PEOPLE`S DEMOCRATIC REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

BLIDA 1 UNIVERSITY
FACULTY OF TECHNOLOGY
DEPARTMENT OF MECHANICS

Thesis
Submitted for obtaining the Master's Degree in
Materials and Surface Engineering

Characterization of Dissimilar Friction Stir Welded Lap Joints of AA2024 and AA7075

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Academic year: 2023/2024

Acknowledgements

الحمد لله والصلاة والسلام على أشرف الخلق محمد صلوات ربي وسلامه عليه. الحمد والشكر كله لله سبحانه عز وجل على تقديره وتوفيقه لإتمام هذا العمل المتواضع

I would like to express all my gratitude to Mrs. Karima Tahar Chaouch for assisting and guiding me through every part of my thesis and for her insightful feedback, let alone her availability. Her constant encouragement and support have been priceless.

I would also like to give special thanks to Mr. Nacer Bacha for sharing his wise and insightful discussions.

A special thanks to Mr. Abdessabour Benamor. His expert advice has been greatly appreciated.

My gratitude to Mr. Mohamed Haif for sharing his expertise in the FSW techniques.

Many thanks to Mrs Chaima Boubker for assisting me during the specimens preparation process.

I am grateful for all the support I received from my parents and my brothers, I wouldn’t have made anything without you.

Finally, I want to acknowledge the support of my friends and colleagues, especially Djeghlaf and Amrouche, and all the members of Mechanical Engineering Club.

Abstract

This thesis investigates the use of Friction Stir Welding (FSW) in lap joint configuration for joining dissimilar aluminium alloys AA2024 and AA7075. The research covers the friction stir welding process in both conventional and lap joint configuration, the properties of AA2024 and AA7075, the advantages of FSW, applications of lap welding, the typical microstructure and the common defects in the lap welding of these aluminium alloys. The Experimental part of this thesis was conducted in two different welding parameters, the first one was welded with a speed of 30 mm/min while the second was in 6 mm/min, even though the rotation speed was 1400 rpm in both of the welds. the experimental results shown that a low welding speed doesn't produce a good quality weld because of the excessive heat flow.

Keywords: FSW, Lap joint, Dissimilar, Aluminium Alloys, AA2024, AA7075.

Resumé

Ce mémoire étudie l'utilisation du soudage par friction-malaxage par recouvrement pour assembler des alliages d'aluminium dissimilaires AA2024 et AA7075. La recherche couvre le processus de soudage par friction-malaxage dans une configuration conventionnelle et par recouvrement, les propriétés de l'AA2024 et de l'AA7075, les avantages du FSW, les applications du soudage par recouvrement, la microstructure typique et les défauts courants dans le soudage par recouvrement de ces alliages d'aluminium. La partie expérimentale de ce mémoire a été menée avec deux paramètres de soudage différents, le premier a été soudé avec une vitesse de 30 mm/min tandis que le second a été soudé avec une vitesse de 6 mm/min, alors que la vitesse de rotation était de 1400 tr/min pour les deux soudures. Les résultats expérimentaux ont montré qu'une faible vitesse de soudage ne produit pas une soudure de bonne qualité en raison du flux de chaleur excessif.

Mots-clés : FSW, Joint par recouvrement, Dissimilaire, Alliages d'Aluminium, AA2024, AA7075.

ملخص

تتناول هذه الاطروحة استخدام التلحيم بالاحتكاك الخلطي (FSW) عن طريق لحم طبقة فوق الأخرى لربط صفائح الألومنيوم غير المتشابهة (AA2024) و (AA7075) .يغطي هذا البحث عملية التلحيم عن طريق الاحتكاك والخلط في كل من الطريقة التقليدية وطريقة لحم طبقة فوق الاخرى، وخصائص سبائك الألومنيوم AA2024 وAA7075، ومزايا اللحام بالاحتكاك الخلطي، ومجالات استعمال هذا النوع اللحام، والبنية المجهرية النموذجية والعيوب الشائعة في لحام السبائك الألومنيوم المختلفة مع بعضها. تم إجراء الجزء التجريبي من هذه الأطروحة بمعاملين لحام مختلفين، حيث تم لحام الجزء الأول بسرعة 30مم في الدقيقة بينما كان اللحام الثاني بسرعة 6مم في الدقيقة، اما بالنسبة لسرعة الدوران فكانت 1400 لفة في الدقيقة في كلا اللحامين. أظهرت النتائج التجريبية أن سرعة اللحام المنخفضة لا تنتج لحاماً بجودة جيدة بسبب التدفق الحراري الزائد.

كلمات مفتاحية: اللحام بالاحتكاك الخلطي، لحام الطبقتين، صفائح المنيوم غير متشابهة، AA2024، AA7075.

Dedication

It warms my heart to dedicate this work to my parents who gave me all and never spared me anything.

I would also like to dedicate this work to the students of Gaza, may allah grant them freedom and peace, for them to build their lives and their country again.

I also dedicate this thesis to Mechanical Engineering Club, may this club rise and forever shine reaching the higher goals.

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Introduction

Introduction

Friction stir welding FSW has emerged as a revolutionary solid-state joining process in materials engineering, offering numerous advantages over traditional fusion welding techniques. Unlike fusion welding, which involves melting and solidification of the base metals, FSW utilizes a non-consumable rotating tool to plastically deform the materials at temperatures below their melting points [1]. This process results in high-quality, defect-free welds with improved mechanical properties, reduced distortion, and the ability to join materials that are otherwise difficult to weld using fusion welding methods [2].

The aerospace and automotive industries have been at the forefront of adopting friction stir welding due to the increasing demand for lightweight, high-strength materials. Aluminium alloys, particularly AA2024 and AA7075, have gained significant attention in these industries for their excellent strength-to-weight ratios and corrosion resistance. However, joining these dissimilar aluminium alloys presents unique challenges due to their differences in composition, microstructure, and mechanical properties. Welding dissimilar materials can lead to the formation of intermetallic compounds, which can significantly impact the joint's mechanical performance and durability [1].

Studying the behaviour of dissimilar friction stir lap welded joints of AA2024 and AA7075 is crucial for understanding the underlying mechanisms that govern the welding process and the resulting joint properties. By characterizing the microstructure and mechanical properties performance of these dissimilar lap joints, we can optimize the welding parameters and develop strategies to mitigate the challenges associated with joining dissimilar aluminium alloys. This knowledge can contribute to the advancement of friction stir welding technology and its widespread adoption in various industries, especially in the fabrication of lightweight, high-performance structures.

This master's thesis aims to provide a comprehensive characterization of dissimilar friction stir welded lap joints of AA2024 and AA7075, focusing on the microstructure and micro-hardness of two welds using different welding speeds. The findings of this research will contribute to the understanding of dissimilar welding processes and provide valuable insights for the design and manufacturing of lightweight, high-strength structures using friction stir lap welding.

Scientific Background

I- Friction Stir Welding Principle:

Friction stir welding (FSW) is a solid-state welding process that uses a combination of friction-generated heat and mechanical stirring to join materials. The basic principle of FSW is based on the use of a non-consumable rotating tool that penetrates the materials to be welded and mixes them to form a solid bond [2].

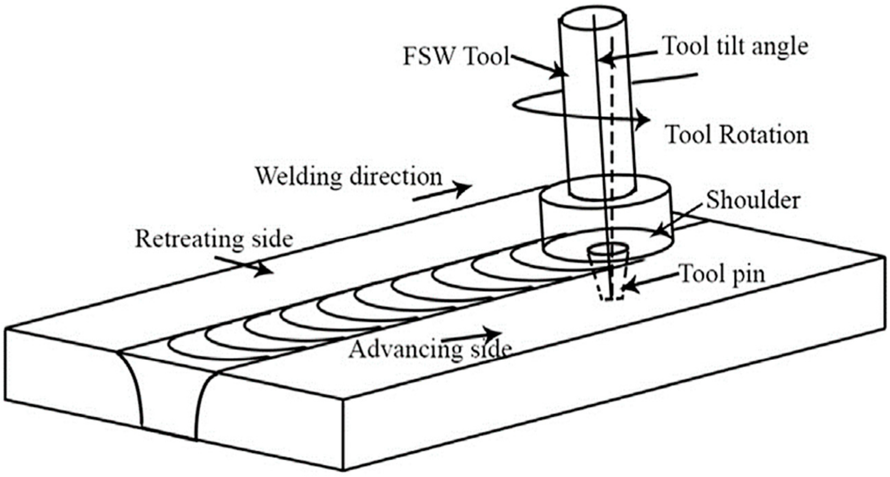

Figure 1.1. Schematic of the FSW Process (Conventional or Butt welding technique) [3]

1-The process of the conventional FSW:

1. ***Material preparation***: The parts to be welded are clamped securely to prevent movement during the welding process. The edges of the parts are prepared to ensure good contact [4].
2. Tool insertion: The welding tool, usually a rotating rod with a shoulder and pin (or tip), is positioned over the weld line. The tool is then pressed into the joint between the parts to be joined. The rotation of the tool generates heat by friction, softening the material adjacent to the pin. [5]
3. ***Mixing and advancing***: The rotating tool moves along the weld line. The heat generated by friction, combined with the pressure exerted by the tool, plasticizes the material. The shoulder of the tool prevents the softened material from escaping and forces it to flow around the pin. The pin mixes the softened material, promoting a homogeneous, strong bond.
4. Joint formation: The movement of the tool along the weld line causes the materials to fuse mechanically. As the tool advances, the material cools and solidifies, forming a continuous,

strong metallic bond. Friction stir welding ends when the tool is removed at the end of the weld line.

5. Characteristics of the welded joint: The joint welded by FSW generally has a fine, homogeneous microstructure, good mechanical strength and an absence of defects typical of fusion welds, such as pores or cracks. The heat-affected zone is also reduced compared to conventional welding techniques [5].

2-The key aspects of friction stir welding (FSW):

Friction stir welding (FSW) is an innovative technique with a number of key features, contributing to its growing popularity in a variety of industrial applications. Here are the key aspects of FSW:

1. Frictional heat generation:

The heat required for welding is generated by friction between the rotating tool and the base material. This heat softens the material without melting it, allowing solid state welding [2].

2. Non-consumable welding tool:

The tool used in FSW is non-consumable and generally consists of a shoulder and a pin (or tip). Tool design plays a crucial role in the process, influencing weld quality and material mixing efficiency [5].

3. Solid state process:

FSW is a solid state process, which means that the materials to be welded do not melt. This reduces metallurgical defects such as porosity and solidification cracks, common in fusion welding techniques [4].

4. Improved microstructure and mechanical properties:

The FSW process generally results in the formation of a fine, homogeneous microstructure in the weld zone, which improves mechanical properties such as tensile strength and hardness.

5. Control of welding parameters:

Welding parameters, such as tool rotation speed, feed rate and application force, are essential for controlling weld quality. Proper optimization of these parameters is necessary to obtain high quality welds [7].

6. Applications for dissimilar materials:

FSW is particularly suitable for welding dissimilar materials. For example, it can be used to weld aluminium alloys of different compositions, which is often difficult with traditional welding methods.

7. Reduced distortion and residual stresses:

FSW generates less distortion and residual stress compared with fusion welding processes, due to the low-temperature nature of the process. This improves the dimensional accuracy of the welded parts [8].

8. Safety and the environment:

FSW is a safer and more environmentally friendly process. It requires no shielding gases, fluxes or filler materials, and generates fewer fumes and toxic emissions. [9]

II- The principle of FSW in Lap joint configuration:

The principle of friction stir welding (FSW) for lap joints is similar to that of butt joints, the only difference is the positioning of the workpieces where in the butt joint we place a piece alongside the other with the edges aligned, while in the lap joint configuration, the two workpieces are arranged so that they overlap. The tool penetrates the upper workpiece and descends until it reaches the lower workpiece, but without passing completely through it. This configuration allows solid joints to be made without compromising the integrity of the materials.

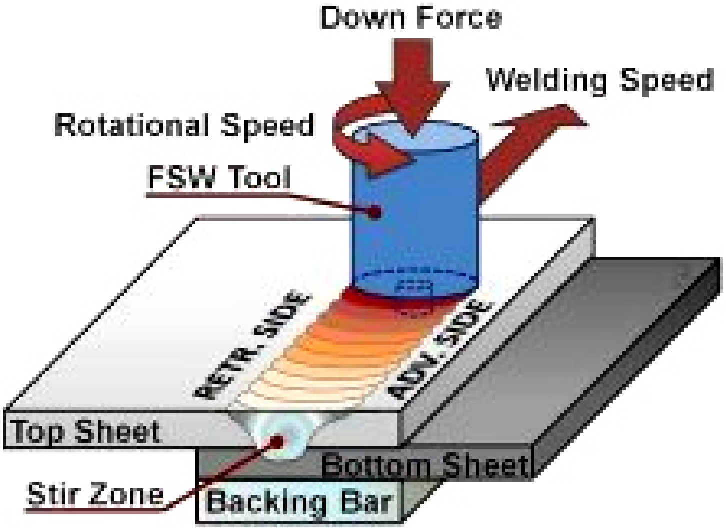

Figure 1.2. Schematic of the FSW Lap Joint Process [15]

III- The advantages of lap joint configuration in Friction Stir Welding:

Friction stir welding lap joint offers several significant advantages over other welding methods, particularly when joining overlapping materials. Here are the main advantages:

1. Excellent weld quality:

FSW lap configuration produces high quality welds with a fine, homogeneous microstructure. The technique minimises common metallurgical defects such as porosities, lack of fusion, and cracking, which are often observed in a butt joint [4] [10].

2. Reducing distortion and residual stresses:

Due to the solid state nature of FSW, heat generation is more controlled and less intense than in fusion welding processes. This leads to a significant reduction in distortion and residual stress, which is particularly beneficial for precision joining and high structural integrity applications [5].

3. Ability to weld dissimilar materials:

FSW lap configuration is effective for welding dissimilar materials, such as different aluminium alloys or even aluminium to other metals. This capability is particularly useful in industries where different materials need to be joined to combine the specific advantages of each material [4].

4. Improved mechanical strength:

FSW lap welds generally exhibit improved mechanical strength due to the homogeneous and fine nature of the microstructure. This includes improved tensile strength, hardness and fatigue resistance [6] [10].

5. Enhanced Fatigue Strength:

Lap welding can improve the fatigue strength of the weld, particularly when using advanced tool designs and techniques [11].

6. Lower production costs:

Due to the reduction in distortion, residual stresses and the absence of consumable materials, lap FSW can lead to significant savings in production costs. In addition, welded parts require less post-processing, which simplifies manufacturing operations [7].

7. Improved Material Flow:

The lap configuration enables better material flow and mixing, resulting in a more uniform microstructure and improved mechanical properties [11].

8. Reduced Tool Wear:

Lap welding can reduce tool wear and extend tool life due to the reduced friction and heat generation during the welding process [10].

9. Improved Welding Speed:

Lap welding can be performed at higher welding speeds, which can increase productivity and reduce the overall welding time [13].

10. Waterproof Solution:

The welds obtained by FSW lap configuration due to their lack of porosities allows it to be waterproof making it suitable for underwater usage.

IV- Applications of Friction Stir Lap Welding of Aluminium Alloys:

Friction lap welding of aluminium alloys is used in a variety of industries because of its unique advantages, such as the production of high quality welds, the reduction of distortion and residual stress, and the ability to weld dissimilar materials. The main applications of this technique are:

1. Aerospace industry

In the aerospace industry, lap FSW is widely used to assemble lightweight but robust structures. Aluminium alloys, such as AA2024 and AA7075, are commonly used in aerospace components due to their high strength-to-weight ratio. Specific applications include:

- Fuselage panels: lap joints create strong, lightweight joints, essential for fuselage structures where weight reduction is critical [4].

- Fuel tanks: Fuel tanks require strong, watertight welds. Lap FSW ensures flawless joints, minimising the risk of leakage, where in figure 4 the screw-on covers are lap welded to the cylindrical tube, ensuring a secure and robust assembly demonstrating exceptional durability and reliability, it was created by STIRWELD INC. – USA [14].

Figure 1.3. Aluminium Fuel Tank Friction Stir Lap welded [14]

2. Automotive industry

Lap FSW is also used in the automotive industry to join aluminium alloy components, helping to reduce vehicle weight and improve fuel efficiency. Applications include:

- Body panels: Lap welds allow aluminium body panels to be welded together efficiently, with good structural integrity and aesthetic appearance without the need for rework. [15].

- Chassis and substructures: Critical chassis and substructure components can be welded with precision, improving vehicle safety and performance [16].

3. Marine industry

Aluminium alloys are increasingly used in marine applications due to their corrosion resistance and light weight. Lap FSW is used to join:

- Boat hulls: Lap welds provide strong, watertight joints, essential for the durability and performance of aluminium vessels [15].

- Deck and superstructure structures: Marine structural components require strong, durable welds to withstand harsh marine conditions [5].

4. Electronics and telecommunications

Electronic and telecommunications devices also benefit from lap FSW, particularly for aluminium assemblies used in enclosures and heat sinks. Applications include:

- Electronic enclosures: Lap welds ensure hermetic and robust joints, protecting sensitive electronic components.

- Heat sinks: Aluminium heat sinks require welds with good thermal conductivity and high mechanical strength to dissipate heat efficiently [17].

5. Railway industry

Lap FSW is used to assemble lightweight, robust structures in the rail industry. Applications include:

- Wagon frames and bodies: Lap welds allow aluminium panels to be welded together efficiently, improving the durability and performance of wagons) [18].

- Structural components: Strong, lightweight welds are essential for railway structures, contributing to train safety and efficiency [15].

V- Example of Friction Stir Lap Welding application:

Stiffened Panels:

Commonly used in several industrial sectors like aeronautical, civil, automotive and engineering, Stiffened panels are composed of a skin and a stiffener as shown in **Figure 1.4**, their main benefit is to significantly increase the bending or buckling stiffness of the panel while ensuring a minimum volume of additional material.

Friction stir lap welding is a permanent and irreversible joining method that has recently been used to join the stiffener to the skin. It has the additional advantage that no drilling or fitting of external elements is required. This assembly technique therefore allows the non-corrosive appearance of the aluminium panel to be maintained. Once welded and installed, the stiffened panel does not need to be inspected afterwards to ensure that the fasteners are secure [19].

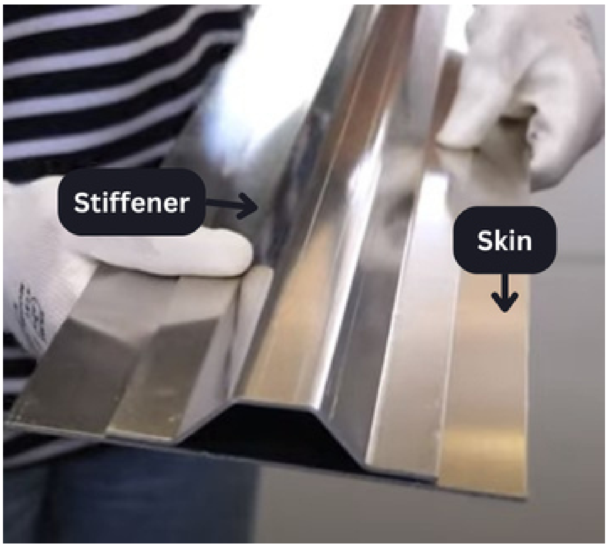

Figure 1.4. Aluminium Skin and Stiffener before welding [19]

Figure 1.5. Stiffened panel during Lap Welding process [19]

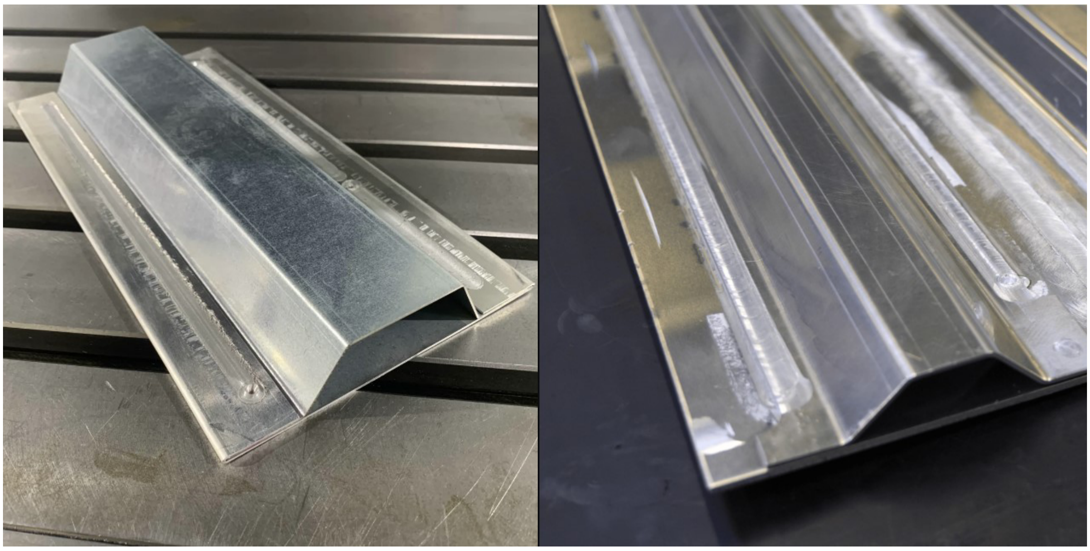

Figure 1.6. Stiffened panels obtained with Friction Stir Lap Welding [19]

VI- Aluminium Alloys Metallurgy

1) Properties of Aluminium Alloy 2024 T3 (AA2024 - T3):

General Characteristics:

- High strength: AA2024 is known for its high strength-to-weight ratio, making it suitable for applications where weight reduction is crucial [20] [21].

- Poor corrosion resistance: AA2024 has poor corrosion resistance unless coated or plated, which can be a limitation in certain applications [20] [23].

- Good workability: The alloy is highly workable, allowing for easy machining and forming operations [21].

- Fair machinability: AA2024 has fair machinability, which can be improved through heat treatment and machining techniques [23].

- Good fatigue resistance: The alloy exhibits good fatigue resistance, making it suitable for applications where cyclic loading is involved [22].

Physical Properties:

- Density: 2.78 g/cm3, slightly higher than pure aluminium [21] [23].

- Thermal conductivity: 120 W/mK, suitable for applications where heat dissipation is important [21] [23].

- Electrical conductivity: 30% IACS, indicating moderate electrical conductivity [21].

- Coefficient of thermal expansion (CTE): 23.2 m/m°C, moderate expansion and contraction with temperature changes [21].

Mechanical Properties:

- Tensile strength: 290-450 MPa (42,100-65,300 psi), high tensile strength suitable for load-bearing applications [21] [23].

- Yield strength: 195-415 MPa (28,300-60,000 psi), high yield strength for structural applications [21] [23].

- Hardness: 50HB-120HB, depending on heat temper, indicating resistance to deformation, abrasion, and scratching [21].

- Fatigue strength: 138 MPa (20,000 psi), good fatigue resistance for cyclic loading applications [21].

- Shear strength: 283 MPa (41,000 psi), moderate shear strength for cutting and shearing stresses [21].

Chemical Composition: (in weight %)

	Al	**Cu**	**Mg**	**Mn**	**Si**	**Fe**	**Cr**	**Zn**	**Ti**	**Other**
Min	90.7%	3.8%	1.2%	0.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Max	94.7%	4.9%	1.8%	0.9%	0.5%	0.5%	0.1%	0.25%	0.15%	0.05%

(AA2024 technical sheet, Smiths Advanced Metals 2023)

Table 1.1. AA2024 Chemical Composition [24]

Weldability by Friction Stir Welding (FSW):

The weldability of AA2024 by FSW is generally good. Studies have shown that FSW can produce high-quality welds in AA2024 with minimal defects and porosity [22]. The process is suitable for joining AA2024 in various thicknesses and temper conditions.

Applications:

AA2024 is commonly used in the aerospace and automotive sectors due to its high strength-to-weight ratio and fatigue resistance. It is often used in aircraft wing and fuselage structures, as well as in automotive applications such as truck wheels and high-stress components [21].

Phases and Microstructure of Aluminium Alloy 2024

Aluminium alloy 2024 has a complex microstructure comprising several phases and intermetallics [25] [26], including:

- Phase α (Solid Aluminium): Primary matrix of the alloy.

- θ phase (Al_2Cu): Copper intermetallic, forms hardening precipitates, responsible for the increase in mechanical strength after heat treatment.

- S Phase (Al_2CuMg): Another intermetallic phase that contributes significantly to the mechanical strength of the alloy.

- Mn, Fe, Si phases: Complex formations of intermetallics containing manganese, iron and silicon, which may appear in minor quantities

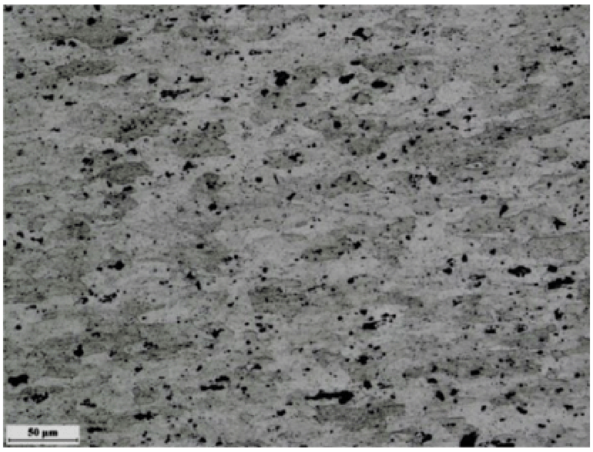

Figure 1.7. AA2024 T3 microstructure [25]

2) Properties of Aluminium Alloy 7075 T6 (AA7075)

General Characteristics

- High strength: AA7075 is known for its high strength-to-weight ratio, making it suitable for applications where weight reduction is crucial [27] [28].

- Good corrosion resistance: AA7075 has good corrosion resistance due to its high zinc content, which helps protect the alloy from corrosion [27] [30].

- Fair machinability: AA7075 has fair machinability, which can be improved through heat treatment and machining techniques [28] [30].

- Good fatigue resistance: The alloy exhibits good fatigue resistance, making it suitable for applications where cyclic loading is involved [27] [28] [30].

Physical Properties

- Density: 2.81 g/cm3, slightly higher than pure aluminium [28] [30].

- Thermal conductivity: 120 W/mK, suitable for applications where heat dissipation is important [28] [30].

- Electrical conductivity: 30% IACS, indicating moderate electrical conductivity [28].

- Coefficient of thermal expansion (CTE): 23.2 m/m°C, moderate expansion and contraction with temperature changes [28].

Mechanical Properties

- Tensile strength: 500-700 MPa (72,500-101,500 psi), high tensile strength suitable for load-bearing applications [27] [30].

- Yield strength: 400-600 MPa (58,000-87,000 psi), high yield strength for structural applications [28] [30].

- Hardness: 50HB-120HB, depending on heat temper, indicating resistance to deformation, abrasion, and scratching [28].

- Fatigue strength: 200-300 MPa (29,000-43,500 psi), good fatigue resistance for cyclic loading applications [28].

- Shear strength: 283 MPa (41,000 psi), moderate shear strength for cutting and shearing stresses [28].

Chemical Composition: (in weight %)

	Al	Zn	Mg	Cu	Mn	Fe	Si	Cr	Ti	Other
Min	87.5%	5.1%	2.1%	1.2%	0.0%	0.0%	0.0%	0.18%	0.0%	0.0%
Max	91.5%	6.1%	2.9%	2.0%	0.3%	0.5%	0.4%	0.28%	0.2%	0.05%

(AA7075 technical sheet, Smiths Advanced Metals 2023)

Table 1.2. AA7075 Chemical Composition [31]

Weldability by Friction Stir Welding (FSW)

The weldability of AA7075 by FSW is generally good. Studies have shown that FSW can produce high-quality welds in AA7075 with minimal defects and porosity [29]. The process is suitable for joining AA7075 in various thicknesses and temper conditions.

Applications

AA7075 is commonly used in the aerospace and automotive sectors due to its high strength-to-weight ratio and corrosion resistance. It is often used in aircraft structures, such as wings and fuselage, as well as in high-stress components in the automotive industry [27] [30].

Phases and Microstructure of Aluminium Alloy 7075

Aluminium alloy 7075 has a complex microstructure [25] composed of several precipitates and intermetallics [26], including mainly:

- Phase α (Solid Aluminium): The main matrix of the alloy.

- η phase ($AlMgZn_2$): A magnesium and zinc intermetallic that contributes significantly to the alloy's strength.

- S phase (Al_2CuMg): Copper and magnesium intermetallic, present in lesser quantities, increasing mechanical strength.

- $MgZn_2$: One of the main precipitated phases that increases the mechanical strength.

- Al_7Cu_2Fe: An iron-containing intermetallic, formed in minor quantities and generally undesirable for her influence on the localized corrosion.

- $Al_{23}CuFe_4$: Another iron-containing intermetallic, also in minor quantities.

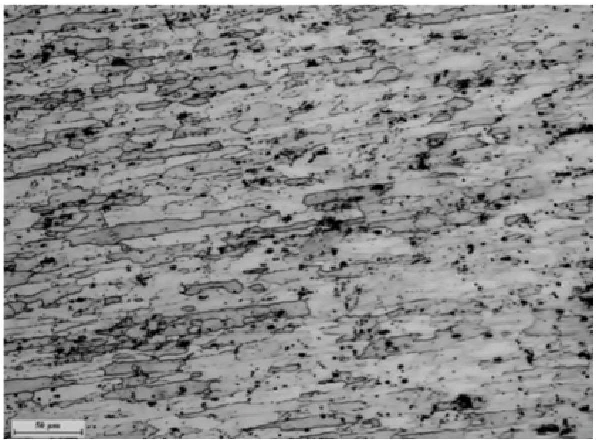

Figure 1.8. AA7075 T6 microstructure [25]

3) What does T3 and T6 stand for in aluminium alloys:

There are two systems of letters and digits used, after the alloy designation number, to define and describe the temper of an aluminium alloy. For the heat treatable alloys of the 2xxx and 7xxx series the following applies: [32]

Temper	Designation
T1	Cooled from a high temperature forming process and naturally aged.
T2	Cooled from a high temperature forming process cold worked and naturally aged.
T3	**Solution treated, cold worked and naturally aged.**
T4	Solution treated and naturally aged.
T5	Cooled from a high temperature forming process and age hardened by heat treatment.
T6	**Solution treated and age hardened.**
T7	Solution treated and deliberately overaged.
T8	Solution treated, cold worked and age hardened.
T9	Solution treated, age hardened then cold worked.

Table 1.3. Aluminium Alloys Temper designations

VII- Applications of AA2024 and AA7075 Aluminium Alloys joined together:

In the aerospace industry, fuselage panels of aircraft are composed of AA2024 skins and strengthened with AA7075 stingers which are often used together in riveted structures.

Riveting is a common assembly method used in aerospace to join different alloys, as it offers a robust and reliable solution capable of withstanding loads and vibrations.

The choice to rivet rather than weld is often dictated by fatigue strength and structural durability requirements, as well as the difficulties associated with welding high-strength alloys such as AA7075.

Replacing Riveting with FSW Lap Welding:

A) Potential benefits:

Replacing riveting with Friction Stir Lap Welding for AA2024 and AA7075 alloys offers several benefits:

1. Reduction of stress concentration points:

Rivets create stress concentration points, which can lead to fatigue cracking. FSW eliminates these points, distributing stress evenly along the weld.

2. Improved aerodynamics:

FSW creates smoother surfaces than rivets, improving the aerodynamics of aeronautical structures.

3. Weight reduction:

Rivets add extra weight. By replacing rivets with FSW, the total weight of the structure can be reduced, which is crucial for aeronautical performance.

4. Improved structural integrity:

FSW provides a more homogeneous and stronger bond between AA2024 and AA7075 alloys, improving structural integrity and durability.

B) Challenges and considerations:

1. Differences in composition and properties:

Welding two different alloys can result in differences in microstructure and mechanical properties, requiring precise control of welding parameters.

2. Reparation and equipment:

FSW requires specialised equipment and careful preparation of the surfaces to be welded.

3. Training and qualification:

Operators must be specially trained for FSW, and welds must be rigorously qualified to meet aviation industry standards.

VIII-Microstructures of Different Zones in Friction Stir Lap Welding of AA2024 and AA7075:

Friction stir welding creates several distinct zones with characteristic microstructures when welding two dissimilar aluminium alloys, such as AA2024 and AA7075. Here is a description of the different zones and their microstructures:

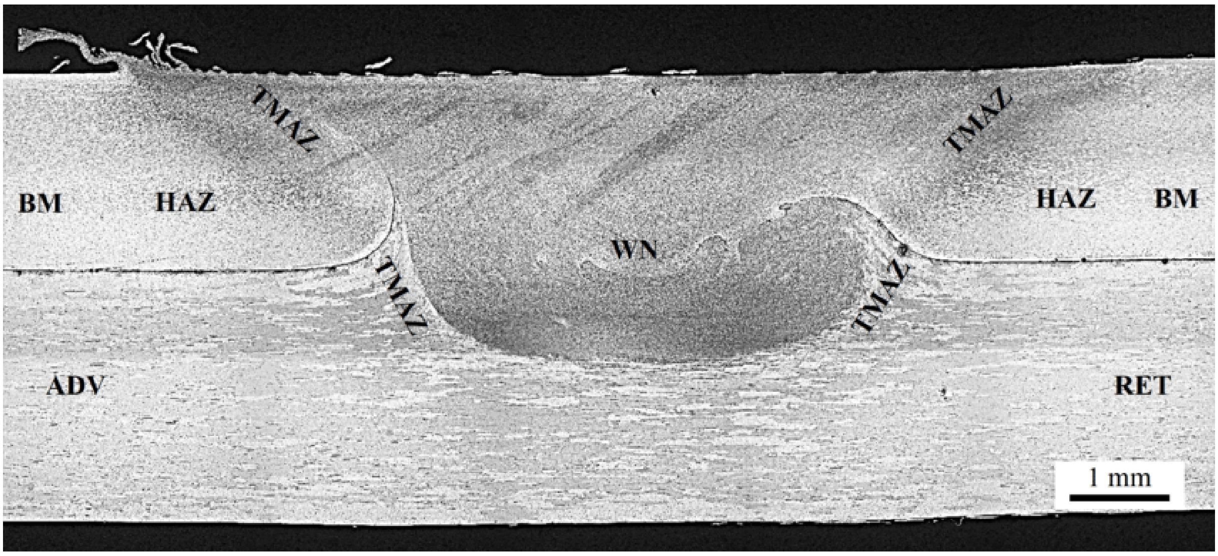

Figure 1.9. Cross-section and microstructural zones of a friction stir welding lap joint [33]

1. Base Metal (BM):

- Description: The original materials, unaffected by welding.
- Microstructure: AA2024 and AA7075 retain their original microstructures, typically equiaxed grains and precipitates of hardening phases (Al2Cu for AA2024 and MgZn2 for AA7075).

2. Heat Affected Zone (HAZ):

- Description: Zone adjacent to the base metal where the temperature is sufficient to affect the microstructure but insufficient to cause mixing.
- Microstructure:
  - AA2024: Grain growth, partial dissolution of hardening phase precipitates (Al2Cu).
  - AA7075: Grain growth, partially dissolved and coarsened MgZn2 precipitates.

3. Thermomechanically Affected Zone (TMAZ):

- Description: Zone where the material has been affected both thermally and mechanically, but without complete mixing.

- Microstructure:
  - AA2024: Plastic deformation and partial reconstitution of precipitates, possible formation of new intermetallic phases.
  - AA7075: Plastic deformation, formation and growth of precipitates of intermetallic phases (Al2CuMg, MgZn2).

4. Stir Zone (SZ):

- Description: Also called Weld Nugget (WN), is the central zone where the material is intensely stirred and recrystallised.
- Microstructure:
  - AA2024 and AA7075: Fine and homogeneous structure due to dynamic recrystallisation, finely dispersed and recrystallised precipitates, possible formation of mixed phases between the two alloys.
  - Mixing interface: Mixture of the two materials with good dispersion of the precipitates and a solid metallurgical bond.

IX- Advancing Side and Retreating Side in FSW Lap Joint:

In friction stir welding (FSW) lap joints, the advancing side and the retreating side refer to the sides of the weld relative to the rotation and movement of the tool. Here’s a detailed look at the differences:

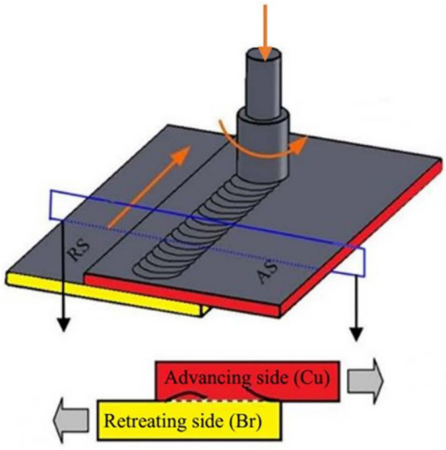

Figure 1.10. Schematic the Advancing and Retreating side on the Lap Joint [34]

1- Advancing Side:

Definition: The side where the direction of tool rotation and the welding direction are the same.

Material Flow: The material moves in the same direction as the tool travel, leading to a more pronounced mixing and plastic deformation.

Heat Generation: Generally, experiences higher heat input due to the combination of rotational and translational movement in the same direction.

Microstructure: Often shows a finer grain structure due to better stirring and mixing action.

Defect Formation: May have fewer defects such as voids or tunnels compared to the retreating side.

2- Retreating Side:

Definition: The side where the direction of tool rotation is opposite to the welding direction.

Material Flow: The material moves in the opposite direction of the tool travel, resulting in less intense mixing.

Heat Generation: Typically experiences lower heat input as the rotational and translational movements oppose each other.

Microstructure: Can have a coarser grain structure due to less effective stirring.

Defect Formation: More prone to defects like voids and lack of fusion because of inadequate mixing and lower heat input.

3- Implications for FSW Lap Joint

Weld Quality: The advancing side generally has a more refined microstructure and better mechanical properties due to better material flow and higher heat input.

Tool Design: The tool's design, including the shape and size of the pin and shoulder, is often optimized to enhance the welding conditions on both sides.

Process Optimization: Parameters such as rotational speed, travel speed, and tilt angle are adjusted to balance the differences between the advancing and retreating sides to produce a uniform and defect-free weld [36].

X- Defects in Friction Stir Lap Welding:

Friction Stir Lap Welding can exhibit several types of defects that can compromise the integrity and performance of the weld. These defects arise due to improper welding parameters, tool design, material properties, and other factors. The common defects observed are:

1. Lack of Penetration:

Description: Occurs when the tool does not penetrate sufficiently into the lower sheet, resulting in an incomplete joint.
Causes: Insufficient tool plunge depth, inadequate heat generation, or incorrect tool design.

2. Void Formation:

Description: Voids or cavities within the weld region due to improper material flow [35].
Causes: Inadequate tool rotation speed, incorrect welding speed, or insufficient axial force.

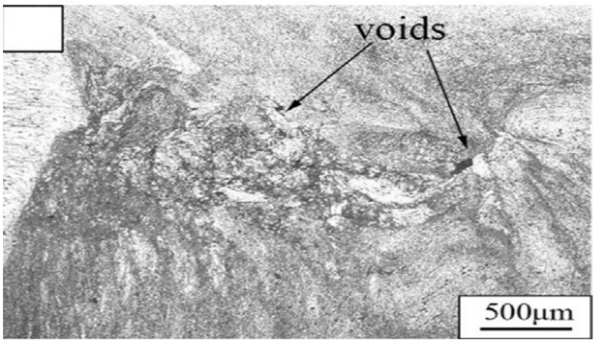

Figure 1.11. Void defect in the Lap Joint [35]

3. Kissing Bond (Incomplete Bonding):

Description: A weak bond between the sheets with minimal metallurgical bonding resulted from the remnant oxide layer. [36]
Causes: Insufficient heating and stirring, poor tool design, or low welding speed.

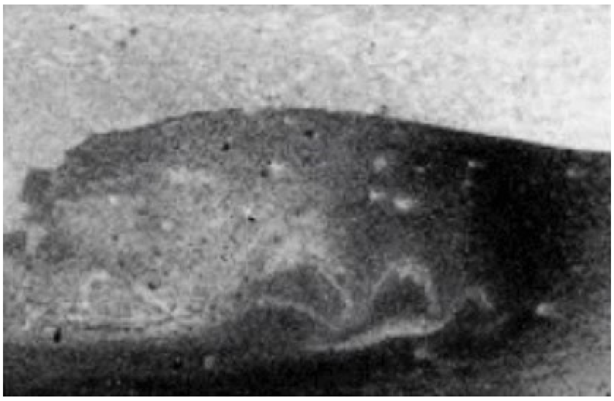

Figure 1.12. kissing bond defect in the Lap Joint [36]

4. Hook Defects:

Description: Hook-shaped defects at the interface of the lap joint, often leading to stress concentration points. The hooking defect occurs on the TMAZ of the Advancing Side.

Causes: Improper tool tilt angle, inadequate plunge depth, or incorrect welding speed.

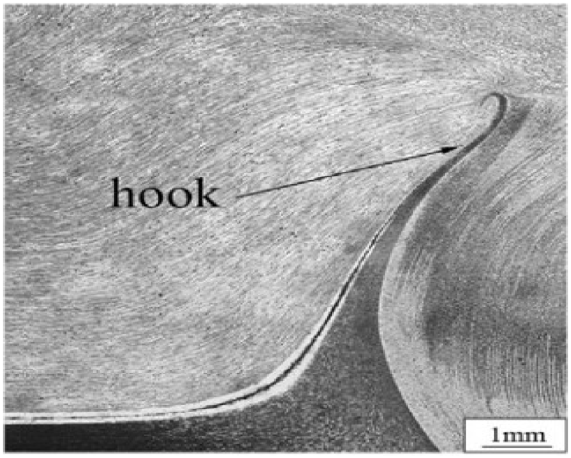

Figure 1.13. Hook defect in the Lap Joint [35]

XI- Vickers Hardness of Lap welded AA2024 and AA7075:

The typical Hardness distribution transverse sections of both AA2024 and AA7075 takes the W-shaped profile, as shown in **Figure 1.14**. This W-shaped profile is caused by the important heat input generated from the friction of the tool, therefor an important decrease of hardness in the Heat Affected Zone, and then an increase in the Stir Zone.

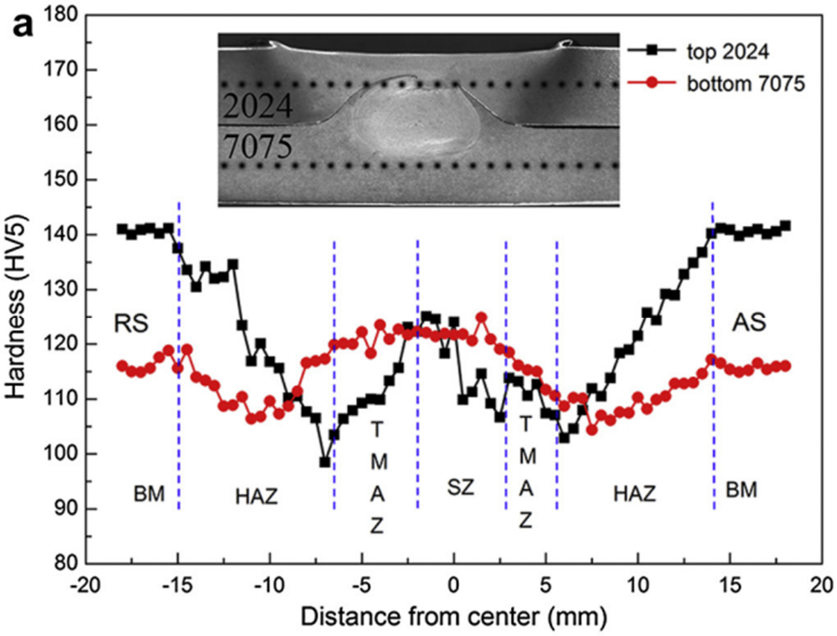

Figure 1.14. Hardness profiles along the transverse sections of 2024/7075 joints [35]

Experimentation

I- FSW tool machining:

1- Material of the tool:

The FSW process requires a hard tool with an excellent wear resistance, for that reason we used K110 as a material for our tool.

K110 (EN X153CrMoV12, AISI D2) is a 12% ledeburitic chromium tool steel that combines excellent wear resistance, compressive strength, and toughness, making it suitable for a wide range of cold work applications [38].

2- Machining:

In our study we used a simple cylindrical shaped tool, for this we used a K110 steel, we cut the 25mm thick K110 steel bar into a small one of 70 mm in length using the Metal Band Saw while applying a lubricant.

Figure 2.1. Metal Band Saw

The steel rod is then machined using a Parallel Turning machine (Lathe) in which the diameter of the rod is reduced progressively by a turning operation with a 0,5mm of material removal depth in each pass until reaching the depth of 5 mm, which created the 15mm diameter shoulder and then the same was done to create the 4mm diameter pin of the FSW tool.

A facing pass was then conducted on the surface of the pin to flatten it.

Figure 2.2. Parallel Turning Machine (Lathe)

The Pin and Shoulder of the friction stir welding tool measure as follow:

Measure	**Shoulder**	**Pin**
Length	/	2,7 mm
Diameter	15 mm	4 mm

Table 2.1. FSW Tool Measurements

3- Tool hardening:

As the Friction Stir Welding process requires a hardened tool, the tool was heat treated in a muffle furnace at the temperature of 1050°C maintained during 45 minutes. The tool is then removed from the muffle furnace and quickly Quenched in Oil.

A Stress Relieving Heat treatment was necessary before putting the tool in use. For this the tool was heated at a temperature of 650°C, maintained for another 45 minutes, at the end of the treatment the FSW tool was left to slowly cool in the furnace.

Figure 2.3. FSW Tool

II- Preparation of the aluminium alloy sheets:

Two medium size sheets of aluminium alloys, one AA2024 T3 with a 2,5 mm thickness and the second one AA7075 T6 with a 1,5 mm thickness, were cut using a Hydraulic Guillotine Shear, creating two small sized sheets of each aluminium alloy with the following measurements:

Measure	AA2024	AA7075
Length	120mm	120mm
Width	105mm	105mm
Thickness	2,5 mm	1,5 mm

Table 2.2. Aluminium Alloy 2024 & 7075 measures

Figure 2.4. Hydraulic Guillotine Shear

III- Friction Stir Welding process:

The friction Stir Welding is a welding technique that uses the rotation of the tool, the vertical movement of the metal sheets and the vertical movement that applies the force of the tool over the metal sheets to allow the friction and heat generation. and the machine that allows all this is the milling machine.

Figure 2.5. Milling Machine

Using the milling machine (figure 20) in the department’s machining workshop for our FSW process, we first inserted our tool into the head of the machine and then adjusted the tilt of the head with a 2° degrees’ angle tilt.

Afterwards we polished the sheets in the joining area and on top of the upper sheet using sandpaper, then we cleaned it from dust and other impurities with Acetone.

Meanwhile, a back plate made out of 4 mm thick steel with the dimensions of 140 mm x 130 mm, was placed above the machine’s table.

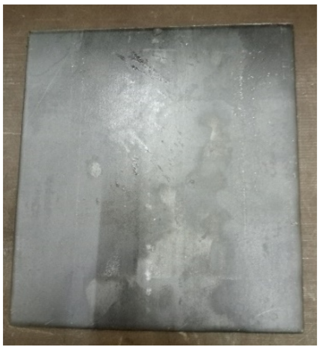

Figure 2.6. Back plate of 14cm x 13cm

Secondly, we carefully placed our 7075 Aluminium alloy sheet directly above the steel back plate, and then we added the 2024 Aluminium alloy sheet on top of it, the sheets were then held tightly using some clamps.

Afterwards, we set the rotation speed at 1400 rpm, and we started the machine, we plunged the tool vertically into the sheets with a depth of 0,3 mm, and we maintained it in the same spot for 60 seconds for what we call it the dwell time.

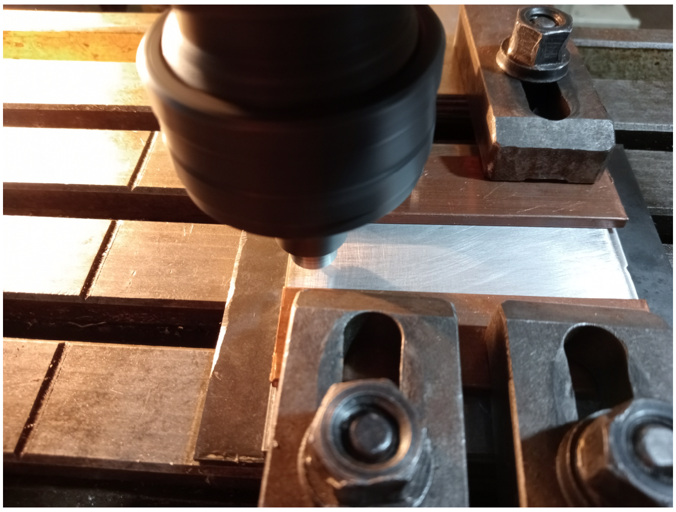

Figure 2.7. The beginning of the FSW operation

Right when the dwell time was over, we started the horizontal tool movement, for the first weld we used a welding speed (tool advancing speed) of 30 mm/min, and for the second one we used a speed of 6 mm/min.

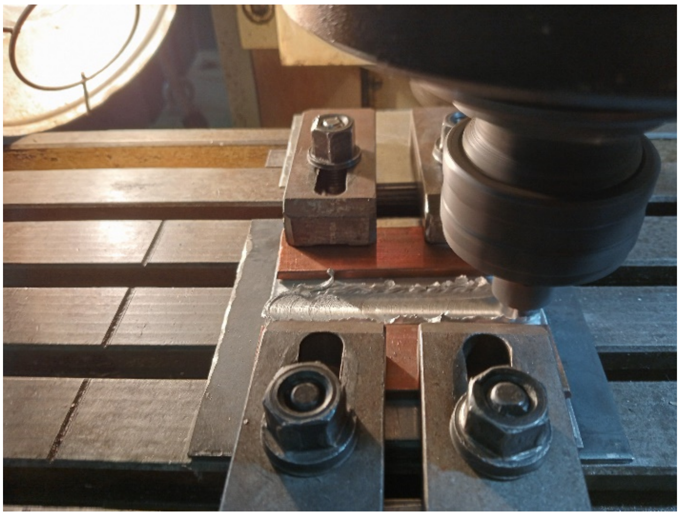

Figure 2.8. During the FSW operation

When the operation was over and the tool has crossed the full length of the sheets leaving a whole at the end of it, we were finally able to turn the machine off and remove our welded sheets.

IV- Specimen preparation for Metallography:

1- Cutting out specimens:

One specimen of each weld was cut from the middle of the weld using the Hydraulic Guillotine Shear, with the dimensions: 35 mm x 25 mm as shown in **Figure 2.9**:

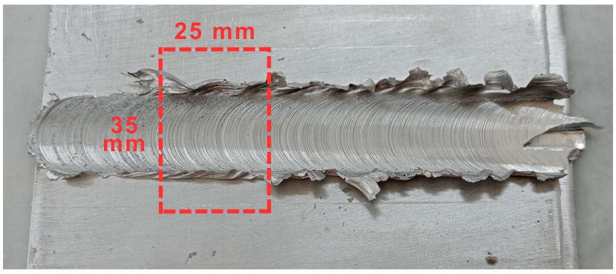

Figure 2.9. Specimen size before cutting

2- Preparing the specimens:

In order to prepare our welded specimens for metallography, we followed these steps:

1. Cleaning the specimens:

We cleaned our specimens using acetone to clear it out of dust, grease or any other impurities.

2. Mounting:

We then Cold Mounted the specimen using an epoxy resin mixed with an epoxy hardener, that we poured into a cylindrical shaped silicone mold in which we placed our specimen horizontally to obtain the cross section of the FSW lap joint.

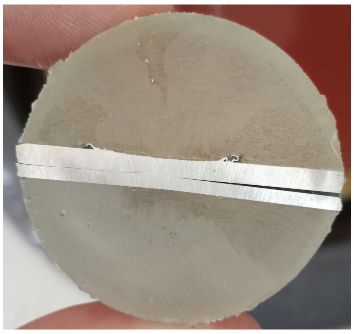

Figure 2.10. Cold mounted welded specimen

3. Grinding and polishing:

Using progressively finer grits of silicon carbide (SiC) sandpaper placed onto a metallographic polishing grinder to polish the specimen. We started from a low granulometry of 220 all the way up to 4000 grit. And then we polished using an electric polishing tool by applying a 1 µm diamond paste until we reached the mirror bright finish of the metal.

Figure 2.11. Metallographic polishing grinder

5. Etching:

In the purpose of revealing the microstructure of our aluminium alloys, the use of Keller's etchant is required for this application. In order to produce 20 ml of Keller’s etchant we mixed the following components:

Chemical Component	Amount
Distilled Water	19 ml
Nitric Acid	0,5 ml
Hydrochloric Acid	0,3 ml
Hydrofluoric Acid	0,2 ml

Table 2.3. Keller’s etchant composition (for 20 ml)

Now that our Keller's etchant is ready, we poured it using a syringe on the top of our mounted specimen for 60 seconds, and then we rinsed it with water, dried it with a blow drier and then we cleaned it with acetone.

V- Metallographic examination:

We utilized an optical microscope to observe the microstructure of our welds, and the different defects present in our joints.

VI- Micro-Hardness testing:

For the mechanical testing of our welds we used Micro-hardness testing. Vickers hardness tests were conducted onto both of the specimens with 50gram force applied.

A linear scanning along each side of the welds (in AA2024 and AA7075). These analysis gives us an overview about the changes that happened along the welds.

Figure 2.12. Micro-hardness testing

Results and Interpretation

I- Macroscopic examination:

Figure 3.1, depicts the joints of both the welds, joint A welded with a speed of 30 mm/min, and joint B welded with a speed of 6 mm/min.

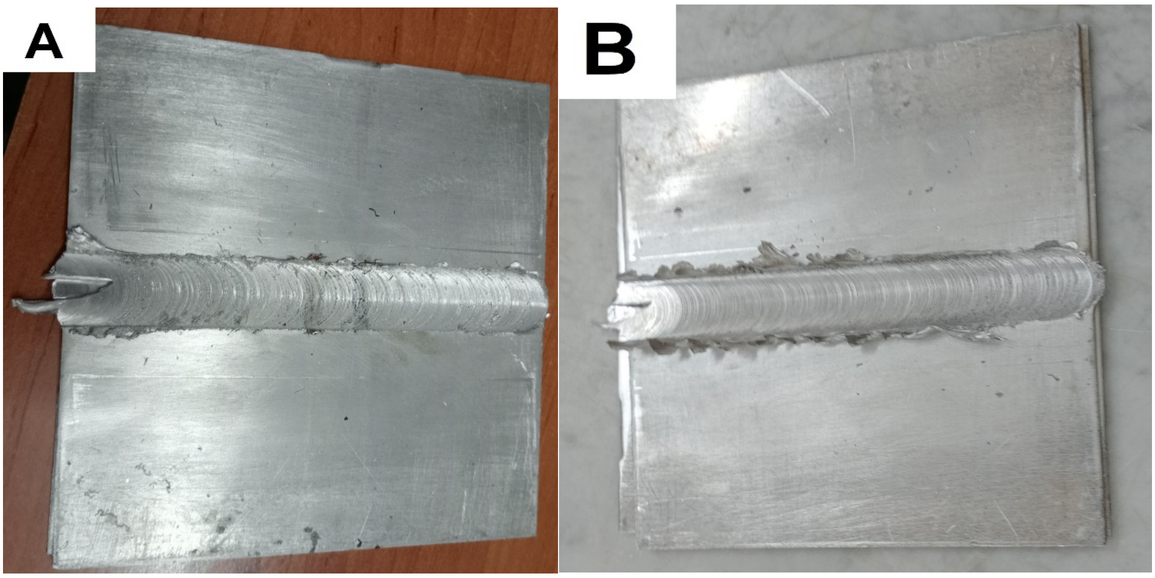

Figure 3.1. Friction Stir Welding Lap joints: A) 30 mm/min, B) 6mm/min

- Visually, the welding joint appears to be continuous without any grooves or discontinuities.
- The width of the welding joint which is equal to 15 mm.

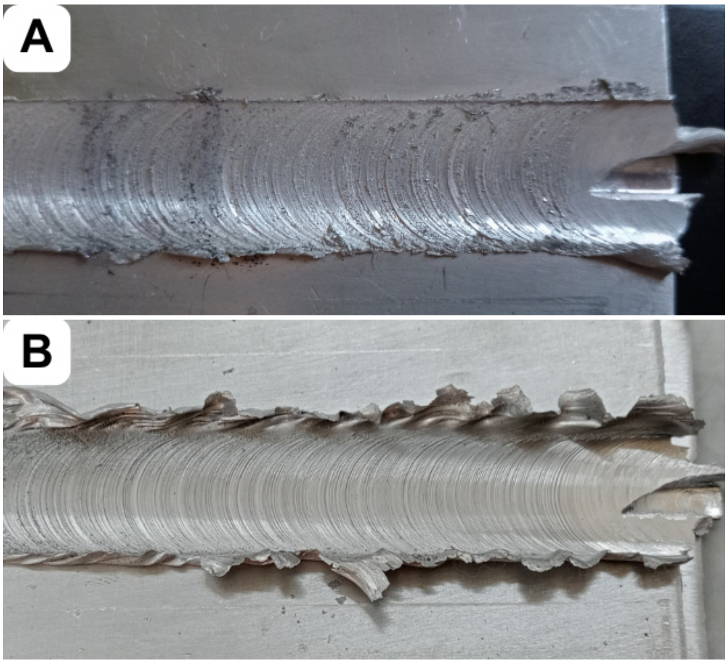

Figure 3.2. FSW tool print in joint: A) 30 mm/min, B) 6mm/min

- The tool print of Weld B is slightly more refined due to the slow welding speed, and for the manual handling of the welding process.
- An excessive flash defect on Lap Weld B made with 6 mm/min welding speed, this defect is due to the important heat flow caused by the slow welding speed, and perhaps applied a slightly more tool penetration than in Lap Weld A.

Figure 3.3 represents a cross section of the FSW lap joints of dissimilar AA2024/AA7075 with different welding speed.

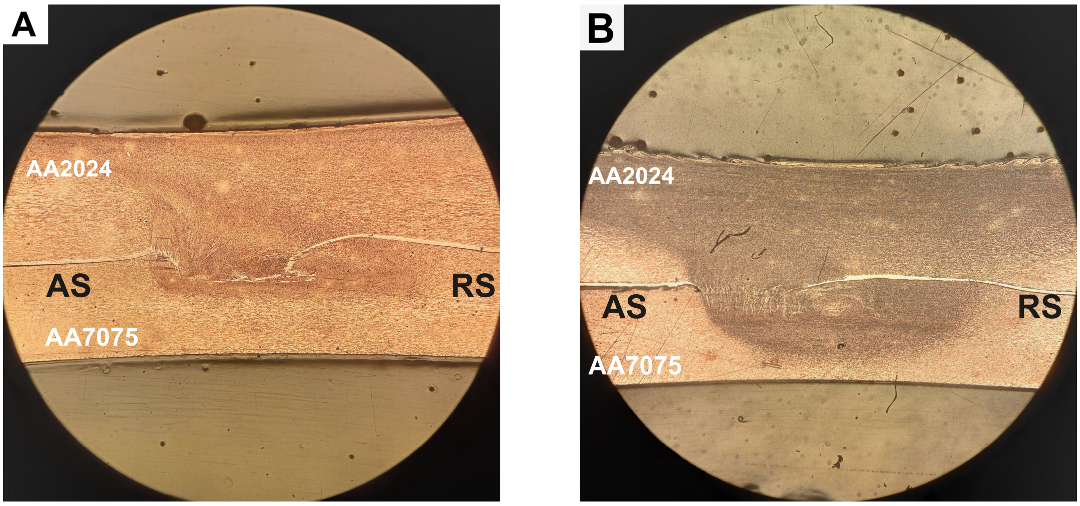

Figure 3.3. Cross-section of the FSW Lap Welds (X25): A (30 mm/min), B (6mm/min)

- The cross section of the welds shows the different welding zones.
- The dark area throughout the welded region in both the Aluminium alloy plates, is the resulted by the chemical reaction and the atomic diffusion.
- The bounded region located in the middle is estimated to be 4.5 mm, which is 0.5 mm larger than the diameter of the tool pin, this can attribute to better adhesion between the AA2024 and AA7075 (a larger Stir Zone).

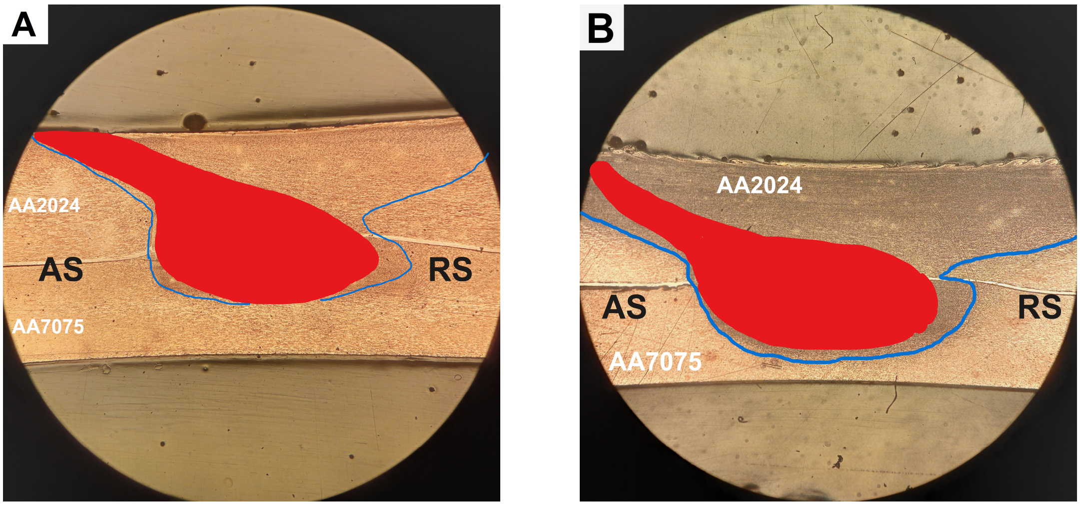

Figure 3.4. The onion morphology of the welds: A (30 mm/min), B (6mm/min)

- The visual aspect of the cross section of both the welds appear to take the shape of an onion with a core in the middle of the stir zone, and a tail reaching from the advancing side.
- There are no tunnelling defects in these welds, nor a lack of penetration, but a hook defect can be seen in both of the welds in the welding region from the advancing side.

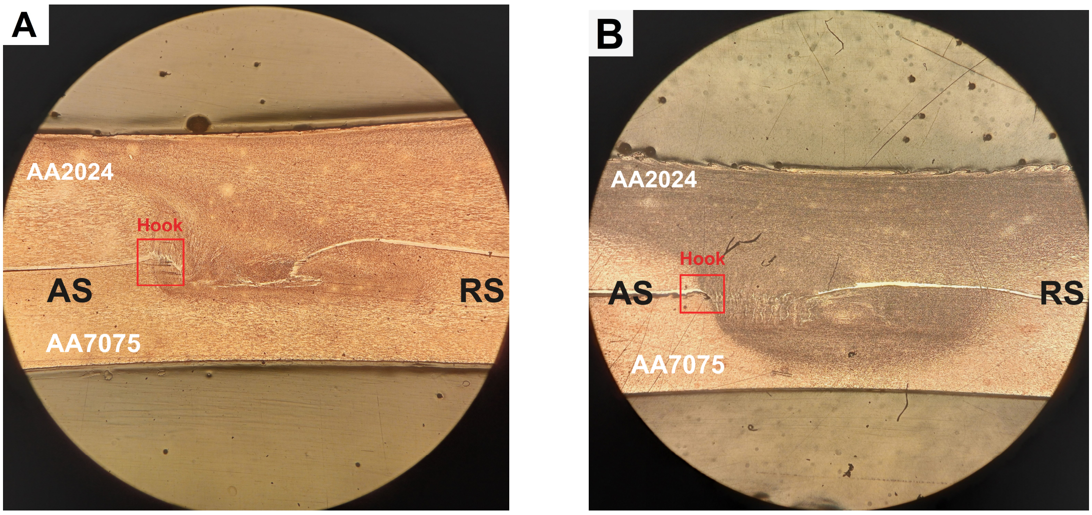

Figure 3.5. The hook defect on welds: A (30 mm/min), B (6mm/min)

II- Microscopic examination:

Using an optical microscope with both the x100 and x200 magnification objectives, we were able to observe the microstructures in the different zones of the FSW lap joints.

Specimen A (welding speed 30 mm/min):

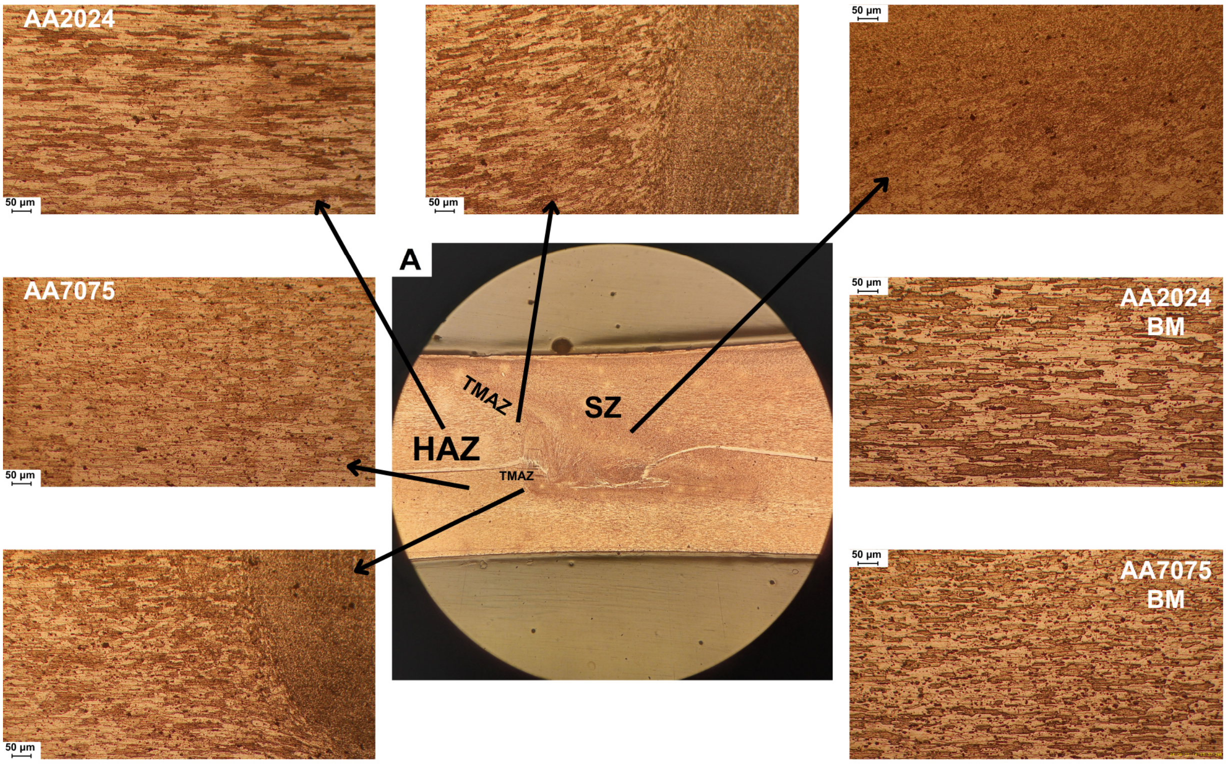

Figure 3.6. Macro and microstructure of Specimen A

Specimen B (welding speed 6 mm/min):

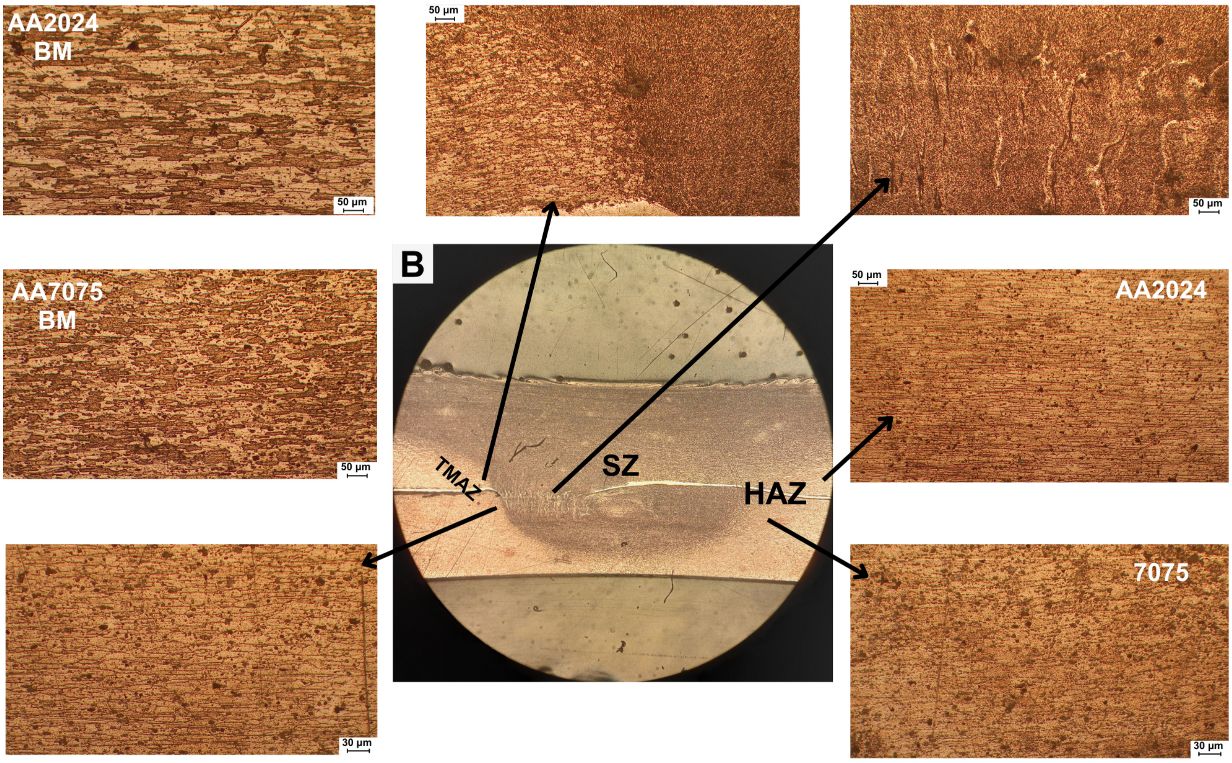

Figure 3.7. Macro and microstructure of Specimen B

Figure 3.6 shows the Macro and Microstructures of the different zones of the Friction stir lap welded joint of Specimen A. and **Figure 3.7** shows the Macro and Microstructures of the different zones of the lap welded joint of Specimen B.

The Lap welded joints appear to be consisted of different welding zones. The large grain size in both BM and HAZ appear to be approximately similar.

In TMAZ, severely deformed and elongated grains are found, which are induced by drastic plastic deformation, these grains are oriented towards the Stir Zone.

A dynamically recrystallized fine equiaxed grains characterize the Stir zone, caused by the drastic deformation induced by the tool stirring during welding.

III- Micro-Hardness testing:

Vickers micro hardness tests conducted over each side of the welding interface with: 0.2 mm above the interface for AA2024 and 0.2 mm below the interface for AA7075

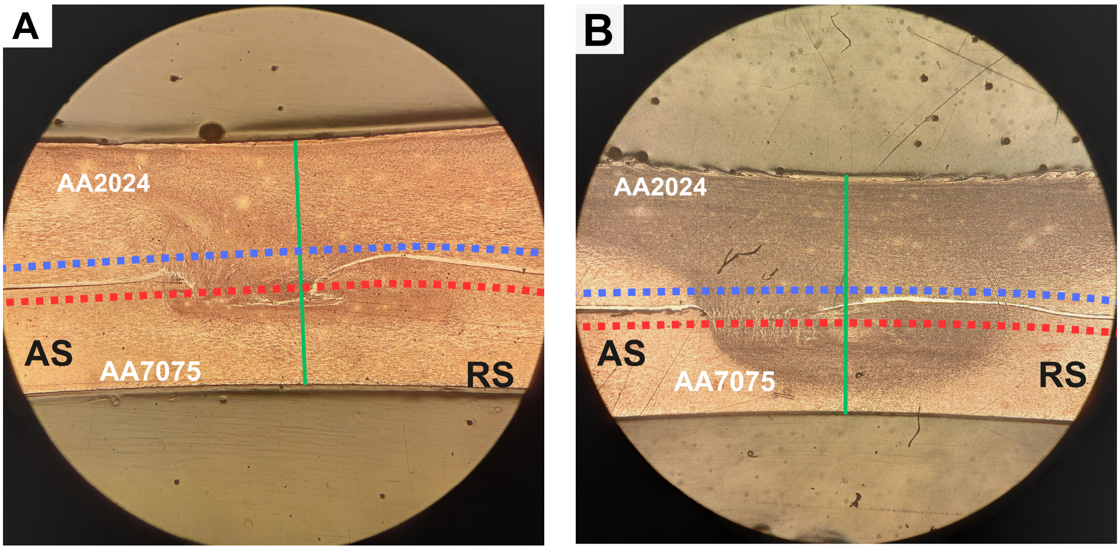

Figure 3.8. Vickers Micro-Hardness testing procedure

These tests allowed us to obtain the following Micro hardness curves:

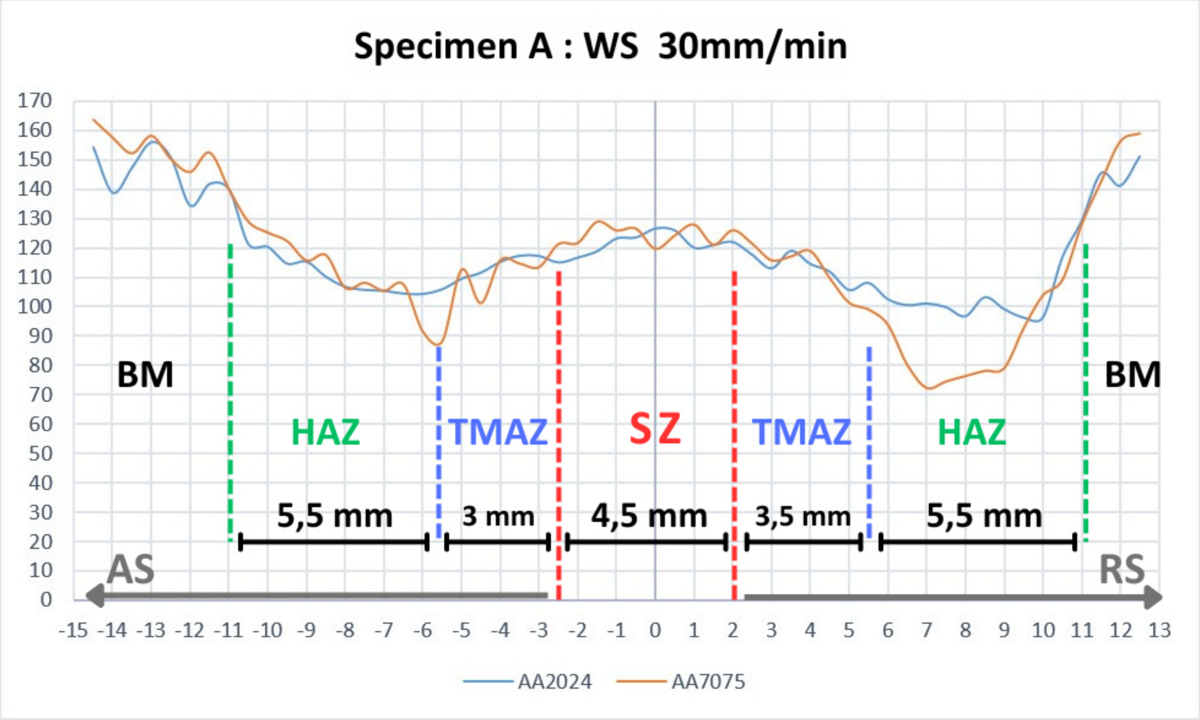

Figure 3.9. Micro-Hardness curves of Specimen A

Specimen B: Welding Speed 6 mm/min:

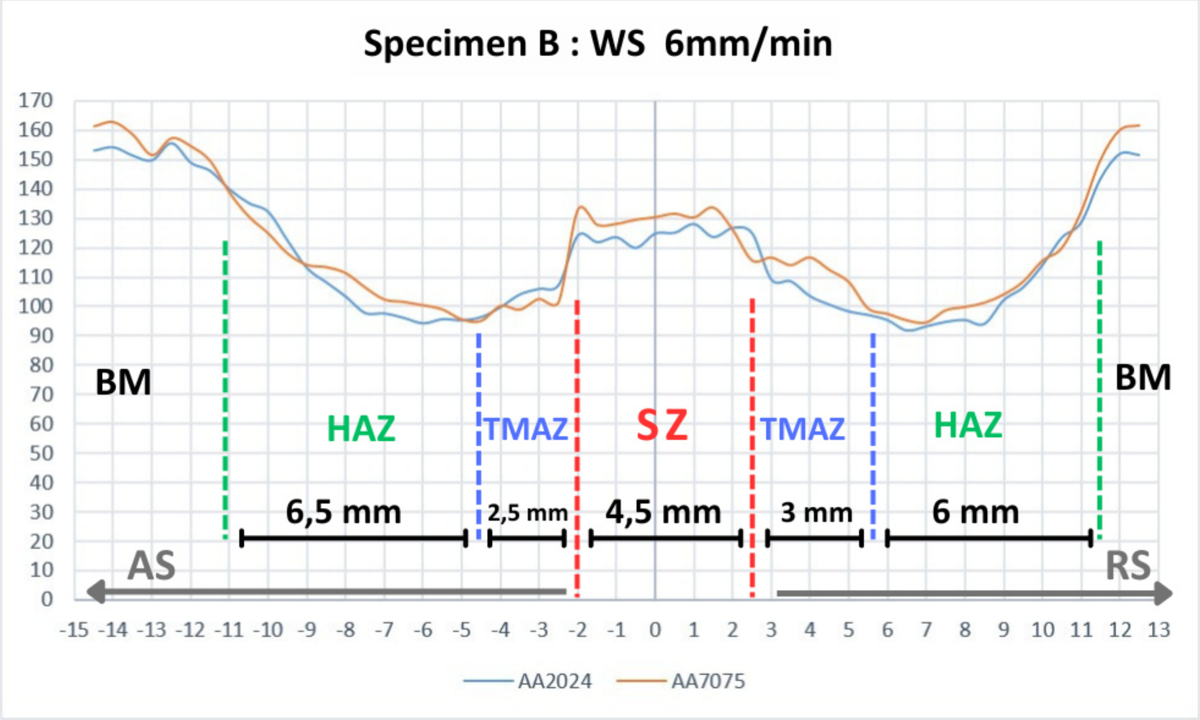

Figure 3.10. Micro-Hardness curves of Specimen B

The average values of Vickers Micro-Hardness test:

VH 0,05	**Specimen A (30 mm/min)**				**Specimen B (6 mm/min)**			
Side	**AA2024**		**AA7075**		**AA2024**		**AA7075**	
	AS	**RS**	**AS**	**RS**	**AS**	**RS**	**AS**	**RS**
Base Metal	145.70		153.71		149.80		154.95	
HAZ	110.58	102.05	110.62	90.61	106.81	103.64	108.60	105.47
TMAZ	114.50	113.81	114.38	114.04	104.34	102.94	100.73	113.90
Stir Zone	122.82		125.03		124.40		129.96	

Table 3.11. Average values of Vickers Micro-Hardness in the different zones of the welds

Figure 3.9 and **Figure 3.10** show the hardness curves of the joints at different welding speeds.

The hardness curve in both of the welds presented a typical "W" morphology along each test of both specimens.

Table 3.11 depicts the average values of Vickers Micro-Hardness in the different zones of both AA2024 and AA7075 of both specimens.

The Micro-Hardness tests were applied 0.2 mm above the welding interface in AA2024 and 0,2mm below the welding interface in AA7075

In Specimen A (**Figure 3.9**) The BM of AA2024-T3 had a hardness of approximately 145.70 HV. The hardness showed an obvious decrease at HAZ and TMAZ. The minimum hardness of approximately 104,5 HV was obtained at HAZ in the Advancing Side, while in the Retreating Side the minimum hardness reached was 96.35 HV, which was attributed to large grain size and less amount of secondary phases. The hardness showed an increase at SZ reaching a maximum of 126.75 HV because of the small grains and perhaps the precipitated secondary phases. In BM AA7075-T6 the hardness was approximately 153.71 HV. The micro-hardness profile showed a decrease at HAZ and TMAZ. The minimum hardness of approximately 88.24 HV was obtained at HAZ in the Advancing Side, at the other hand the minimum hardness of 72.41 HV in the Retreating Side, which was caused by the large grain size and a lack of precipitates. The hardness showed an increase at SZ reaching a maximum of 128.9 HV because of the small grains and perhaps the precipitated phases.

In Specimen B (**Figure 3.10**) The BM of AA2024-T3 had a hardness of approximately 149,80 HV. The hardness showed an obvious decrease at HAZ and TMAZ. The minimum hardness of approximately 94.32 HV was obtained at HAZ in the Advancing Side, while in the Retreating Side the minimum hardness reached was 91.87 HV, which was attributed to large grain size and less amount of secondary phases. The hardness showed an increase at SZ reaching a maximum of 128.17 HV because of the small grains and perhaps the precipitated secondary phases. In BM AA7075-T6 the hardness was approximately 153.71 HV. The hardness showed a decrease at HAZ and TMAZ. The minimum hardness of approximately 95.03 HV was obtained at HAZ in the Advancing Side, at the other hand the minimum hardness of 94.48 HV in the Retreating Side, which was caused by the large grain size and a lack of precipitates. The hardness showed an increase at SZ reaching a maximum of 133.58 HV because of the small grains and perhaps the precipitated phases.

Comparing the sizes of the zones in both of the specimens, we can observe that the Specimen A with the welding speed of 30mm/min shows a little bit larger Thermomechanical Affected Zones but smaller Heat Affected Zones. While in Specimen B with the welding speed of 6mm/min shows a smaller Thermomecanically Affected Zones with larger Heat Affected Zones. This is due to the greater heat flow caused by the slower welding speed.

Conclusion

The aim of this study is to evaluate the effect of the FSW welding speed on the microstructural behaviour and micro-hardness of Lap joints.

The results show the following points:

- Visual observation shows that a lower welding speed causes a flash defect.
- Hook defect is present in both the welds and can diminish the mechanical resistance of the weld.
- The microscopic observation shows the different zones and their grain sizes, the BM and HAZ grains are almost identical in size but gets smaller near the TMAZ. The TMAZ grains are severely deformed and elongated in the orientation of the SZ. The stir zone shows a fine equiaxed grains.
- The micro-hardness tests conducted in both the aluminium alloy sheets along the welding interface, gave us a clear view over the mechanical properties of the welds.
- The curves of VH take the W-shape.
- The values of micro hardness reach the lowest points in the HAZ especially in the Retreating side.
- The welding speed of 6 mm/min resulted in a larger HAZ, and lower VH values in this zone.
- The welding speed of 30 mm/min resulted in a slightly larger TMAZ.

In perspective, we recommend the study of:

- The different parameters of the FSW on lap joints of dissimilar aluminium alloys, like the rotational speed, the force of penetration.
- The evaluation of the resistance of the welded joints with different welding parameters.
- The effect of the tool geometry on the microstructure and resistance of the weld.

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