a slight increase in hardness values is observed near the interface, attributed to localized plastic deformation. However, this increase is less pronounced than that observed in joints with an "S" geometry, since, in joints without an "S" geometry, failures occurred predominantly in the intermetallic layer (IMC), limiting the extent of plastic deformation in the steel to areas very close to the interface.

3.7.3 - Fatigue results

As previously mentioned regarding the parameters used for the fatigue tests, Table 6 summarizes the loading conditions applied to both joint geometries, with and without the “S” profile. The same testing criteria were maintained for both configurations to ensure a consistent comparison of their fatigue performance.

Table 6: Parameters used for fatigue test

Parameters	With “S” shape	Without “S”
Static Load	2877 [N]	2300 [N]
Percentage of static load	60%	60%
Ratio	0.1	0.1
Maximum load	1726.2 [N]	1380 [N]
Minimum load	172.62 [N]	138 [N]
Average (impute machine)	949.41[N]	759[N]
Amplitude	1553.58[N]	1242[N]
$\frac{1}{2}$ Amplitude (impute machine)	776.79[N]	621[N]

These parameters were defined to produce a controlled cyclic loading condition capable of inducing progressive damage in the interfacial region, allowing the evaluation of the fatigue life and failure mechanisms associated with each joint geometry. The experimental campaign aimed to determine how the “S”-profiled interface influences the stress distribution and crack initiation mechanisms at the aluminum–steel interface, compared to the linear configuration. In addition, the analysis included the influence of interfacial microstructural defects, such as irregular IMC layers, inclusions, and voids, on the mechanical response. The following images and graph summarize the main results obtained, highlighting the fracture locations, failure mechanisms, and fatigue life behavior for both joint geometries.

According to the results shown in Figure 33, the “with S-shape” joints exhibited a larger scatter in the results, with fatigue lives ranging from 2×10^3 to 10^6 cycles, a behavior directly linked to the presence of defects in the aluminum and at the interface, such as steel inclusions, irregularities, and full penetration voids. Some specimens experienced premature failure in the aluminum substrate, caused by crack initiation at these defects, while others—free from critical discontinuities, achieved infinite life ($N > 10^6$ cycles), demonstrating the potential of the “S” geometry when properly consolidated.

In contrast, the joints “without S-shape” geometry displayed lower variability and a more uniform and predictable mechanical behavior. Failures occurred mainly within the IMC layer, resulting in brittle interfacial fractures, although two specimens also achieved lives beyond 10^6 cycles, indicating that a thin and homogeneous IMC layer can provide satisfactory fatigue resistance.

Overall, the results show that the “S” geometry enhances stress redistribution and global ductility, but the fatigue performance remains strongly dependent on microstructural integrity. When the interface and substrates are free from defects, the “S”-profiled joints outperform the without “S” ones; however, in the

presence of discontinuities, premature failure occurs in the aluminum, significantly reducing the fatigue life.

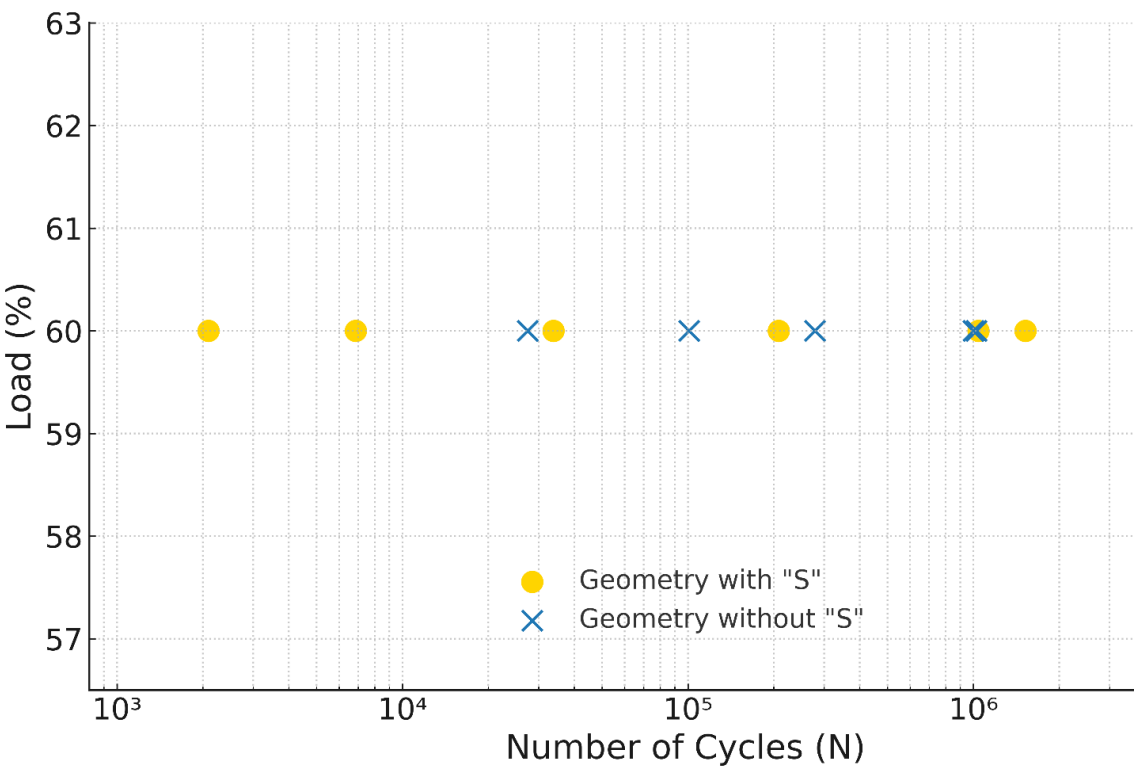


Figure 33: Comparison of fatigue life between “with S-shape” and “without S-shape” profiled joints at 60% Load level

The failure modes resulting from the fatigue tests are shown in Figure 34 for the “without S-shape” joints and in Figure 35 for the “with S-shape” joints.

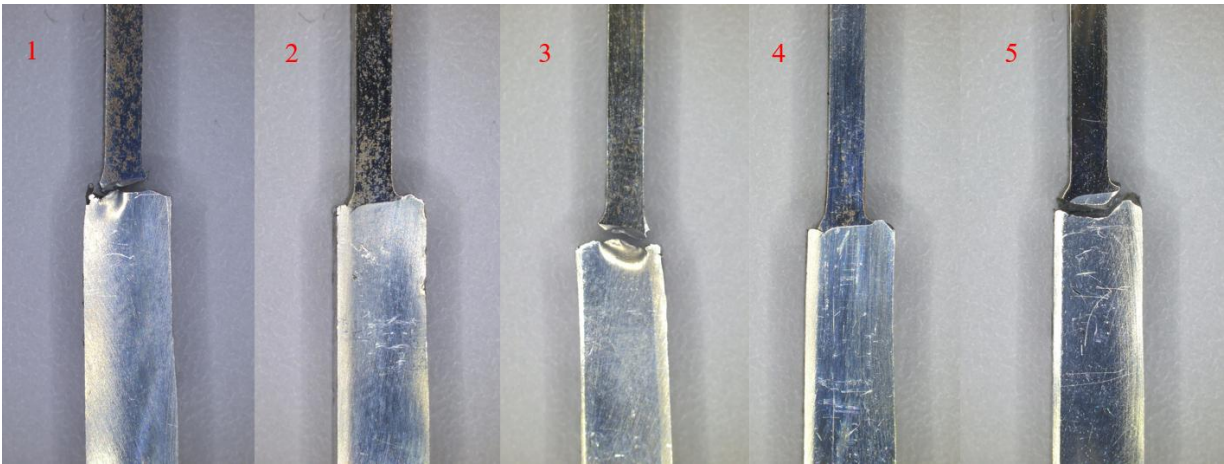


Figure 34: Failure modes observed in “without “S” shape” profiled joints after fatigue testing

The Figure 34 illustrates the fatigue behavior of the joints without the “S” geometry during axial cyclic loading tests. Each photograph corresponds to one of the tested specimens, showing the different failure modes and mechanical responses observed throughout the fatigue cycles.

In the specimens that failed, fracture occurred predominantly within the IMC layer, characterizing a brittle interfacial failure. Crack initiation took place at the aluminum–steel interface, where the IMC acted as a stress concentration zone. Although slight plastic deformation was observed in both the aluminum and the steel, it was limited to the regions adjacent to the IMC, confirming that this layer being hard and brittle, significantly restricted the overall deformability of the joint. This behavior indicates that in without “S” joints, the dominant failure mechanism is interfacial, governed by the fragility of the continuous IMC layer. In contrast, two specimens did not fail within the test duration, achieving infinite life ($N > 10^6$ cycles). This result suggests that when the intermetallic layer is thin, homogeneous, and free of discontinuities, the joint can withstand cyclic loading without significant crack propagation. Therefore, the fatigue performance of the joints without the “S” profile is highly dependent on the integrity and thickness of the IMC layer: even small microstructural variations in this region can lead to contrasting behaviors, from premature interfacial fracture to virtually unlimited fatigue resistance.



Figure 35: Failure modes observed in “with S-shape” profiled joints after fatigue testing

The Figure 35 illustrates the fatigue behavior of the “S”-profiled joints after cyclic loading tests, highlighting the different failure modes and mechanical responses observed in the tested specimens. Each photograph represents a distinct sample, allowing for the analysis of the influence of microstructural characteristics and local defects on the fatigue life of these dissimilar AA6061-T6–St37 joints.

In the specimens that failed, fracture occurred predominantly on the aluminum side, rather than at the interface, indicating that the failure mechanism was governed by defects within the aluminum substrate, such as steel inclusions, interfacial irregularities, and full penetration voids. These defects acted as preferential crack initiation sites, which propagated rapidly under cyclic loading, leading to premature failure. The regions close to the interface exhibited considerable plastic deformation, suggesting stress redistribution and higher overall ductility compared to the joints without the “S” geometry.

In the first specimen on the right, despite the presence of such defects, the fatigue life reached approximately 200,000 cycles, demonstrating intermediate performance and indicating that crack propagation was delayed by the higher plastic deformability of the aluminum. The second and the sixth specimen, however, exhibited infinite life ($N > 10^6$ cycles), indicating the absence of critical defects and excellent metallurgical integrity of both the interface and the substrate. In contrast, the third, fourth, and fifth specimens showed failure modes similar to the first, with localized plastic deformation in the aluminum and crack initiation associated with base material defects, but with significantly shorter fatigue lives, not exceeding 30,000 cycles, which is well below the expected performance.

Overall, the results confirm that the fatigue behavior of the “S”-profiled joints is strongly influenced by the microstructural quality of the aluminum and the interface. When free from critical discontinuities, these joints exhibit excellent durability and fatigue resistance; however, the presence of inclusions, irregularities, and voids severely reduces local strength and accelerates failure, thus limiting the service life under cyclic loading.

Chapter 4

Numerical model

4.1 - Introduction

Numerical simulation has proven to be a fundamental tool in understanding and predicting the mechanical behavior of welded joints, especially in advanced processes such as FSW. This study is developed from an experimental analysis presented in the previous chapter, which evaluates the tensile behavior of dissimilar joints between AA6061-T6 and St37, with different interface geometries, with and without "S" profile. The main objective is to develop and validate a three-dimensional numerical model capable of simulating the fracture behavior of these joints under monotonic loading, highlighting the influence of the interface geometry and the thickness of the IMC layer on the global structural response.

Based on the experimental results, where the IMC zone is often shown to be the initial point of failure, the model focuses on the detailed representation of this region. To this end, it adopts a cohesive contact approach governed by a bilinear tensile-separation law, suitable for brittle or semi-ductile interfaces, allowing for consistent simulation of the initiation and propagation of damage. This technique is justified by the geometric complexity of the interface and the need to avoid problems associated with the mesh, particularly in areas of high stress concentration.

Considering that, in the quasistatic tests, the failures in test 1 and 3 occurred in the steel substrate, it is concluded that the fracture in St37, and not at the interface with the intermetallic compounds (IMC) indicates that the FSW-welded connection zone presented superior structural integrity to the base material itself. Thus, the St37 steel proved to be the weakest link in the joint.

Based on this observation, it was initially decided to perform a numerical simulation considering only the properties of the base materials (St37 and AA6061-T6), explicitly disregarding the properties of the intermetallic layer. To this end, a simplified approach was adopted, using a generic static step, with the aim of verifying whether the finite element analysis would reproduce the same fracture behavior observed experimentally.

Subsequently, to increase the representativeness of the model and investigate the effects of the intermetallic layer on the location of the failure, the IMC characterization will be incorporated into the simulation. The numerical model was implemented in Abaqus/CAE – Explicit, adopting a three-dimensional dynamic explicit formulation. The total simulation time was defined as 1 second, which represents the duration of the quasi-static loading stage. The automatic incrementation control was used, allowing Abaqus to determine the stable time increment. To ensure numerical stability and reduce computation time without compromising accuracy, a semi-automatic mass scaling procedure was applied. The mass scaling was defined to achieve a target time increment of 1×10^{-5} s, applied at the beginning of the step and uniformly over the entire model. This approach adjusts the mass of the smallest elements only when necessary to meet the stability condition, thus avoiding unrealistic inertial effects during the analysis. The time scaling factor was maintained at 1.0, ensuring that the analysis proceeds in real physical time (without time acceleration). This configuration guarantees an optimal balance between numerical stability, simulation accuracy, and computational efficiency. Geometric nonlinearities resulting from large deformations and displacements were also considered, in order to promote a more realistic approximation to the physical behavior of the joint.

The properties attributed to the IMC layer will be calibrated based on data from the scientific literature and adjusted to the specific conditions of the FSW welding between AA6061-T6 and St37. This characterization aims to ensure the applicability of the model in real scenarios of structural design and evaluation. The integration between numerical modeling and experimental results constitutes an essential step to understand the impact of interface geometry and IMC quality on the mechanical performance of dissimilar joints, contributing to the refinement of design criteria and the optimization of welding parameters.

4.2 - Definition and Configuration of the Numerical Model

The methodology adopted in this work is based on the integration of previously performed experimental tests and three-dimensional numerical simulations conducted in the commercial software Abaqus/CAE – Explicit, widely used in the analysis of nonlinear phenomena, such as large deformations, contact and damage propagation. The approach followed involved the following main steps:

4.2.1 - Definition of the geometric model

The numerical models were developed based on the actual dimensions of the specimens used in the tensile tests, including the interface geometries with and without "S" profile. To ensure greater accuracy in the simulation results, the critical measurements of the region of interest were obtained with the aid of an EMSPIRA 3 LEICA digital magnifying glass, with 100% magnification, allowing the capture of geometric details with high resolution. This approach ensured a faithful representation of the real physical characteristics of the interface between the metal substrates, especially the exact shape of the joint. The methodology for acquiring and processing the dimensions was based on the image shown in Figure 36, used as a direct reference for the construction of the geometric models in the simulation software.

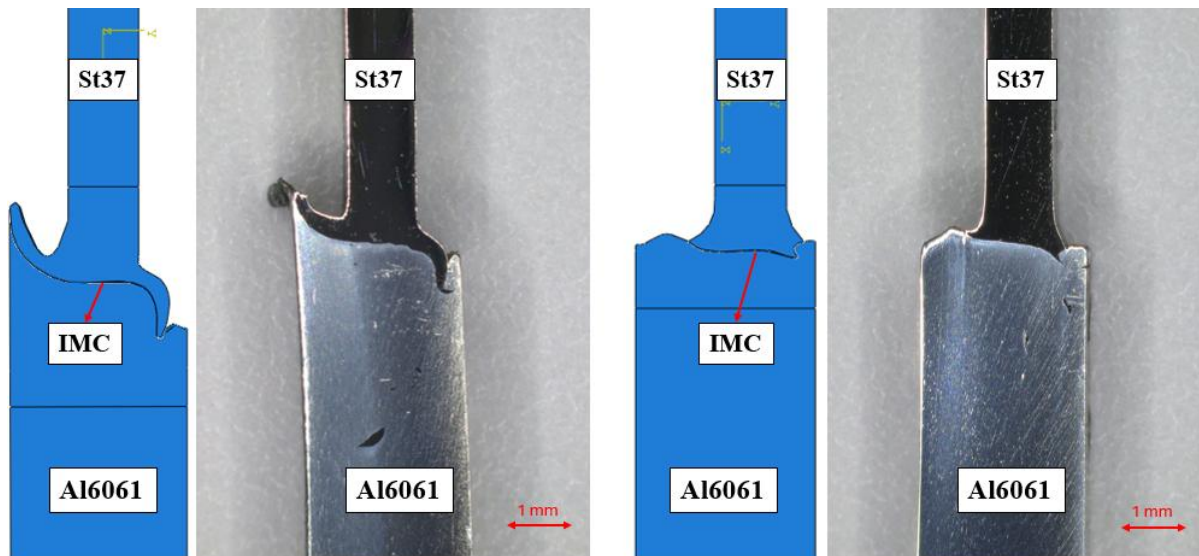


Figure 36: Joint geometry from EMSPIRA 3 LEICA (100% magnification, 1 mm length) and corresponding Abaqus/Explicit model

4.2.2 - Modeling of material properties

It is important to highlight that the quantitative analysis of the numerical results obtained is not fully feasible in the present study, due to the unavailability of certain specific mechanical properties of the IMC, such as stiffness and cohesive strength. These properties were not subject to experimental characterization in this work, therefore, values reported in the pertinent scientific literature were adopted, whenever possible. Despite this limitation, the focus of the discussion is on the global behavior of the joint under monotonic loading, with emphasis on the qualitative comparison between the failure modes observed experimentally and those simulated numerically. As for the metallic substrates, the elastic properties and density were assigned based on the technical specifications described in Table 7.

Table 7: Basic material properties input in numerical model for the substrates.

Material	Young's modulus [GPa]	Poisson's ratio	Mass density [kg/m ³]
St37	207	0.28	7850
AA6061-T6	69	0.33	2700

The data presented in Table 8 represent the input parameters used for the cohesive contact simulation. These values were determined iteratively through multiple simulations until a good agreement with the experimental results was achieved.

Table 8: Materials properties inputs for IMC

Shape	Fracture energy G_c (N/mm)	Cohesive strength of T_{ul} (MPa)	stiffness K (N/mm ³)
With “S”	0.123	600	74E6
Without “S”	0.123	220	49E6

4.2.3 - Mesh definition and boundary conditions

The domain was discretized using three-dimensional solid finite elements of the C3D4 type, which are particularly suitable for analyses involving contact and failure zones, due to their ability to accurately represent complex stress and strain states. To ensure a balance between computational accuracy and simulation time, a mesh convergence analysis was performed, in which the size of the elements was iteratively adjusted until numerically stable results were obtained.

To define the boundary conditions, two constraints were applied in the initial step, which were propagated to the subsequent steps of the simulation. One of these conditions consisted of the embedding applied to the lateral base of the aluminum substrate, while the other corresponded to the application of a controlled displacement of 4 mm along the longitudinal axis, as illustrated in Figure 37 and 38.

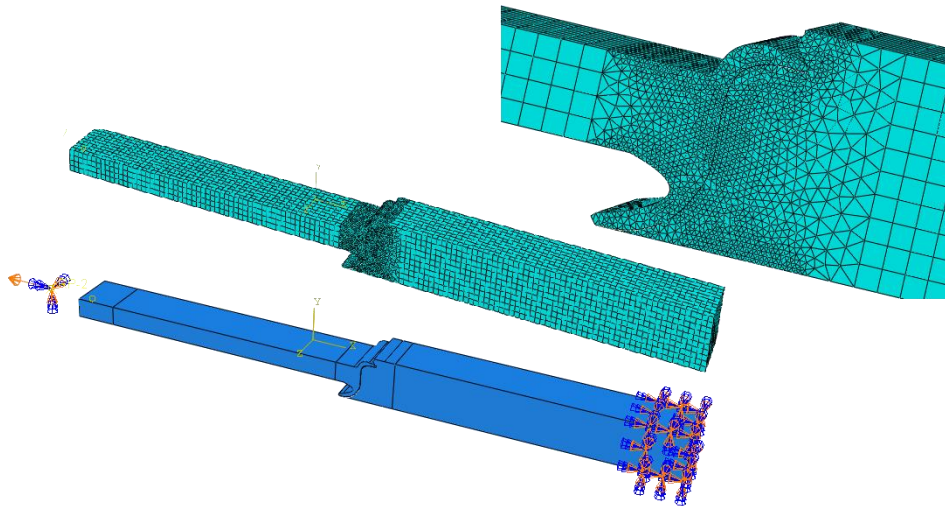


Figure 37: Model boundary conditions for “with S-shape”

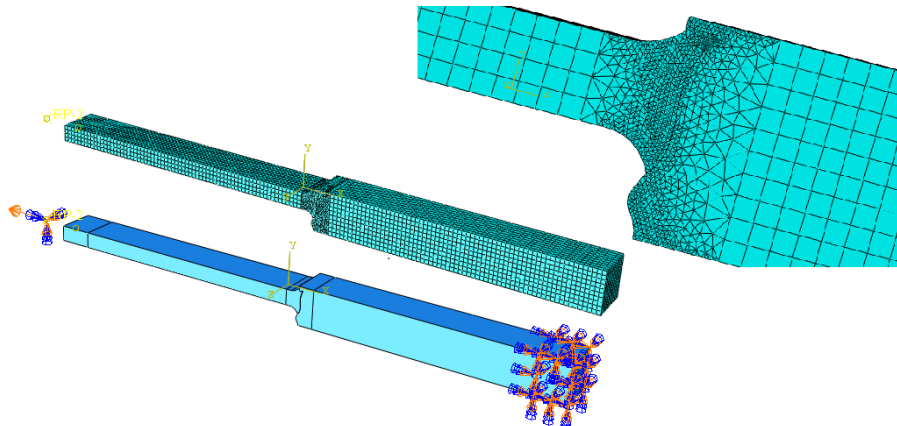


Figure 38: Model boundary conditions for “without S-shape”

The mesh was strategically refined in different regions of the model, with the aim of adequately capturing the expected stress gradients. For this purpose, each substrate (AA6061-T6 and St37) was subdivided into two distinct partitions. A variable mesh strategy was employed, resulting in elements with an average size of 0.5 mm in the less critical areas of the substrates, which are in the subtract as C3DR8 element type. In the critical region of the interface between the materials, where the IMC layer occurs, free tetrahedral elements of the C3D4 type were used, with a reduced size of approximately 0.1 mm, allowing a detailed resolution of the local stresses and the onset of damage propagation.

4.2.4 - Results

The following results correspond to the quasi-static simulation, in which only the elastic-plastic properties of the constituent materials AA6061-T6 and St37 were considered, while the influence of the IMC layer was deliberately neglected. In this analysis, the connection between the two materials was modelled using a “Tie” constraint, which enforces full continuity of displacements and stresses across the contact interface. The use of this constraint completely removes the effect of the intermetallic layer, even if it is included in the model, allowing the evaluation of the structural behaviour purely associated with the intrinsic mechanical properties of the base materials. The stress distribution obtained from the numerical simulation is presented in Figure 39, showing the von Mises stress in MPa, contours along the welded joint under quasi-static loading conditions.

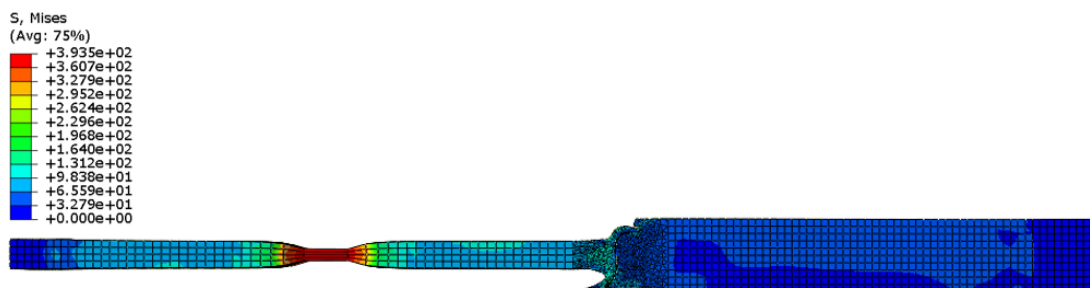


Figure 39: Numerical Simulation of stress distribution

This analysis confirms that the numerical model is properly calibrated for subsequent simulations involving the IMC interface. The predicted failure location in the current quasi-static simulation is consistent with the experimental observations, where the fracture initiated and propagated within the steel substrate, indicating that the model accurately captures the global mechanical response of the joint. The correlation between the experimental and numerical results is presented in Figure 40, showing that both the simulation and the quasi-static tensile test exhibit fracture initiation in the steel substrate, confirming the model's ability to reproduce the actual failure behaviour of the join

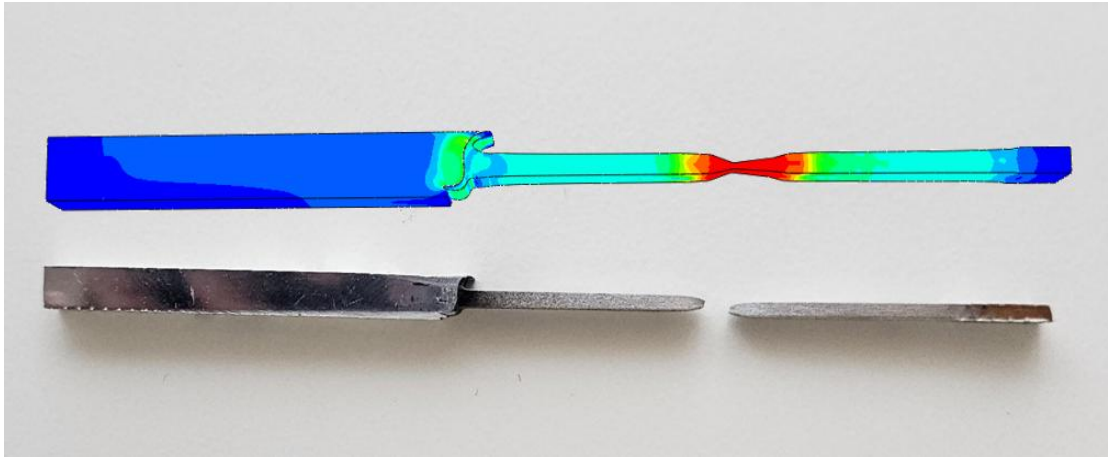


Figure 40: Failure location in quasi static test and the numerical model

To validate the numerical model, the Load–Displacement curve obtained from the simulation was compared with the corresponding results from the quasi-static experimental tests. This comparison aims to confirm the correlation between the simulated and experimental responses, demonstrating that the numerical model reproduces the global mechanical behaviour observed experimentally, as illustrated in the figure 41.

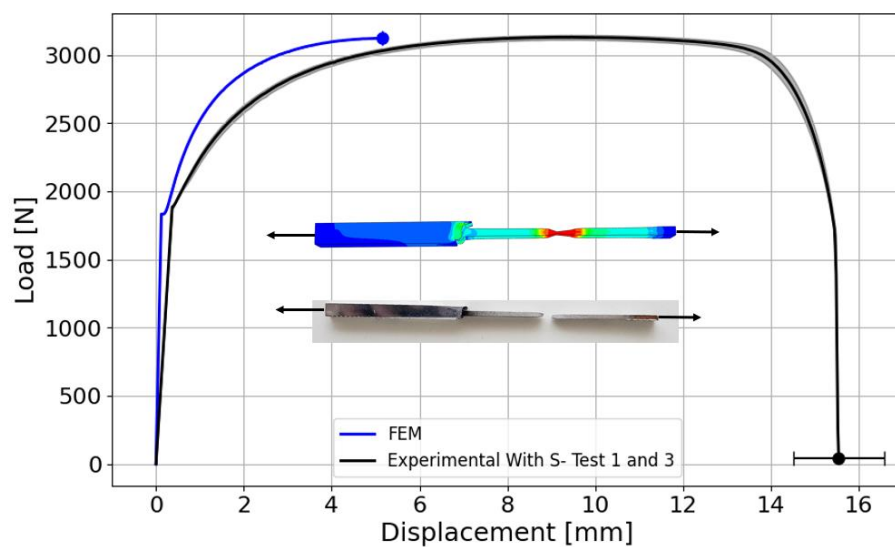


Figure 41: Comparison between experimental and numerical load–displacement curves

The graph shows good agreement between FEM and experimental (Test 1 and Test 3) results, with similar behaviour and very close maximum loads, confirming that the model is properly calibrated to reproduce the joint's mechanical response.

Following these results, the numerical model was further refined by introducing a cohesive surface at the aluminum–steel interface, thus accounting for the presence and mechanical contribution of the IMC layer. This improvement provides a more realistic representation of the interfacial behaviour and allows the analysis of damage initiation and propagation within the joint. The cohesive surface model was implemented to capture the onset and evolution of interfacial failure between aluminum and steel. Figure 42 presents the evolution of the cohesive damage variable (CSMAXSCRT) for the joint with the “S” profile, illustrating the progressive degradation and eventual separation along the interface.

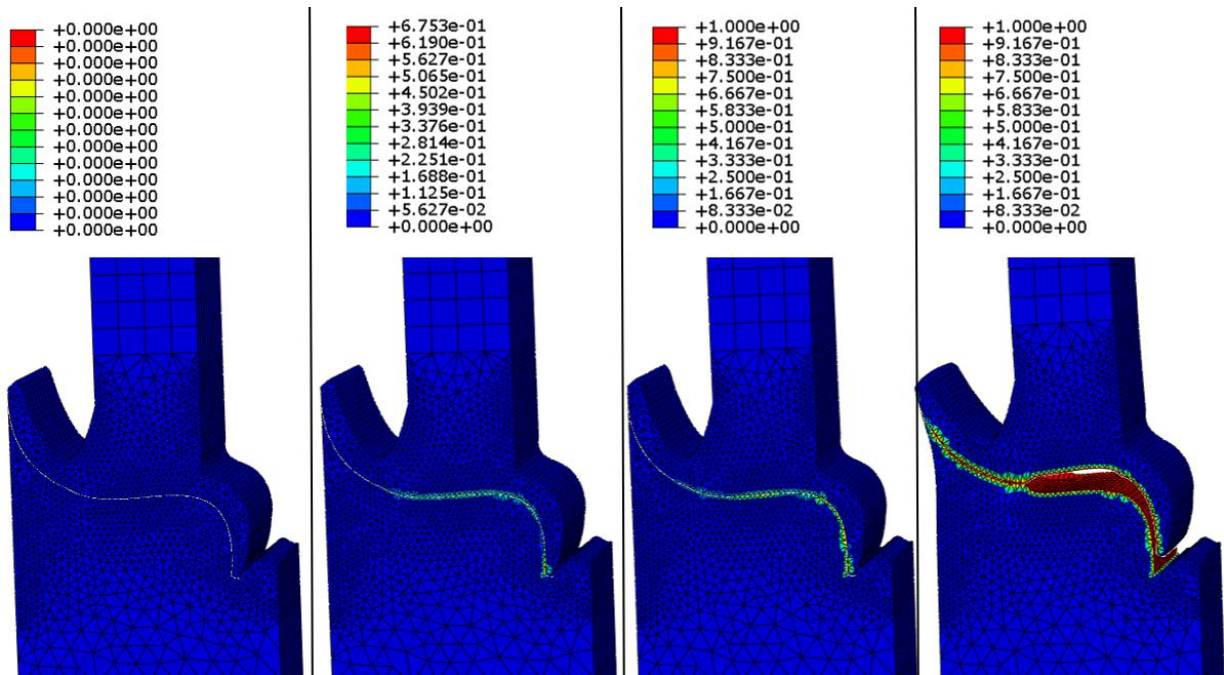


Figure 42: Cohesive surface damage initiation (CSMAXSCRT) results for joint with "S" shape

Figure 42 illustrates the evolution of the CSMAXSCRT field throughout the loading increments, showing the progressive development of shear damage along the AA6061-T6–St37 cohesive interface. The variable CSMAXSCRT represents the state of damage initiation, where a value of 0 corresponds to an intact interface (no damage), and 1 indicates complete failure of the cohesive surface. At the early stages of loading, shear damage initiates locally in the central region of the interface and subsequently propagates toward the areas of higher curvature, where stress concentration is more pronounced. As the load increases, the damaged zone progressively extends along the interface until it reaches the critical failure threshold, represented by the red regions in the contour plot. This evolution clearly demonstrates the nucleation and propagation of the interfacial crack governed by the cohesive shear failure criterion, confirming the model's ability to accurately reproduce the delamination process associated with the IMC layer in dissimilar joints.

Figure 43 compares the numerical (FEM) and experimental (Test 2 – with S-shape) load–displacement responses. The numerical model reproduces the overall behaviour observed experimentally, showing an initial linear elastic stage followed by plastic deformation and progressive interfacial damage. The predicted maximum load and the displacement at failure are in good agreement with the experimental results, confirming that the cohesive parameters and boundary conditions were properly calibrated. The contour plot and the experimental fracture image inserted in the graph illustrate that the failure initiates at the aluminum–steel interface and propagates along the S-shaped region, consistent with both the numerical prediction and the physical test. This agreement validates the model’s capability to capture the global mechanical response and the failure mechanism of the dissimilar joint.

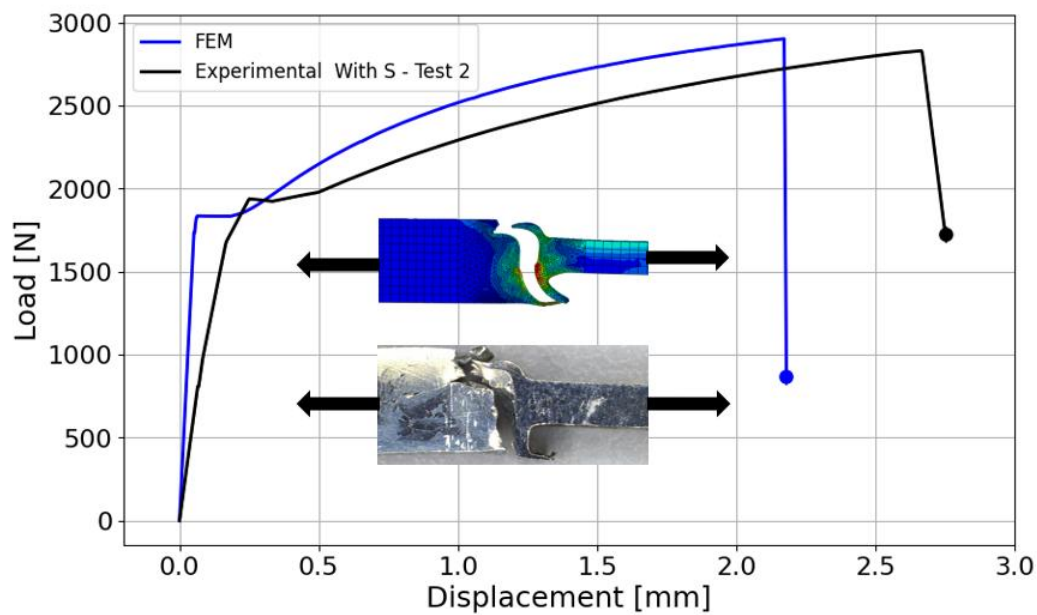


Figure 43: Comparison between numerical (FEM) and experimental (Test 2) results

The graph shows good agreement between the numerical (FEM) and experimental (Test 2) results, as this specimen exhibited failure within the IMC layer. The curves display an elastic-plastic behaviour followed by a softening stage associated with cohesive failure at the interface. The maximum load predicted by the model (2902 N) is close to the experimental value, validating the cohesive parameters and fracture energy adopted to represent the mechanical behaviour of the IMC layer.

Figure 44 shows the evolution of the CSMAXSCRT field for the joint “without the S-shape” profile, illustrating the progressive development of interfacial shear damage. The cohesive surface variable ranges from 0 (undamaged) to 1 (complete failure), representing the initiation and propagation of delamination along the aluminum–steel interface.

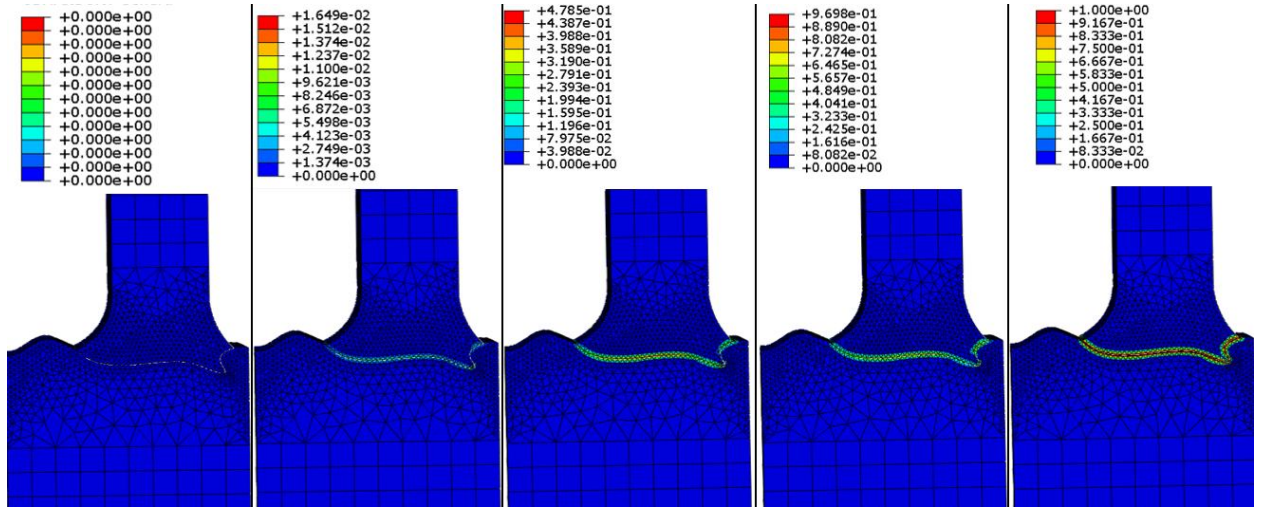


Figure 44: Cohesive surface damage initiation (CSMAXSCRT) results for joint without "S" shape

The evolution of the CSMAXSCRT (Cohesive Surface Maximum Shear Stress Criterion) throughout the loading process for the joint without S-shape geometry reveals the progressive stages of cohesive damage initiation along the Al–Fe interface. At the early loading steps, damage nucleates locally in areas of elevated shear stress concentration, particularly near the edges of the IMC layer. With increasing load, a gradual propagation of the damage field occurs along the interface until the critical threshold (CSMAXSCRT = 1.0) is reached, marking the onset of delamination. The results demonstrate that the failure mode is mainly interfacial, with negligible plastic deformation in the substrates, confirming that the dominant damage mechanism arises from the cohesive degradation of the Al–Fe bond.

Figure 45 below illustrates the evolution of the CSDMG field, which represents the cohesive damage variable ranging from 0 (no damage) to 1 (complete failure), for the joint “without S-shape” profile.

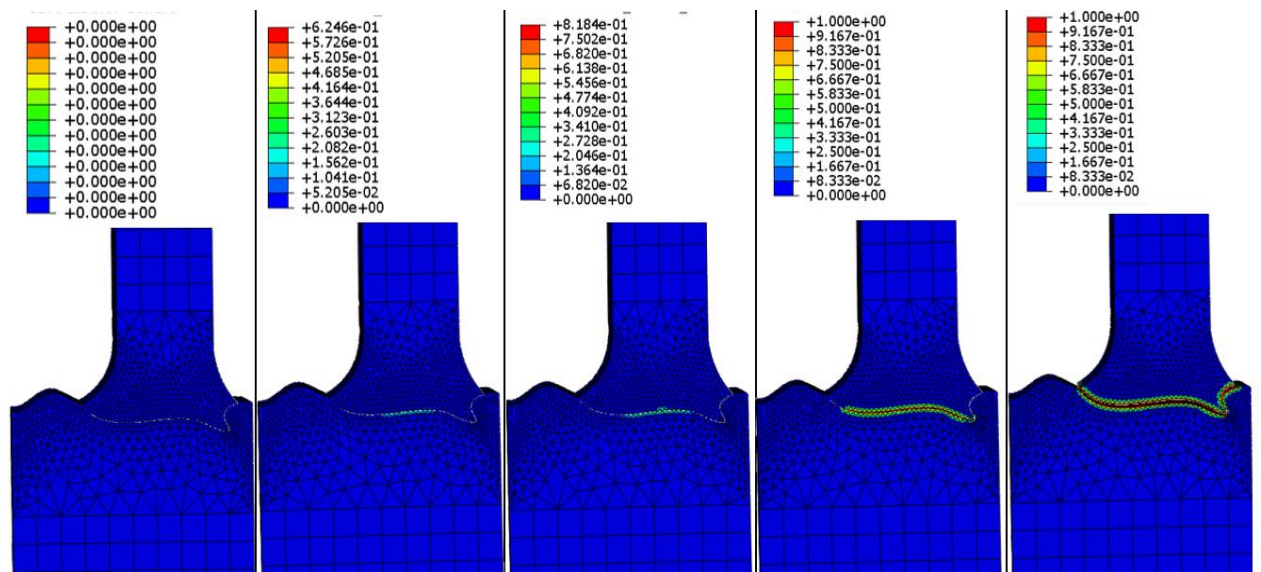


Figure 45: Evolution of the CSDMG (Cohesive Damage Variable) in without "S" shape

The figure illustrates the evolution of the CSDMG (Cohesive Damage Variable) during loading for the joint without S-shaped geometry, showing the progressive development of cohesive damage and failure along the Al–Fe interface. In the initial stages, damage nucleates at the central region of the interface, where the highest shear and tensile stresses are concentrated. As loading increases, the damage propagates laterally until reaching values close to $\text{CSDMG} = 1$, indicating the complete rupture of the IMC layer. A slight plastic deformation is also observed in the substrates adjacent to the IMC, particularly in regions close to the interface, caused by the localized stress transfer during delamination. This behavior confirms that the fracture is predominantly cohesive, with localized interaction between the intermetallic layer and the substrates, validating the calibrated fracture energy and interfacial strength parameters adopted in the numerical model.

The comparison between the numerical (FEM) and experimental results for the joint “without S-shape” profile is shown in Figure 46.

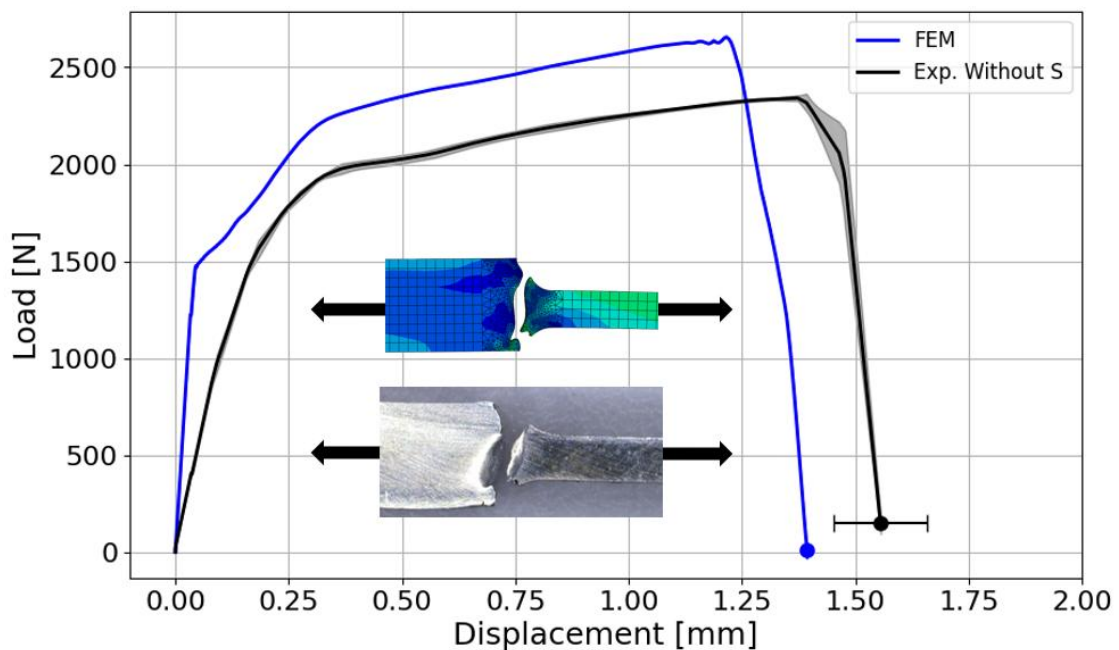


Figure 46: Comparison between numerical (FEM) and experimental without "S" results

The graph compares the numerical results obtained from the finite element model (FEM) with the experimental data for the joints without S-shaped geometry, showing an overall good correlation between both approaches. The numerical model accurately reproduces the elastic-plastic response observed experimentally, capturing the stiffness evolution and the failure point with reasonable precision. The FEM predicts a slightly higher maximum load (~ 2600 N) and a lower displacement at failure (~ 1.25 mm) compared to the experimental average (~ 2300 N and ~ 1.5 mm, respectively), indicating a slight overestimation of structural stiffness. This deviation may result from idealized assumptions regarding the mechanical properties of the IMC layer and the applied boundary conditions. The abrupt load drop after the peak corresponds to the cohesive failure of the Al–Fe interface, confirming that the selected cohesive parameters and fracture energy values adequately represent the interfacial fracture behaviour observed in the experiments.

Chapter 5

Conclusions and future work

This work presents an integrated experimental and numerical approach to studying the mechanical and fatigue behavior of dissimilar AA6061-T6 with St37 joints produced by Friction Stir Welding (FSW), with a special focus on the influence of interface geometry. The comparison between joints with and without an S-shaped profile allowed us to understand the relationship between interface morphology, intermetallic layer formation, and overall structural integrity.

Quasi-static tests showed that joints with an S-shaped profile exhibited greater ductility and stress redistribution, failing preferentially in the base materials, while joints without an S-shaped profile exhibited premature ruptures in the IMC layer, revealing their brittle nature and sensitivity to monotonic loading. Fatigue tests confirmed the importance of microstructural quality and the absence of local defects, with the more homogeneous S-shaped geometry samples achieving lives exceeding 10 cycles, demonstrating the role of geometry in improving durability.

A three-dimensional model was also developed in Abaqus/Explicit to simulate the mechanical behavior and damage propagation in the joints, initially without cohesive properties, to validate the overall behavior and geometry of the interface. The numerical results showed good agreement with the experimental data, accurately reproducing the load-displacement behavior and failure location.

As future work, we recommend integrating the experimental cohesive properties of the IMC layer into the numerical model, as well as implementing coupled thermomechanical analyses to better represent the thermal cycle and diffusion phenomena. Furthermore, we propose the use of advanced numerical models, such as the eXtended Finite Element Method (XFEM), to enable explicit simulation of crack initiation and propagation at the interface and in the base material, without the need to pre-define failure trajectories. The

combination of CZM and XFEM models represents a promising step towards the in-depth understanding of fracture mechanisms and the optimization of dissimilar FSW joint design in automotive and aerospace applications.

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Appendices

Appendix A

Paper

Influence of Weld Profile on the Fatigue Performance of Aluminum–Steel Friction Stir Welded Joints

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Abstract

The use of multi-material structures in the transportation industry has become increasingly important for achieving lightweight yet durable designs. Among the available joining technologies, Friction Stir Welding (FSW) stands out as an effective solid-state process for combining dissimilar materials such as aluminum and steel. This study presents an integrated experimental investigation of the mechanical performance and fatigue behaviour of dissimilar AA6061-T6 aluminum–St37 steel joints produced by FSW. Particular attention is given to the effect of weld interface geometry, specifically the presence or absence of an “S-shaped” profile on the structural strength, fatigue life, and failure mechanisms of the joints. Quasi-static tensile tests were conducted under displacement-controlled conditions to assess joint strength and deformation behaviour, while axial fatigue tests were performed under load-controlled cyclic loading at room temperature. The results demonstrate that the “S”-profiled joints exhibit higher ductility and improved stress redistribution, achieving superior fatigue resistance when free from microstructural discontinuities. Conversely, joints without the “S” geometry show more brittle interfacial failure dominated by the intermetallic compound (IMC) layer.

Key words: Intermetallic compound; Failure mechanism; Friction Stir Welding; Stress ratios; fatigue life

1. Introduction

The automotive industry is moving towards lightweight multi-material structures, particularly aluminum and steel joints, to increase fuel efficiency and reduce CO₂ emissions [1]. Although these materials offer high strength-to-weight ratios, their joining presents challenges due to brittle intermetallic compounds (IMCs) that weaken mechanical properties [2]. Advanced solid-state welding techniques such as friction stir welding (FSW) and friction stir self-piercing riveting (F-SPR) minimize IMC formation, improving joint strength, fatigue resistance and manufacturing efficiency, making them crucial to the future of sustainable vehicle design [3]. However, the fatigue performance of these joints remains a critical factor in ensuring their long-term durability and reliability under cyclic loading conditions [2]. Therefore, fatigue

testing is essential to assess the structural integrity and service life of aluminum-steel joints, guiding further optimization of welding processes for improved automotive application [3]. According to [4] the mechanical strength of FSW joints is strongly influenced by several factors, such as process parameters, tool geometry, and the properties of the materials being joined. Key variables including welding speed [5], tool rotation [6], axial load, plunge depth, and tilt angle [5] directly affect joint performance. Proper adjustment of these parameters makes it possible to achieve welds with tailored strength characteristics. In addition, evaluating the tensile response of FSW joints is essential to ensure the structural reliability of welded components.

The use of dissimilar aluminum-steel joints offers both economic and functional advantages, combining aluminum's low density with steel's high strength to achieve lightweight, cost-effective structures with enhanced mechanical performance [7]. However, joining aluminum to steel poses significant technical challenges due to their physical and chemical incompatibility. The large difference in melting points (~850 °C), distinct oxide formation, and low mutual solubility hinder homogeneous bonding [8]. Moreover, aluminum exhibits a thermal expansion coefficient and specific heat nearly twice that of steel, thermal conductivity about six times higher, and a much lower elastic modulus, along with an electrochemical potential difference of 1.22 V. These discrepancies in thermophysical and mechanical properties promote the formation of intermetallic compounds (IMCs), heat-affected zones (HAZs), bonding defects, geometric distortions, and degradation of joint strength [9, 10].

Aluminum and steel exhibit extremely low mutual solubility, which promotes the formation of Fe_xAl_x intermetallic compounds (IMCs) during joining. These IMCs arise from solid-state reactions between iron (Fe) and aluminum (Al) under the thermal and mechanical conditions typical of welding. The specific intermetallic phase formed depends on the local Fe/Al atomic ratio, with compositions leading to phases such as $FeAl_3$, Fe_2Al_5 , or $FeAl$, each possessing distinct structural and mechanical properties that critically affect joint integrity and strength [9].

During Friction Stir Welding (FSW), the material undergoes complex thermal cycles generated by frictional heating and intense plastic deformation [11]. The non-uniform temperature distribution across the joint induces thermal stresses that often exceed the elastic limit, leading to localized plastic deformation. As a result, uneven heating and cooling generate residual stress within the welded region, which can significantly reduce the load-bearing capacity of the structure. High residual stress concentrations near the weld interface also increase the susceptibility to brittle fracture and fatigue failure [12].

The main objective of this article is to determine the fatigue life of aluminum-steel joints produced by Friction Stir Welding (FSW) and to evaluate the influence of interface geometry, specifically the presence or absence of an "S"-shaped profile, on the mechanical performance and fatigue resistance of these dissimilar joints.

A series of FSW specimens were tested to analyze their fatigue behavior and cyclic mechanical response, complemented by microstructural characterization to correlate interface morphology with fatigue performance.

The outcomes of this study contribute to a deeper understanding of how interface design affects the durability and structural reliability of aluminum-steel hybrid joints, providing valuable insights for

optimizing FSW parameters and joint geometries in automotive and aerospace applications where lightweight and high-performance materials are critical.

2. Experimental Procedure

In this study, two distinct welding configurations were designed to join dissimilar materials of different thicknesses (Al–St). A specific butt joint arrangement, shown in Figure 1, was developed to connect 5 mm-thick AA6061-T6 aluminum plates to 2 mm-thick St37 carbon steel plates. To investigate the mechanical response and fatigue behavior of the Friction Stir Welded (FSW) joints, both quasi-static and fatigue tests were performed on two interface geometries: one with an S-shaped profile and another without it. The primary objective was to examine how these FSW joints respond under cyclic loading, focusing particularly on the influence of the weld interface geometry namely, the presence or absence of the “S” profile. The experimental analysis aimed to evaluate the effects of these geometric variations on fatigue strength, crack initiation, and propagation during the loading cycles. The two joint configurations are illustrated in Figure 2. The main mechanical, physical and mechanical properties of the base materials relevant to this study are summarized in Table 1.

Table 1: Material properties of the St37 steel and AA6061-T6 aluminum

St37 Carbon Steel	AA6061-T6 Aluminum	
Tensile strength - 370 MPa	Tensile strength - 241 MPa	
Yielding strength - 200 MPa	Yielding strength – 145 MPa	
Vickers hardness - 120 HV	Vickers hardness - 75 HV	
Chemical composition:	Chemical composition:	
Fe: 99.43 – 99.75% C: 0.08% Mn: 0.25 – 0.4% S: 0.05% P: 0.04%	Al: 98.56%-98.6% Si: 0.4%-0.8% Fe: 0.70% max Cu:0.15- 0.40% Mn: 0.15% max	Mg: 0.8-1.20% Zn: 0.25% max Ti: 0.15% max Cr: 0.04 - 0.35 Others: 0.15%

To ensure the production of reliable dissimilar joints with the intended thickness configuration, a custom FSW clamping jig was employed. The setup consisted of aluminum support plates of 1 mm and 2 mm thickness, positioned respectively below and above the St37 steel substrate, to compensate for thickness mismatch and eliminate gaps between the specimen, the welding table, and the tool shoulder.

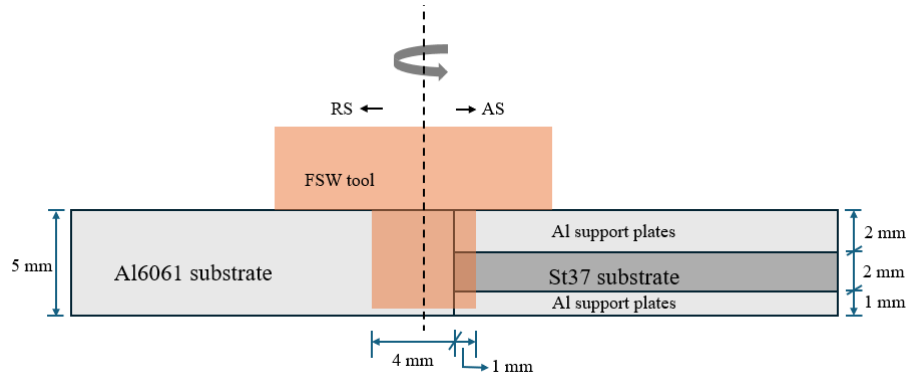


Figure 1: Schematic representation of the FSW mount apparatus used to manufacture the Al-steel joints

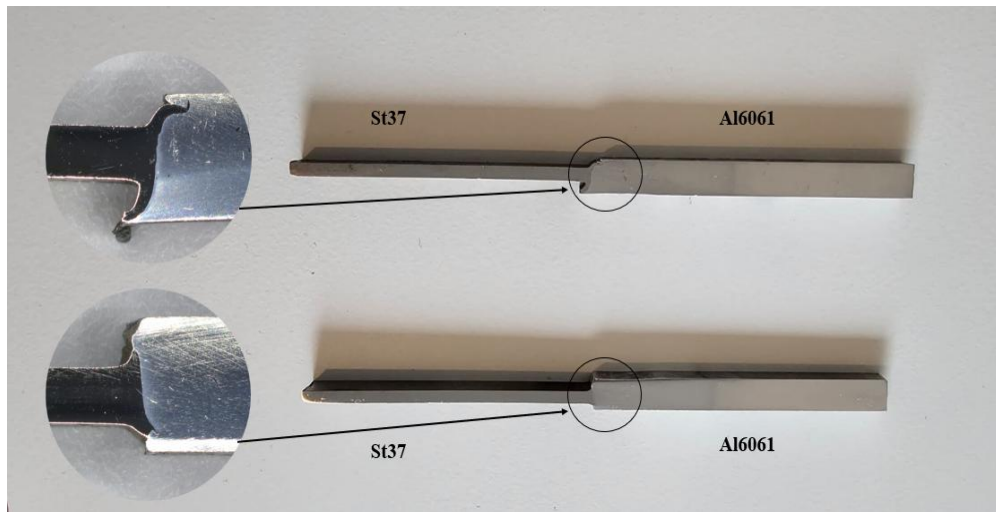


Figure 2: Joint configurations with an "S" shape on top and without "S" shape on the bottom

During welding, the FSW tool pin was positioned with a slight offset toward the retreating side (RS), penetrating approximately 4 mm into the AA6061-T6 substrate and 1 mm into the St37 steel substrate, while maintaining a tool tilt angle (θ) of 2.5° . The tool, made of H13 tool steel, had a shoulder diameter of 18 mm, a pin length of 4.7 mm, and a pin diameter of 5 mm, as illustrated in Figure 3. The rotational speed (ω) was set to 950 rpm, with counterclockwise (CCW) rotation, whereas the traverse speed (V_x) was varied between 10 and 20 mm/s to investigate the influence of welding parameters on heat generation, material flow, and the resulting joint quality. Those parameters and specifications of the tools can be seen in Table 2

Table 2: FSW parameters and tool specifications

FSW parameters	Tool specifications
- Tool rotation speed (ω): 950 RPM, CCW	- Material: H13 tool steel
- Tool traverse speed (V_x): 10-20 mm/s	- Tool shoulder diameter: $\varnothing$ 18 mm
- Tool tilt angle (θ): 2.5°	- Tool shoulder concavity: 2.5°
- Pin plunge depth: 4.7 mm	- Tool pin diameter: $\varnothing$ 5 mm
- Tool offset: 1.5 mm to RS	- Tool pin length: 4.7 mm

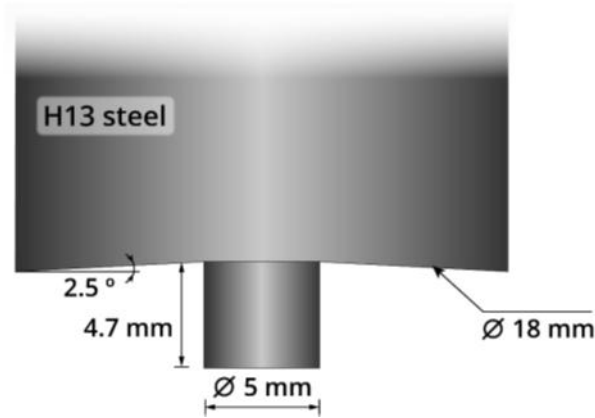


Figure 3: Schematic representation detail of the tool's shoulder and pin, with the respective dimensions.

2.1. Testing procedures

Prior to mechanical testing, metallographic samples were extracted from three specimens of each joint geometry, with and without the “S” profile, to enable a comparative evaluation of interfacial quality. The samples were prepared following standard metallographic procedures such as polishing and analysed under a high-resolution optical microscope to assess the microstructural integrity of the weld interface.

The analysis focused on characterizing the intermetallic compound (IMC) layer formed between aluminum and steel, identifying discontinuities, thickness variations, and FSW-related defects, as well as irregularities in the base materials such as inclusions, voids, or incomplete bonding. This preliminary characterization was crucial for correlating microstructural imperfections with the mechanical behaviour observed in the tensile and fatigue tests, providing a clearer understanding of how joint geometry influences IMC formation and overall performance.

The metallographic analysis of samples A, B, and C, presented in Figure 4, corresponds to the joints with the “S”-shaped geometry and reveals interfacial and structural defects characteristic of aluminum–steel joints produced by Friction Stir Welding (FSW), which are expected to strongly influence their mechanical performance. Sample A exhibited an irregular and thick intermetallic compound (IMC) layer with a wavy morphology, resulting from excessive heat input and extended dwell time that promoted the uneven diffusion of aluminum and iron, forming brittle Fe_2Al_5 and FeAl_3 phases [9]. Although these phases ensure metallurgical bonding, their hardness and brittleness act as stress concentrators, leading to premature interfacial fracture. Samples B and C contained steel inclusions within the aluminum matrix, attributed to tool-induced mechanical dragging from excessive penetration or unbalanced rotation-to-traverse ratio. These inclusions serve as crack initiation sites under cyclic loading, reducing fatigue resistance.

Regions with incomplete metallurgical bonding and voids were also identified, associated with insufficient heat generation and poor plastic flow, resulting in weak adhesion and reduced load-bearing area. The coexistence of these defects—irregular IMC layers, inclusions, voids, and lack of bonding—indicates thermal and mechanical non-uniformity during processing, which compromises ductility, ultimate strength,

and fatigue life. Consequently, a decrease in maximum load, total deformation, and number of cycles to failure is anticipated compared with defect-free joints.

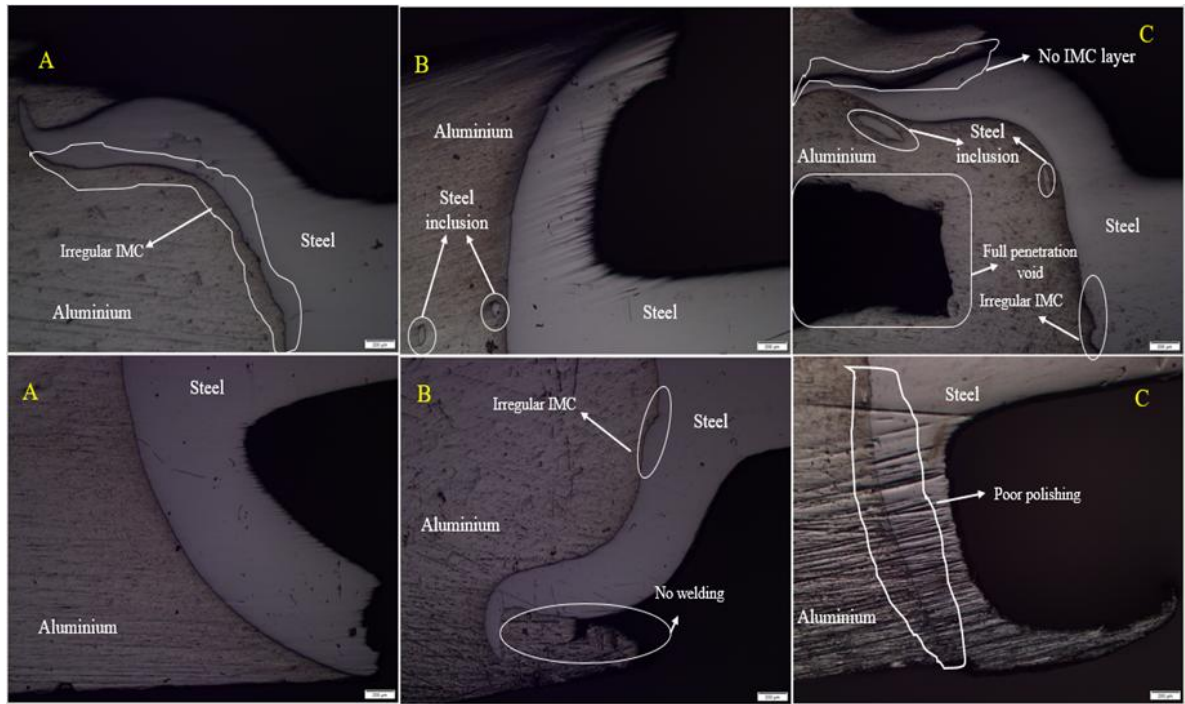


Figure 4: Microstructural characterization of interfacial defects in “S” profiled joints (Samples A, B, and C)

Figure 5 presents the metallographic analysis of samples A, B, and C corresponding to the joints without the “S”-shaped geometry. This configuration was examined to evaluate how the absence of geometric modulation affects the formation of the intermetallic compound (IMC) layer and the overall integrity of the aluminum–steel interface.

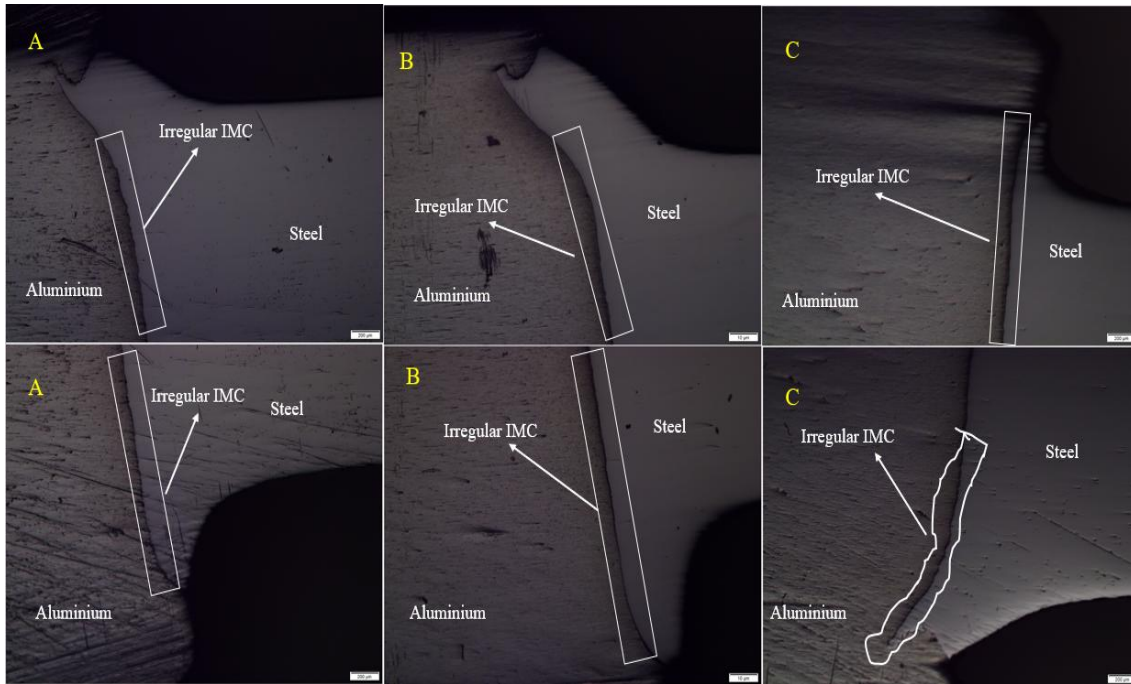


Figure 5: Microstructural characterization of interfacial defects in without “S” profiled joints (Samples A, B, and C)

In all samples (A, B, and C), the intermetallic compound (IMC) layer appeared continuous but with variable thickness and wavy contours, reflecting uneven diffusion between aluminum and steel and localized thermal instability during FSW. Although the irregularity was less pronounced than in the “S”-profiled joints, thickness variations indicated heterogeneous plastic flow and heat input under tool action.

In the “S”-profiled joints, the IMC layer was generally thicker and more discontinuous, with regions showing no bonding, steel inclusions, and full-penetration voids, evidencing more complex thermo-mechanical conditions. Conversely, in joints without the “S” profile, the interface was more linear and uniform, suggesting steadier diffusion and reduced material turbulence. However, this apparent uniformity can be detrimental: a continuous, thick IMC layer acts as a brittle barrier, lowering ductility and fatigue resistance, whereas the “S” geometry enhances mechanical interlocking and energy absorption despite localized imperfections.

2.2. Mechanical tests

2.2.1 Tensile test

Quasi-static tensile tests were conducted to mechanically characterize the welded joints produced with two interface geometries: S-shaped and without S-shape. These tests provided load–displacement curves for both configurations, allowing a direct comparison and correlation between joint performance and the presence of the “S” profile. The experiments were carried out using an INSTRON® universal testing machine (Model 3367, Norwood, MA, USA) under controlled ambient temperature and humidity. A constant crosshead speed of 1 mm/min was applied, as recommended for quasi-static testing. The load was applied longitudinally, with the joint interface facing the testing machine. Additionally, each test was recorded in macro mode to capture the deformation and failure process in detail. The load–displacement

data were synchronized with the video recordings, enabling a combined analysis of the global mechanical response and local failure mechanisms until complete specimen separation.

2.2.2 Fatigue test

Following the quasi-static tensile tests, fatigue tests were conducted to assess the cyclic behaviour and service life of the welded joints, focusing on the influence of the interface geometry (with and without “S” profile) on mechanical performance. The experiments were carried out on an Instron 8801 servo-hydraulic testing machine as shown in Figure 6, equipped with a high-precision load cell and dynamic force control system. To minimize bending effects and ensure a predominantly axial loading condition, the specimens were rigidly aligned along the loading axis using custom-designed fixtures.

The tests were performed under load control with a stress ratio of $R = 0.1$ (minimum stress equal to 10% of the maximum stress) and a sinusoidal frequency of 10 Hz, following the ASTM E466 [13] standard for force-controlled constant-amplitude axial fatigue tests. The applied load amplitude corresponded to 60% of the average maximum load obtained from the quasi-static tests, ensuring a realistic service stress level without exceeding the local elastic limit of the joints. Throughout the tests, axial displacements and the evolution of cyclic stiffness were continuously monitored until complete failure or stabilization of deformation, enabling the determination of the number of cycles to fracture (N_f).

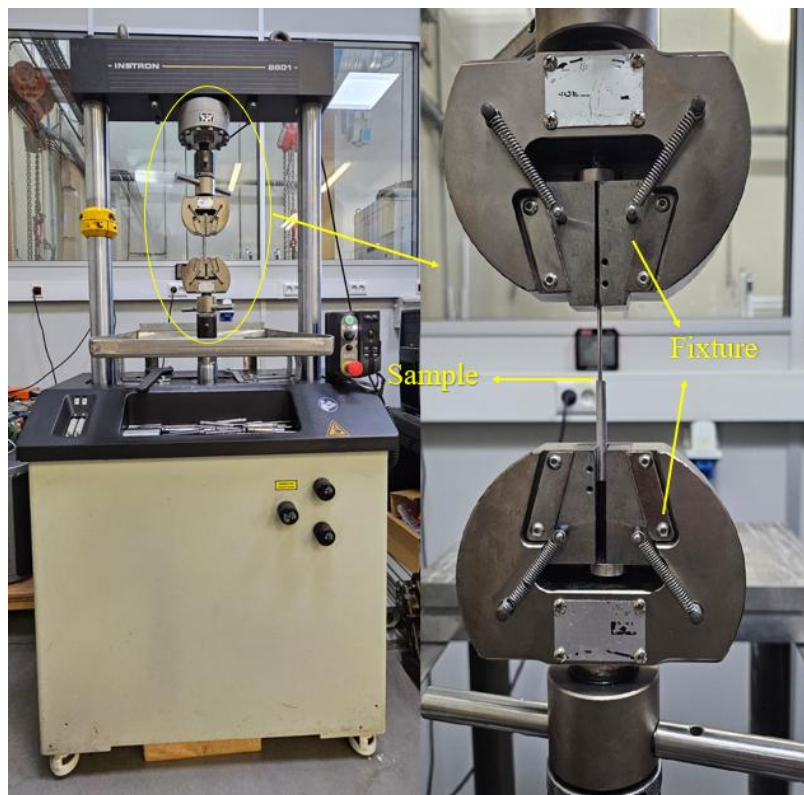


Figure 6: Fatigue test setup

3 Results and discussion

3.2 Tensile test results

The results of the tensile tests conducted on specimens with two interface geometries, S-shaped (with “S” profile) and without S-shape, are presented and discussed in this section. For each configuration, four specimens with the S-shaped profile and three without it were tested, ensuring sufficient data for a consistent and reliable analysis.

S-shape (“S” profile)

For the S-shaped configuration, four tensile tests were conducted to evaluate the mechanical behavior and failure location. The results that can be seen in Figure 7 revealed consistent trends among specimens. Tests 1 and 3 exhibited similar tensile strength values, with failure occurring in the steel base material. In contrast, Tests 2 and 4 also showed close agreement but failed at the aluminum side and within the intermetallic compound (IMC) region, indicating a mixed failure mode.

The load–displacement curves from the tensile tests of S-shaped welded joints showed in Figure 7 revealed significant variations in mechanical behavior among the four specimens, with maximum loads ranging from 2418 N to 3149 N. Samples 1 and 3 showed higher ductility and failed in the steel base material, indicating efficient FSW processing and good joint integrity. Conversely, Samples 2 and 4 failed prematurely at the IMC–aluminum interface or within the aluminum substrate, reflecting brittleness associated with the thickness and continuity of the intermetallic layer. These results highlight that microstructural features, interface quality, and base material properties decisively influence the mechanical performance of S-shaped FSW joints.

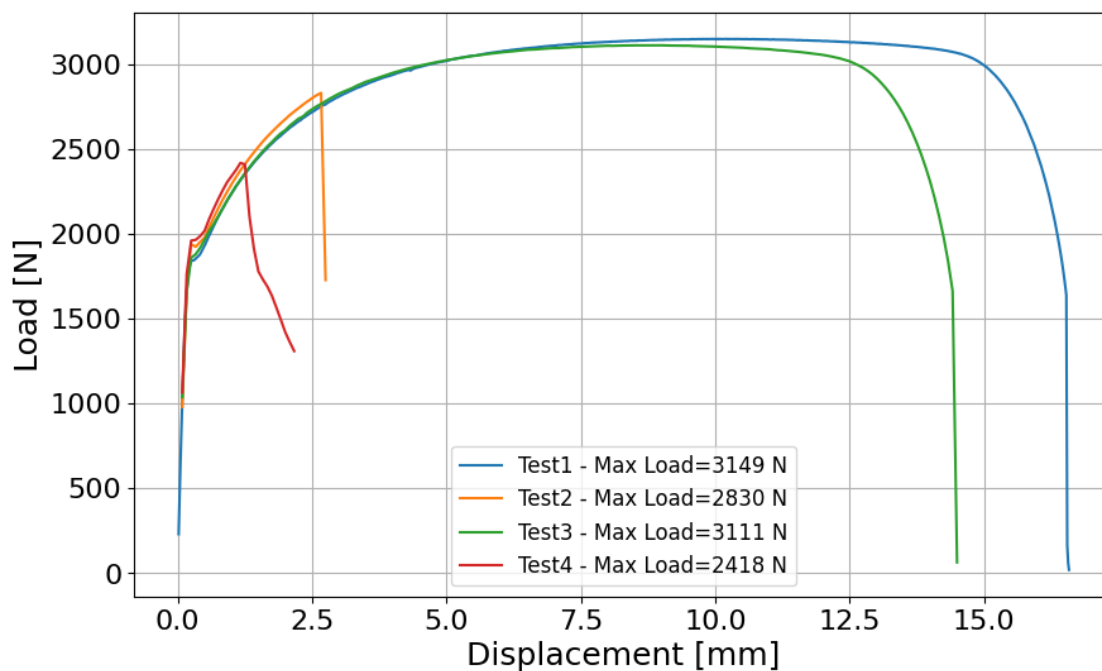


Figure 7: Load vs. Displacement curve of the S-shape specimens

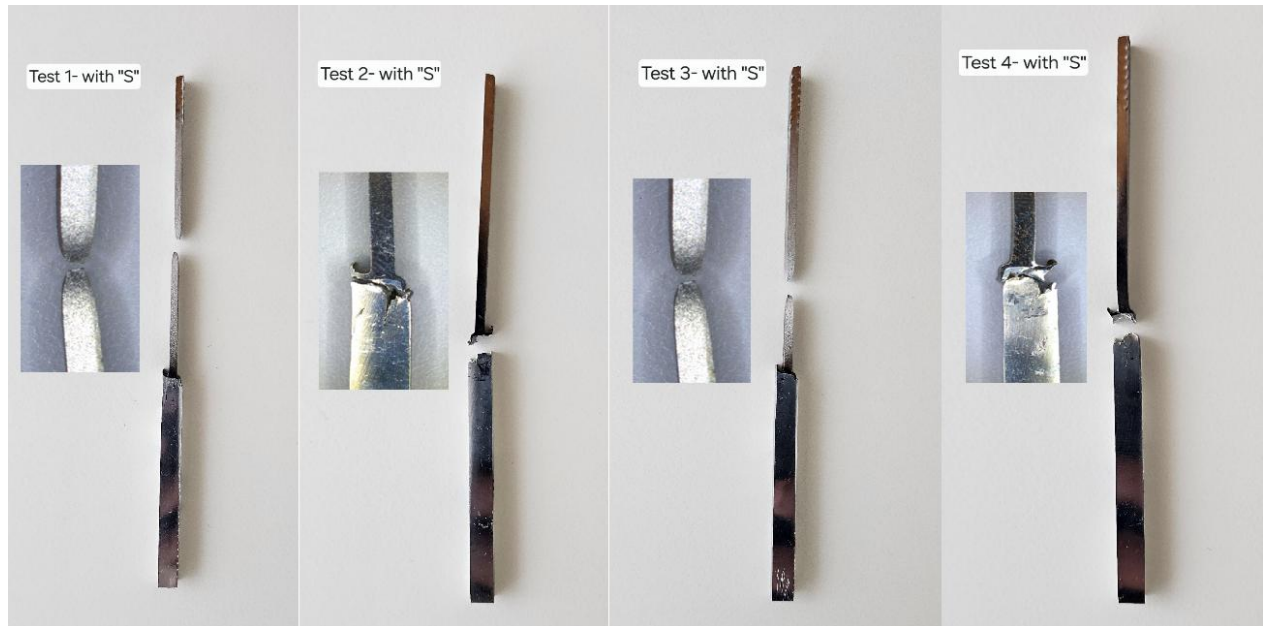


Figure 8: Joints with "S" shape after performing tensile test.

Without S-shape

After testing the joints without the "S" profile, three specimens were analyzed to assess the influence of geometry on mechanical performance. The results showed high consistency in both maximum load and failure location, with all fractures occurring within the intermetallic compound (IMC) region. Unlike the S-shaped joints, where failures often occurred in the base materials, the absence of the "S" geometry led to localized stress concentration and higher brittleness in the IMC under monotonic loading, highlighting the beneficial role of the S-shaped configuration in redistributing stresses and improving joint strength.

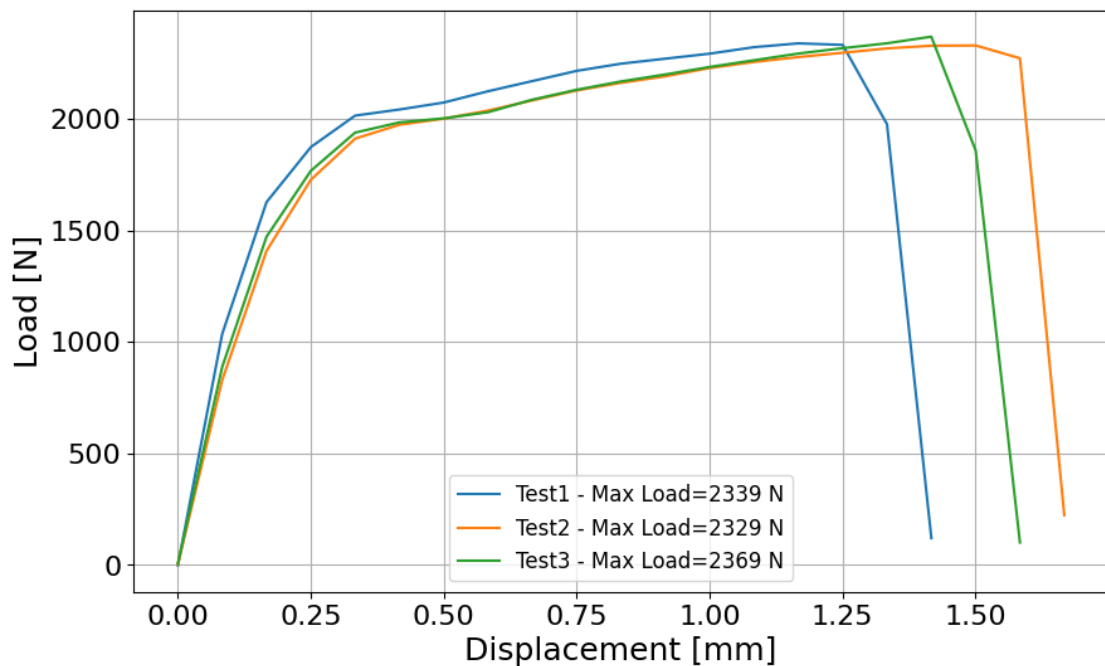


Figure 9: Load vs. Displacement curve of the without S-shape specimens

The load–displacement curves obtained from the tensile tests on FSW joints without the “S” geometry exhibited a predominantly elastic response, followed by a very limited plastic deformation before failure. The maximum loads recorded (2339 N, 2329 N, and 2369 N) were highly consistent, indicating uniformity in both the manufacturing process and material properties. In all specimens, fracture occurred suddenly within the intermetallic compound (IMC) layer, revealing a brittle failure mechanism typical of this region, where the absence of the “S” geometry prevents effective stress redistribution.

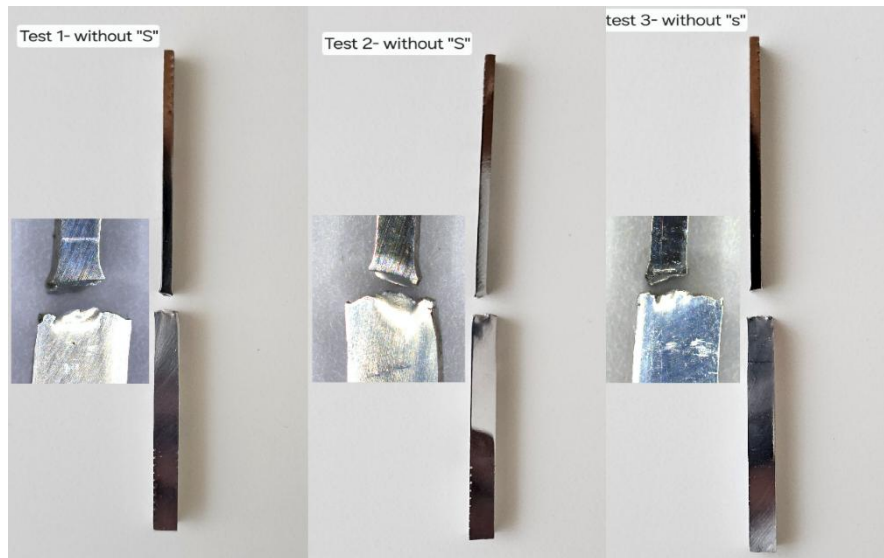


Figure 10: Joints without "S" shape after performing tensile test.

3.3 Fatigue test results

As previously mentioned regarding the parameters used for the fatigue tests, Table 3 summarizes the loading conditions applied to both joint geometries, with and without the “S” profile. The same testing criteria were maintained for both configurations to ensure a consistent comparison of their fatigue performance.

Table 3: Parameters used for fatigue test

Parameters	With “S” shape	Without “S”
Average of Static Load	2877 [N]	2300 [N]
Percentage of static load	60%	60%
Frequency	10 Hz	10 Hz
Ratio	0.1	0.1
Maximum load	1726.2 [N]	1380 [N]
Minimum load	172.62 [N]	138 [N]
Average (impute machine)	949.41[N]	759[N]
Amplitude	1553.58[N]	1242[N]
½ Amplitude (impute machine)	776.79[N]	621[N]

After establishing the tensile behaviour of the joints, fatigue tests were conducted to evaluate their performance under cyclic loading conditions. These tests aimed to characterize the resistance of the dissimilar aluminum–steel joints to progressive damage and to identify the dominant failure mechanisms. The results presented in the following sections compare the fatigue behaviour of the joints with and without the “S” profile, providing insights into the influence of interface geometry on crack initiation, propagation, and overall fatigue life.

The figure 11 presents the fatigue behaviour of the “S”-profiled joints under cyclic loading, illustrating distinct failure modes among the tested specimens. In most cases, fractures occurred on the aluminum side rather than at the interface, indicating failure governed by substrate defects such as steel inclusions, interfacial irregularities, or voids that acted as crack initiation sites. The regions near the interface exhibited notable plastic deformation, evidencing stress redistribution and higher ductility compared to joints without the “S” geometry. Fatigue life varied widely: while some specimens failed prematurely ($<30,000$ cycles) due to localized defects, others reached up to 200,000 cycles or even exceeded 10^6 cycles, demonstrating that the absence of critical defects and improved metallurgical integrity significantly enhance fatigue resistance.

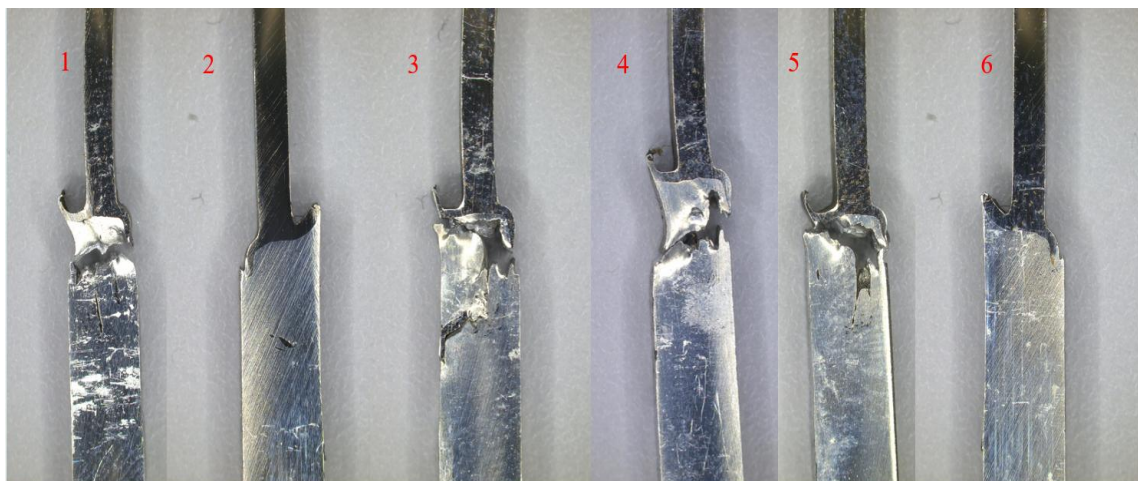


Figure 11: Failure modes observed in with ‘S’ profiled joints after fatigue testing

The figure 12 illustrates the fatigue behaviour of the joints without the “S” geometry under axial cyclic loading. In the failed specimens, fracture occurred predominantly within the intermetallic compound (IMC) layer, indicating brittle interfacial failure. Cracks initiated at the aluminum–steel interface, where the IMC acted as a stress concentrator. Limited plastic deformation was observed near the interface, confirming that the hard and brittle IMC restricted joint deformability. This demonstrates that, in joints without the “S” profile, the dominant failure mechanism is interfacial and governed by the fragility of the continuous IMC layer. Conversely, two specimens endured more than 10^6 cycles without failure, suggesting that a thin, homogeneous, and defect-free IMC can sustain cyclic loading without significant crack growth. Thus, the fatigue performance of non-S-shaped joints is strongly influenced by the microstructural integrity and thickness of the IMC layer

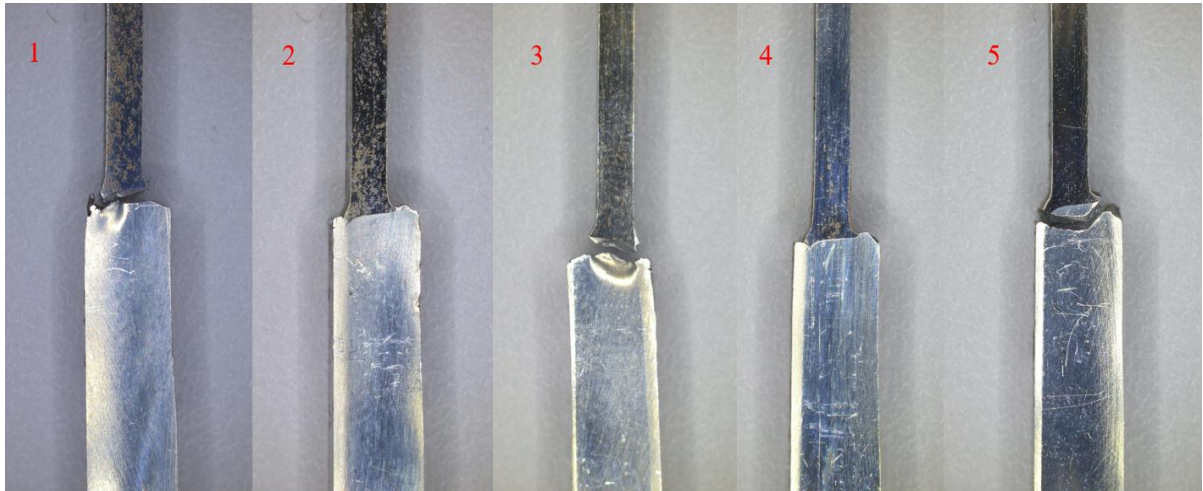


Figure 12: Failure modes observed in without ‘S’ profiled joints after fatigue testing

Figure 13 presents the relationship between the number of cycles (N) and the applied Load Ratio for both interface geometries. The Load Ratio represents the percentage of the average static strength obtained from quasi-static tensile tests for each configuration. It can be observed that the “S”-profiled joints exhibited a larger scatter in fatigue life (2×10^3 – 10^6 cycles), directly associated with defects in the aluminum substrate and at the interface, such as steel inclusions, irregularities, and full-penetration voids. Some specimens failed prematurely in the aluminum due to crack initiation at these discontinuities, while defect-free samples reached run-out of $N > 10^6$ cycles, confirming the potential of the “S” geometry when properly consolidated.

In contrast, the joints without the “S” geometry showed lower variability and a more uniform mechanical response, with failures mainly occurring in the IMC layer and characterized by brittle interfacial fracture. However, a few specimens with thin and homogeneous IMC layers achieved fatigue lives beyond 10^6 cycles, indicating adequate fatigue resistance under controlled interfacial growth.

Overall, the “S” geometry enhances stress redistribution and global ductility, but the fatigue performance remains highly dependent on microstructural integrity. When the interface and substrates are defect-free, the “S”-profiled joints outperform the flat ones; however, in the presence of discontinuities, premature failure occurs in the aluminum, markedly reducing fatigue life.

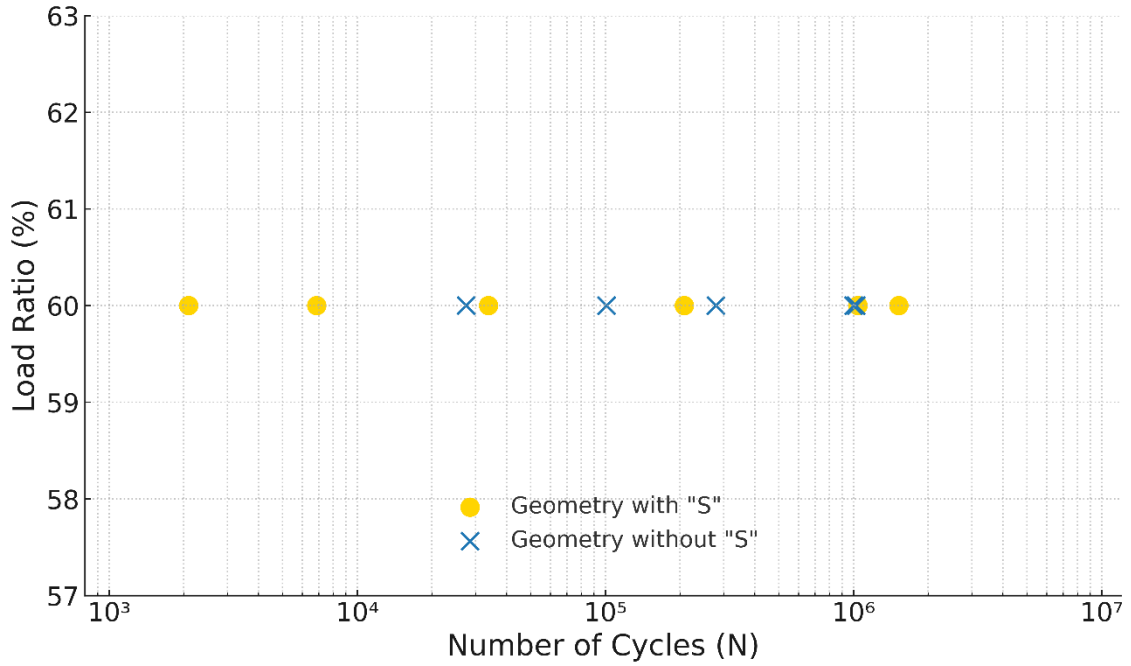


Figure 13: Comparison of fatigue life between “S” and without “S” profiled joints at 60% Load level

4 Conclusion

- The FSW joints with the “S” profile exhibited a clear elastic stage followed by a broad plastic region, achieving total displacements above 10 mm and demonstrating high global ductility with a smooth elastic–plastic transition. The maximum loads ranged from 2830 N to 3149 N, with consistent results across tests, indicating good weld quality and efficient stress redistribution. Failures mainly occurred in the base materials (steel or aluminum), confirming the mechanical integrity of the interface.

In contrast, joints without the “S” profile showed limited plastic deformation, smaller total displacements (below 1.6 mm), and a sudden transition to failure, reflecting reduced ductility and interface brittleness. Their maximum loads (2329 N–2369 N) were slightly lower but notably less ductile. All fractures occurred within the intermetallic compound (IMC) layer, highlighting that the absence of the “S” geometry hinders uniform stress distribution and promotes localized brittle failure.

- The “S”-profiled joints exhibited greater scatter in fatigue life, ranging from 2×10^3 to over 10^6 cycles, reflecting the strong influence of microstructural defects in the aluminum and at the interface, such as steel inclusions, irregularities, and full penetration voids. Specimens containing such defects failed prematurely in the aluminum substrate, whereas defect-free joints achieved

infinite life ($N > 10^6$ cycles), demonstrating the effectiveness of the “S” geometry when properly consolidated.

Conversely, the joints without the “S” geometry showed lower variability and more uniform mechanical behavior. Failures occurred mainly within the intermetallic compound (IMC) layer, leading to brittle interfacial fracture; however, two specimens also surpassed 10^6 cycles, confirming that a thin and homogeneous IMC can ensure adequate fatigue resistance.

Overall, the results confirm that the “S” geometry promotes improved stress redistribution and global ductility, enhancing fatigue performance when the microstructural integrity of the joint is preserved. In contrast, the presence of discontinuities critically reduces fatigue life, particularly through premature crack initiation in the aluminum substrate.

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