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Active and Passive filling friction stir repairing of AISI 304 alloy.

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1. Introduction

For many years, the sheet metal fabrication industry, driven by the need to reduce costs, waste, and processing times, has heavily invested in **Friction Stir Repair (FSR)**. This technique has proven particularly advantageous for several reasons:

- **Weld repair:** FSR can be used to repair defects such as voids or cracks that can occur during traditional fusion welding. This helps to avoid discarding the entire workpiece and can save time and money.
- **Repair of existing components:** FSR can be used to repair cracks or damage to existing structural components in various industries such as aerospace, automotive, and construction. This allows for extending the service life of components and reduces the need for replacements.
- **High-strength joints:** FSR creates strong, high-quality joints with mechanical properties close to the original material. This is particularly important for critical applications where reliability is essential.
- **Solid-state process:** Unlike fusion welding which uses heat to melt the metal, FSR is a solid-state process. This reduces distortion of the material and makes it suitable for heat-sensitive metals.
- **Maintenance of structural integrity:** FSR allows parts to be repaired without compromising their structural integrity, ensuring they maintain the same strength and durability characteristics.

In addition to these benefits, FSR is a versatile and adaptable process that can be applied to various component geometries and sizes. Furthermore, it's a relatively safe and environmentally friendly process.

1.1 Literature Review

Before discussing the main experience of this thesis, will be analyzed various aspects of friction stir repair by examining different methodological aspects of the process and observing the work done by various scholars and researchers in the scientific literature.

Friction Stir Spot Welding (FSSW)

FSSR is an application of friction stir spot welding where not only the joining between the two sheets takes place but the repair of any surface defects. Friction Stir Spot Welding is a weld that is done in a single spot (so there is no tool feed rate involved). For the conduct of FSSW process tests, scientific articles used as a starting point are shown here for understand the relation between process parameters and the finished product.

Microstructure and Mechanical Properties of Dissimilar Friction Stir Spot Welding Between St37 Steel and 304 Stainless Steel [1]

Raza and Yapici's objective in this experimental activity is to weld two dissimilar sheets (St37 steel and AISI 304) each with a thickness of 2mm, followed by conducting hardness tests, tensile tests, and drawing conclusions. The tool used has a shoulder diameter of 16 mm, a set shoulder plunge depth of 0.1 mm, and a pin diameter of 2.7 mm and were carried out two sets of experiments with different process parameters.

Set 1) rotation speed 630 rpm, dwelling time 6 s, plunge rate 168 mm/min

Set 2) rotation speed 1250 rpm, dwelling time 6 s, plunge rate 36 mm/min.

Subsequently, a Vickers hardness test was conducted with a 100 g load and a dwell time of 10 s. The tensile test, instead, was conducted at a speed of 2 mm/min. Following this, the sample was examined under a microscope, and conclusions were drawn:

1) The FSSW process has produced solid welds between St37 and 304 steel plates without any local melting and macroscopic cracks in the workpiece or the stir zone at all rotational speeds. The results from XRD and EDS tests confirmed that any intermetallic compounds, particularly chromium carbide, could not be detected in any of the welds created at the rotational speeds of 630 and 1250 rpm.
2) Compared to resistance spot welding (RSW), friction stir spot welding (FSSW) achieved a more uniform distribution of joint hardness.
3) In this investigation, two distinct failure modes were observed through creep studies during the tensile/shear test. These included shear failure and mixed shear/tensile failure. These failure modes varied based on the bond length (weld nugget size), rotational speed, and crack propagation path.

Effects of interlayer on the friction stir spot welding of stainless steel [2]

In this study, Jousefian aims to use FSSW technique to join two 1 mm thick AISI 304 sheets while examining the effect of a 2 mm thick intermediate sheet. Tests were conducted using different techniques to fill the hole:

- The first one is FSSW with a peculiarity: a 2 mm thick Al-Mg-Si sheet has been inserted, allowing a 30% enhancement in the mechanical strength of the joint (Figure 1a).

-The second one is known as Rotational Friction Spot Welding (RFSSW) (Figure 1b). In this case, a pin-tool pair was used, responsible for filling the surface cavity again.

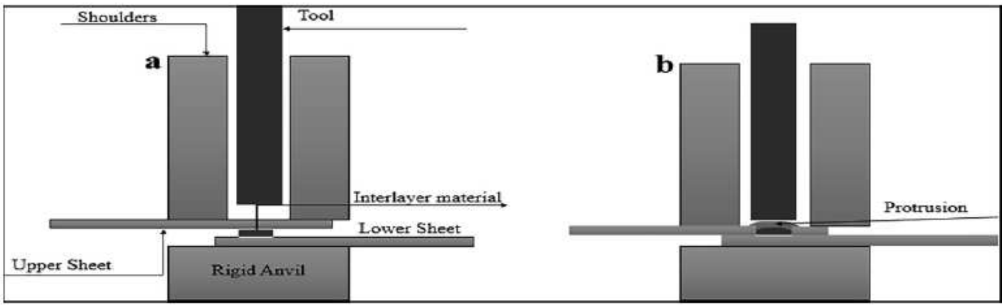

Figure 1: the two different techniques of filling the hole.

The tool used is a Pinless one with a shoulder diameter of 10 mm, a plunge rate of 15 mm/min and a rotation speed of 2000 rpm were selected. After the process, a microscopic check and Lap Shear Analysis were performed, it has been shown that the optimized penetration depth and the material of the intermediate layer have a significant influence on the mechanical properties of the joint, and that:

-Weld joints without a weld hole exhibit consistent mechanical behavior due to the inclusion of interlayer material during FSSW.

- The intermediate material supported the formation of a hook-like structure within the upper sheet, thereby enhancing the strength and ductility of the joint. The joint strength meets AWS standards in terms of load-bearing capacity for the overlap shear configuration.

Microstructure, texture, and mechanical properties of a nickel-free high nitrogen duplex stainless steel processed through friction stir spot welding [3].

Here, the authors investigated the grain refinement mechanism during FSSW of single-crystal austenitic stainless steel. It was found that at a lower penetration depth, continuous dynamic recrystallization is the primary restoration mechanism both in the thermomechanically affected zone (TMAZ) and the stir zone. The semi-finished products were homogenized at 1100 °C for 120 minutes, hot-rolled at a temperature of 1100-1200 °C for 20 minutes, and finally solution-treated at 1100 °C for 30 minutes. The resulting sheets (made of Nickel-free AISI 304) have a thickness of 2 mm. Specimen parts were welded at three rotational speeds (400, 500, and 600 rpm), with a feed rate of 3 mm/min, a depth of 2.5 mm, a dwelling time of 2 s, and a tungsten carbide (WC) tool with an 8 mm diameter and a shoulder diameter of 20 mm.

After conducting both tensile and Vickers hardness tests, it was observed that in the stir zone and the TMAZ, the hardness values are significantly higher than those of the base metal. This is attributed to the development of substructure and grain refinement as well as the precipitation of Cr and N during Friction Stir Spot Welding. The hardness value decreases with an increase in the tool's rotational speed, which can be explained by the grain size increase, as stated by the Hall-Petch equation.

Friction stir spot welding of single-crystal austenitic stainless steel [4]

In this experimental research, Jeon and Mironov investigate the morphological changes during the FSSW of a 5 mm thick specimen entirely made of single-crystal austenitic steel, particularly focusing on the formation of new grain boundaries due to material rotation during the process.

The tool is made of a Cobalt alloy, with a shoulder diameter of 15 mm. The pin has a length of 1.8 mm and tapers from 6.0 mm at the shoulder to 3.5 mm at the tip.

In order to have an accurate idea of the microstructural evolution and material flow during tool penetration, three welding tests were conducted at a constant tool rotation speed of 300 RPM and varying plunge depths of 1, 1.5, and 1.9 mm. It was demonstrated that crystal rotations are primarily associated with simple shear deformation. During the pin penetration phase, the grain structure evolution was dominated by continuous recrystallization, breaking down the single crystal into an ultrafine-grained microstructure with an average grain size of 0.2 μm.

However, during the contact phase with the shoulder, the associated heat input increase induced discontinuous recrystallization, which coarsened the grain structure and led to the recrystallization of the twinned structure. It was deduced that the discontinuous recrystallization was mainly of a static nature and occurred during the FSSW cooling cycle.

Friction Stir Spot Welded Joints of 409L Stainless Steels Fabricated by a Convex Shoulder Tool [5]

In this current study, Hossain and Hasan aim to investigate the deformation of FSSW-welded joints by monitoring the axial force applied during the process. Two 1.2 mm thick 409L stainless steel (SS) sheets were joined using FSSW, employing a tool with a spiral convex shoulder made of a polycrystalline cubic boron nitride (PCBN) compound. The tests were conducted at a rotation speed of 1400 rpm, a traverse speed of 8 mm/min, a plunge depth of 1.45 mm, and a dwell time of 6 s.

The microstructural analysis reveals that the microstructure, which is quite similar to that in the stir zone of FSW joints in the same SS, was induced in the stir zone of the FSSW joint, even though the mixing mechanism of FSSW might be significantly different from that of FSW. The microstructural analysis also suggests that both continuous dynamic recrystallization and recovery occurred in the stir zone during FSSW. The observation of the FSSW joint under the indicated shear load reveals that cracks, resulting from the interfaces between the upper and lower sheets, propagated within the weld along the interfacial surfaces, leading to a shearing/breakage. Ultimately, the fracture extended along the weld circumference and became a typical "tearing fracture" of the nugget.

Exit-hole repairing in friction stir welding of AA5456 pipe using consumable pin [6]

The purpose of the experiment is to assess the capability of the Friction Stir Welding (FSW) process to FSW joint of AA5456-O aluminium as an inner pipe (rolled plate) with a 2.5 mm thickness and AA5456-H321 aluminium as an outer pipe with a 5 mm thickness. using a consumable pin. The Aim is to investigate the effects, pin geometry, rotational speed, and plunge speed on the mechanical properties and microstructure of the joints. The shape of consumable pins was prepared in different types, are shown in table 1.

Cone Angle [°]	Tip Pin Diameter [mm]	Shoulder Diameter [mm]
8	5.31, 4.81 ,4.31	8
9	5.31, 4.81 ,4.31	8
10	5.31, 4.81 ,4.31	8

Table 1: Tool's different features.

Here in table 2 are shown the process parameters whit a short summary of optimized parameters for AA5456 alloy:

Parameter	Tested Values	Parameters for AA5456
Pin Rotation Speed [rpm]	400, 500, 800 , 980	800 rpm
Plunge Speed [mm/min]	1, 5, 20, 50	50 mm/min
Pin Geometry	Various variants	AA5456, Cone Angle: 8°
Preheating	Evaluated effect on FFSW process optimization	Not specified

Table 2: process parameters.

The results and conclusions of the study are as follows:

- Microscopic observations and mechanical tests confirmed that the FFSW process can repair exit holes with adequate mechanical performance. The relative tensile strength is 77% and the relative elongation is 82% compared to TIG fusion welding.
- Preheating and the use of additional external heat sources can improve the efficiency of the FFSW process by facilitating material flow.
- The best result was achieved using a similar consumable pin (AA5456) with an 8° cone angle, a pin length of 8 mm, and a pin tip diameter of 4.31 mm, with a plunge rate of 50 mm/min and a rotation speed of 800 rpm.
- Among the dissimilar pins, the AA2024 pin showed better performance than the AA7075 pin in interfacial mixing.
- No variations in the distribution of chemical elements at the interfaces were observed, and no intermetallic phases were formed.
- Numerical simulation of the FFSW process was in good agreement with experimental results.

In conclusion, the FFSW method using a semi-consumable aluminium alloy pin was effective in repairing exit holes in AA5456 aluminum tube joints, allowing for solid-state welding and mechanical mixing below the junction materials' melting point.

Friction Stir Repair

Now the use of FSSW to repair sheet metal will be addressed (used for the second phase of the experiment)

Friction Stir Repair could be performed in different ways, these are the most important ones:

- Additive manufacturing for Friction Stir Repair (FSAM);

- Active-Passive Filling Friction Stir Repairing (A-PFFSR).

- Self-refilling friction stir Welding (SRFSW)

Each paper will highlight the correlation between the materials, the process chosen (methods, parameters, and tools), and the results obtained in terms of microstructure and macroproperties.

Additive manufacturing for Friction Stir Repair (FSAM)

Is a technique that combines elements of both traditional Friction Stir Repair (FSR) and Additive Manufacturing (AM). utilized a rotating tool that generates frictional heat at the workpiece interface, this heat softens the material, allowing for manipulation and bonding, but unlike FSR, FSAM introduces new material through a feedstock, typically a metal rod or wire.

Here are some articles where we show various facets of the additive manufacturing process applied to stir repair.

Solid-State Metal Additive Manufacturing for Structural Repair [7]

The purpose of this study is to examine the potential of solid-state additive manufacturing of metals for structural repair. The objective is to restore the original geometry of damaged components and ensure good mechanical performance after repair. The study focuses in particular on two additive manufacturing processes: cold spraying and additive friction stir deposition (AFSD). The applications of these processes for repairing surface damage, volumetric filling, feature reconstruction, and crack repair are explored. The strengths and limitations of both processes are identified, and possible future research directions are suggested to improve their performance.

Cold spray involves accelerating small metal particles to high velocities using a high-pressure gas. When these particles impact a substrate, they undergo deformation and create interfacial bonding and mechanical interlocking. This process can repair surface damage, such as corrosion and wear, and is particularly suitable for field repair due to its portability. However, it may result in porosity in the as-deposited state, especially in high-strength materials.

AFSD utilizes frictional heat and plastic deformation to achieve strong bonding and create fully dense as-repaired materials. It can be used to repair various types of damage, including surface damage, volumetric filling, feature reconstruction, and crack repair. AFSD offers excellent mechanical properties in the as-repaired state and is particularly suitable when structural integrity is a high priority. However, it requires accurate and rigid positioning of the tool head and is currently less portable compared to cold spray.

The advantages of both processes include the absence of melting, which prevents issues like solidification porosity and high residual stress associated with fusion-based repair approaches. Cold spray is highly portable and suitable for field repair, while AFSD provides excellent mechanical properties. However, both processes have limitations. Cold spray may result in porosity in the as-deposited state, especially in high-strength materials. AFSD requires precise positioning and is currently less portable. Further research is needed to improve porosity control and deposition precision in cold spray, as well as scalability and material choice in AFSD.

Additive Friction Stir-Enabled Solid-State Additive Manufacturing for the Repair of 7075 Aluminium Alloy [8]

The purpose of this study is to investigate the use of solid-state friction deposition for the repair of volumetric damage in AA 7075. The study focuses on repairing cylindrical holes and long, wide square grooves. The aim is to assess the repair strategy, examine the quality of the repair, and compare it with other repair approaches. The ultimate goal is to achieve high-quality and highly flexible repairs using solid-state friction deposition. The repair process involves additive friction stir deposition, which gradually transitions the material flow from the base material to the stirred material. This ensures strong adhesion between the base material and the repair volume, minimizing the likelihood of failure. Sufficient material flow eliminates any sharp interface between the deposited material and the side wall of the hole or groove, resulting in a gradual transition and improved repair quality. However, in the lower portions of the repair, cracks and kissing bonds can be observed, indicating a lack of mixing between the side wall and the deposited material. Optimization of processing conditions can lead to significantly improved repair quality, in table 3 they are summarized:

Experiment	Repair Type	Travel Path	Repair Dimensions [mm]	Processing Conditions
1	Double-hole filling	Travel, dwell, travel	6.35 and 3.76 cylindrical	Traverse Speed: 0.32 mm/s; Linear Feed Rate: 0.1 mm/s
2	Single hole filling	Travel, dwell, lift	6.35 cylindrical	---
3	Long, wide groove filling	Travel	Long square groove: 12.7 wide, 3.76 deep	Traverse Speed: 0.42 mm/s; Linear Feed Rate: 0.06 mm/s

Table 3: Summary of the experimental details.

Despite the imperfect repair quality, the results are promising. With systematic optimization work on process control and repair strategies, achieving high-quality and highly flexible repairs using additive friction deposition is anticipated.

Evaluation of additive friction stir deposition of AISI 316L for repairing surface material loss in AISI 4340 [9]

The purpose of the study is to assess the deposition of AISI 316L using the Additive Friction Stir Deposition (AFSD) technique to repair the loss of surface material in AISI 4340. The research provides valuable insights into potential repair strategies for AISI 4340 steel using the deposition technique of AISI 316L through AFSD. Additive Friction Stir Deposition (AFSD) is an additive manufacturing technique that combines material deposition and mechanical processing to create or repair existing parts. In this technique, a non-consumable rotating tool is used to mix and deposit the feed material onto the substrate surface. The feed material is supplied through a central channel of the rotating tool, while the tool itself is moved along the substrate surface to deposit the material. In the experiment, two different repair geometries were employed: groove filling and surface coating. Metallography, microhardness, and wear and mechanical tests were conducted. Two different steel alloys were utilized: AISI 4340 as the substrate and AISI 316L as the feed material for deposition through AFSD. The welding parameters chosen for this study are: Tool rotation rate=500rpm, translation speed=102 and 204 mm/min (two different set of operation), with a depositation rate of 26640mm^3/min.

Two different repair geometries were evaluated: groove filling and surface coating. The results of metallography, microhardness, wear, and mechanical tests demonstrated that the microstructure of the deposited material was refined with a reduction in grain size and plastic deformation, albeit with a decrease in strength and hardness compared to the original feed material. However, the corrosion resistance of the deposited material was improved compared to the original substrate. Overall, the results suggest that the AFSD technique can be employed as an effective repair strategy for surface material loss in AISI 4340.

Evaluation of Microstructure and Mechanical Properties of Al-Zn-Mg-Cu Alloy Repaired via Additive Friction Stir Deposition [10]

The objective of this study is to evaluate the microstructure and mechanical properties of an Al-Zn-Mg-Cu alloy repaired using the solid-state friction-based additive manufacturing process (AFS-D). The AFS-D technique was applied by using a rotating tool with a specific geometry to mix and deposit the filler material into the damaged area. The rotating tool is inserted into the damaged area and moved along the groove to deposit the filler material. The feedstock is deposited through the center of the hollow rotating tool via an actuator that forces material onto the softened substrate. The combination of pressure, frictional heat, and severe plastic deformation of both substrate and feedstock creates a metallurgical bond, which allows for deposition of consecutive layers upon a substrate. After repairing the plate with the AFS-D process, the repaired plate was subjected to standard T6 heat treatment. The microstructure was analysed through EBSD scans and post-mortem analysis. Mechanical properties were evaluated through tensile and fatigue testing.

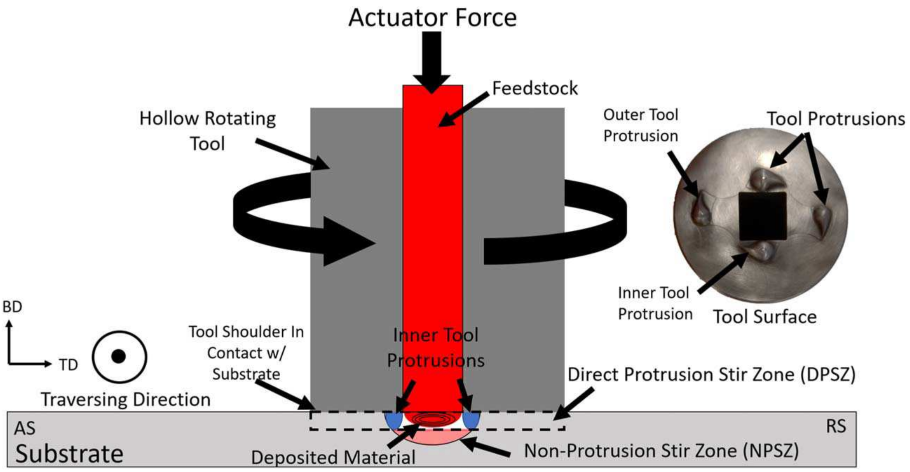

Figure 2: Schematic of the AFS-D repair process for depositing the feedstock within the damaged region.

The depositional parameters were 225 rpm tool rotational speed, with feedstock feed rate of 50.8 mm/min, and traversing velocity of 50.8 mm/min. The tool features four protrusions on the front side, each extending 2.23 mm into the substrate. These protrusions are arranged in pairs and are offset from the center of the tool.

Optical analysis and EBSD (Electron Backscatter Diffraction) revealed variations in the microstructural characteristics of the repaired plate, highlighting differences between the Direct Protrusion Zone (DPSZ) and the Non-Protrusion Mixing (NPSZ).

The DPSZ exhibited a uniform microstructure of equiaxed grains without material flow lines, while the NPSZ was characterized by material flow lines between the substrate and the deposited material. These findings provide valuable insights into the repair and resulting microstructure, contributing to the understanding and optimization of additive manufacturing processes.

Repair of aluminium 6061 plate by additive friction stir deposition [11]

The objective of this study is to investigate the use of Additive Friction Stir Deposition for repairing sheets made of Al 6061-T651. The research focuses on filling grooves made on the surface of the sheet using AFSD with filling material in 6061-T6 alloy. The goal is to assess the effectiveness of the AFSD process in repairing aluminum sheets and analyze the mechanical properties of the filling material, as well as the limitations of the AFSD process. Three groove geometries (V, R, and S) were evaluated, and process parameters were adjusted to ensure adequate deposition rates and complete groove filling. After deposition, metallographic analyses, tensile tests, and fatigue tests were conducted to assess the effectiveness of the AFSD process and the mechanical properties of the samples. Tensile tests were performed according to ASTM B557-15, while fatigue tests involved fully reversed loading cycles (R = -1) controlled by the load. The test results were analyzed to evaluate the quality of repairs and the mechanical performance of the samples.

Layer number	2			3	4
Groove geometry	V	R	S	R	R
Tool rotation rate, ω [RPM]	325	325	325	325	325
Feedstock feed rate, V_{feed} [mm/s]	2.1	1.3	2.5	2.5	2.5
Tool translation speed, V_{tool} [mm/s]	2.8	3.4	2.1	3.4	2.5
Layer thickness, z_{step} [mm]	1.0	0.5	1.0	1.0	1.0
Layer cross section, $W_{tool} \cdot z_{step}$ [mm^2]	39.0	19.9	39.0	39.0	39.0
Deposition rate, R_{dep} [mm^3/s]	187.3	112.2	224.4	224.4	224.4
Volume of layer at traverse rate, R_{layer} [mm^3/s]	107.3	67.4	82.7	132.2	99.1
Fill ratio, R_{dep}/R_{layer}	1.7	1.7	2.7	1.7	2.3

Table 4: parameters for cover passes.

The conclusions reached are as follows:

1) Additive Friction Stir Deposition (AFSD) has been assessed as an effective method for filling grooves in 6061-T651 aluminium sheets.
2) The microstructures of AFSD samples exhibit effective mixing between the filling material and the substrate to a depth of over 3 mm.
3) Below this depth, poor adhesion between the filling material and the substrate was observed due to insufficient deformation.
4) The mechanical properties of the filling aluminium were evaluated as superior to code requirements and published results for fusion welding of 6061-T6 aluminium.
5) Opportunities for process optimization through ongoing development were identified, including optimizing tool and groove geometries, process parameters, and filling material selection.

Limitations of the AFSD method identified in the study, such as effective mixing depth and loss of temper in the precipitation-hardened alloy, could be mitigated with further optimizations.

In summary, the study demonstrated that Additive Friction Stir Deposition can be used to repair 6061-T651 aluminum sheets, but there are limitations that require further process improvements.

Wire-Based Friction Stir Additive Manufacturing toward Field Repairing [12]

The objective of this study is to address the issues related to large cracks or partial wear in structural parts made of aluminum alloy. A solid-state repair approach called wire-based friction stir additive manufacturing (W-FSAM) is proposed, which allows for continuous wire feeding without a large axial force compared to conventional solid-state repair technologies and is suitable for field repairs.

The aim is to restore the original geometry of the part and improve its mechanical performance, thus reducing costs. The process is carried out using a technique called wire-based friction stir additive manufacturing (W-FSAM). This technique involves the continuous feeding of wire without a large axial force compared to conventional solid-state repair technologies. In the W-FSAM process, a threaded screw is used to continuously transport and compress the thermoplastic materials. The pin probes facilitate the plastic flow of the filler materials inside the pre-repair groove. During the process, the thermoplastic materials come into direct contact with the edges of the groove thanks to the mixing effect of the probes. This promotes heat dissipation, resulting in the formation of fine grains. The W-FSAM process allows for good adhesion and filling between the feeding materials and the side edges of the groove, producing a repaired area with recrystallized grains.

The process parameters used in the W-FSAM process are as follows in Table 5:

Parameter	Wire feed speed [mm/min]	Rotation speed [rpm]	Feed speed [mm/min]	Pluge depth (for probes) [mm]	Diameter of movable shoulder at the root of the probes [mm]	Diameter of fixed shoulder on the storage chamber [mm]	Diameter of Al-Si alloy wires used as feed materials [mm]
Value	3000	1200	600	0.1	14	24	2.4

Table 5: Process parameters.

These parameters have been selected to achieve good adhesion and filling between the feed materials and the side edges of the groove, producing a repaired zone with recrystallized grains.

The conclusions of this study are as follows:

1) A solid-state repair technique called wire-based friction stir additive manufacturing (W-FSAM) has been proposed for repairing volumetric defects in structural parts;
2) The W-FSAM technique allowed for good adhesion and filling between the feedstock materials and the sidewalls of the groove, producing a repaired zone with recrystallized grains;
3) The mechanical properties of the parts repaired with the W-FSAM technique reached 93% and 98% compared to the base metal in terms of ultimate strength and percentage elongation, respectively;
4) The W-FSAM technique has demonstrated the ability to achieve nearly equal strength repairs compared to traditional welding repair technologies.

Towards Friction Stir Remanufacturing of High-Strength Aluminum Components [13]

The aim of this study is to examine the repair of volumetric defects in high-strength aluminum alloy components through the Friction Stir Remanufacturing (FSR) technique. Various consumable pins for FSR have been designed, and the effects of the conical angle of the pin on load transmission and pin fracture have been examined before the dwelling phase, and are descripted in Table 6:

Pin type	Top diameter (mm)	Conical angle (°)
1	3.4	13
2	3.4	14
3	3.4	15
4	3.4	16
5	3.2	14
6	3.6	14
7	3.8	14

Table 6: Geometric dimensions of the consumable pins.

The study involved four main processes for repairing volumetric defects using FSR technique:

- Plunging stage: The rotating pin was plunged into the conical hole (Figure 3(a));

Repairing stage: The rotating pin was held in position for 5 s after the shoulder contacted the upper surface of the workpiece. During this phase, the pin was broken due to the combined effects of material softening and load transfer (Figure 3(b));

- Processing stage: The rotating pin moved along the processing direction to forge the repaired zone (Figure 3(c));
- Retracting stage: The rotating pin was retracted from the workpiece (Figure 3(d));

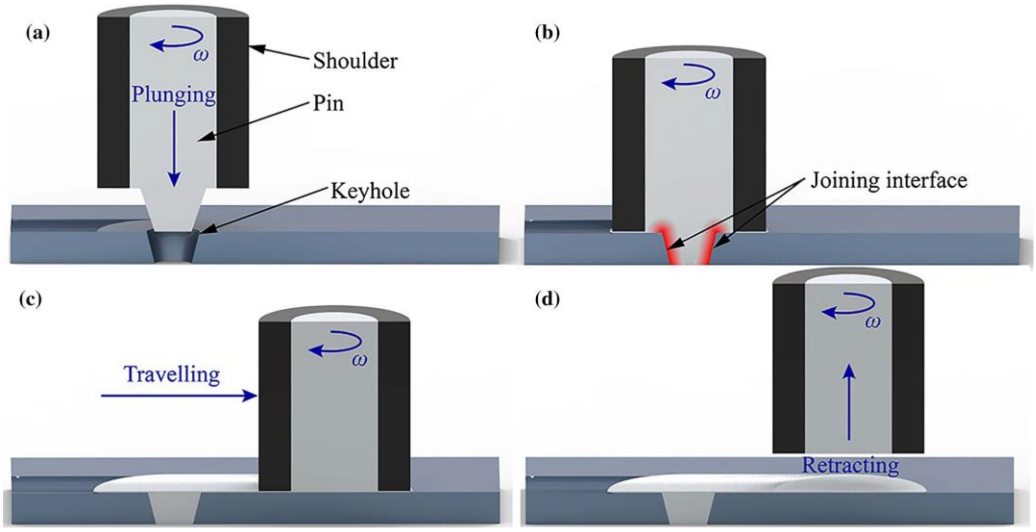

Figure 3: Working principle of the consumable pin in the friction stir remanufacturing.

For the experiment were chosen a constant rotational velocity of 800 rpm, a plunge speed of 2 mm/min, and a processing speed of 300 mm/min were employed under a tilting angle of 1.5°. The plunge depth of the shoulder was 0.1 mm. Different tool with different conical angle were used.
The results of the study have demonstrated that the Friction Stir Remanufacturing (FSR) technique is effective in repairing volumetric defects in high-strength aluminium alloy components. Specifically, the use of consumable pins with a conical angle of 3° led to increased load transmission and reduced pin fracture compared to other conical angles. Furthermore, the repaired zone exhibited a surface free of noticeable defects. The tensile strength of the repaired zone was evaluated and compared with that of a defect-free reference object, demonstrating that FSR can effectively repair defects without compromising the component's strength.

Active-Passive Filling Friction Stir Repairing (A-PFFSR).

Is a welding technique used to eliminate forging defects, such as cavities and porosity, in metals. It works by melting the material surrounding the defect and mixing it with additional filler material to create a solid joint. It is still a developing technique, but it can be optimized for repairing critical metal components in industries such as aerospace and automotive. This technique can repair casting defects that would be difficult to achieve with other methods by imparting high mechanical properties, close to those of the base metal, however, there the process can generate a lot of heat, which could affect the properties of the surrounding metal and more time is needed to carry out the process.

This method ingeniously merges the principles of both active and passive filling, leveraging their unique advantages to achieve superior repair results.

Firstly, let's delve into the realm of active filling. During this phase, supplementary material is introduced to the afflicted joint, strategically targeting areas of concern. This added material, often an alloy or metal compatible with the joint, serves to fortify and reinforce weakened sections. Utilizing the energy harnessed from friction stir welding, this filler material seamlessly integrates into the joint, bolstering its structural integrity.

Conversely, passive filling operates on a different principle. Rather than introducing additional material, the focus shifts to the redistribution and blending of existing material within the damaged region. Through the precise manipulation of the friction stir welding tool, the aim is to realign and consolidate the material, effectively eradicating defects and bolstering the joint's resilience. This phase showcases the ingenuity of leveraging the inherent properties of the joint material itself for repair purposes. By seamlessly integrating both active and passive filling methodologies, this approach offers unparalleled versatility and efficacy in joint repair. Initially, active filling addresses specific concerns, such as filling gaps or reinforcing critical areas. Subsequently, the passive phase seamlessly blends the added material with the existing substrate, ensuring a harmonious transition and optimal repair outcomes.

Here are some articles where some details and variations of the Active-Passive Filling Friction Stir Repairing process are shown.

Active-passive filling friction stir repairing of casting defects in ZL210 aluminium alloys [14]

In this experiment Active-passive filling friction stir repairing (A-PFFSR) was employed to eliminate the casting defects in the base material. In the A-PFFSR process, casting defects were initially drilled using a gradually tapered drill. Subsequently, the keyhole-shaped defect was filled with materials from the surrounding area and additional filling material. The process utilized a non-threaded pin tool with six spiral grooves. The procedure was divided into two phases: the Active Filling (AF) phase and the Passive Filling (PF) phase. The filling material was then softened and transferred under high temperature and material flow produced by the non-threaded pin tool's rotation. Finally, a Surface Friction Stir Repair (SFSR) phase was performed, during which the rotating tool moved straight for 15 mm after a 5-second pause. This way, volumetric defects, such as the keyhole-shaped defect, could be completely filled and repaired. In the table , all the process parameters adopted for this study are reported.

Parameter	Range/Value
Rotation Speed [rpm]	800-1200
Traverse Speed [mm/min]	50
Filling Depth [mm]	1-1.5
Shoulder Diameter (1st phase AF) [mm]	6
Shoulder Diameter (2nd phase AF) [mm]	10
Pin Length [mm]	4

Table 7: Process Parameters.

The results of the study indicate that the rotational speed has a significant effect on the mechanical properties of the repaired joints. With an increase in rotational speed, the tensile strength and elongation of the repaired joint initially increase before decreasing. Additionally, it was observed that the formation of a high-quality welding surface, the development of homogeneous interfacial microstructures, and the reduction of weld thinning are important factors influencing the mechanical properties of the repaired joints. Specifically, it was noted that a rotational speed of 1200 rpm led to minimum tensile strength and elongation due to the occurrence of stress concentration phenomena both in the welding zone and on the surface of the joint during the tensile test. Furthermore, the reduction in weld thinning reduced the support area of the repaired joint, further decreasing tensile strength. In general, the study has demonstrated that the A-PFFSR process can be successfully used to repair casting defects in aluminium alloys, and the selection of appropriate process parameters is crucial to achieving repaired joints with satisfactory mechanical properties.

Eliminating Keyhole by Ultrasonic-Assisted Passive Filling Friction Stir Repairing Process [15]

The aim of this study is to investigate the effect of adding ultrasound to the Ultrasound-Assisted Passive Filling Friction Stir Repair (U-PFFSR) process for repairing volumetric defects, such as "keyholes," in an AZ31B magnesium alloy. The objective is to assess how ultrasound influences surface formation, microstructural properties, microhardness, and tensile strength properties of the repaired joints. In the experiment, an AZ31B magnesium alloy was used as the base material. The procedure for the Ultrasound-Assisted Passive Filling Friction Stir Repair (U-PFFSR) process was divided into four phases:

1) Drilling: During this phase, a pinless tool with a diameter of 10 mm was used to drill a "keyhole" with a depth of 1.5 mm.
2) Filling: Subsequently, a filling material (FM) was inserted into the "keyhole."
3) Repair: During this phase, the rotating pinless tool with a diameter of 14 mm made contact with the filling material, continued moving along the depth of the "keyhole" to a predetermined depth, and paused for a few s. Ultrasound was active during this phase.
4) Surface Repair: Finally, a Surface Friction Stir Repair (SFSR) process was performed, during which the rotating tool moved along the upper surface of the AZ31B magnesium alloy plate to achieve optimal surface formation of the repaired joint.

During the Ultrasound-Assisted Passive Filling Friction Stir Repair (U-PFFSR) process, the following process parameters were utilized:

- Ultrasound Power: Various ultrasound powers were tested, including 250, 500, 750, and 1000 W.
- Ultrasound Vibration Frequency: The ultrasound vibration frequency was maintained at 19 kHz.
- Tool Rotation Speed: The tool rotation speed was kept at 1200 revolutions per minute.
- Tool Plunge Speed: The tool plunge speed was maintained at 2 mm/min.
- Tool Plunge Depth: The tool plunge depth was kept at 0.1 mm.

These parameters were adjusted to assess the effect of ultrasound on the repair process and the properties of the repaired joints.

Microstructural analyses and tensile strength tests were conducted during the experiment to evaluate the properties of the repaired joints.

Here is what emerges from the post-process experimental analyses:

1) Surface Appearance: The addition of ultrasound led to a reduction in the size of flashes on the upper surface of the repaired joint, resulting in a smoother surface with fewer visible flashes.
2) Microstructure and Interface Behaviour: Ultrasound influenced the size and shape of the Stir Zone (SZ) and eliminated "kissing bond" defects between the filling material (FM) and the base metal.

3) Microhardness: Ultrasound affected the microhardness distribution, with an increase in microhardness in the Stir Zone (SZ).
4) Tensile Strength Properties: The addition of ultrasound significantly increased the tensile strength of the repaired joint. Ultrasound has proven to enhance the quality of the repair process, reducing defects, and improving the mechanical properties of the repaired joint. In summary, the addition of ultrasound has led to significant improvements in the quality and properties of the repaired joints, demonstrating the potential of ultrasound as an effective method for repairing volumetric defects in magnesium alloys.

Multilayer friction stir plug welding: A novel solid-state method to repair cracks and voids in thick aluminium plates [16]

The purpose of the study conducted by researchers is to develop and evaluate a new repair method called "active-passive filling friction stir repairing" (A-PFFSR) to eliminate volumetric defects such as keyholes, tunnels, and cavities that occur during the friction stir welding (FSW) process in joints of 7N01-T4 aluminium alloys. These defects can be detrimental to the mechanical properties of welded joints. The specific goal is to successfully repair a 4 mm deep keyhole and achieve improved metallurgical alloy under rational parameters using the A-PFFSR process. Additionally, the study aims to investigate the effect of the non-threaded tool rotational speed on the microstructures and mechanical properties of the repaired joints, with the intention of optimizing the process and enhancing the quality of the repaired welds. The A-PFFSR process unfolds in several phases:

1)Defect Preparation: Before initiating the repair, a keyhole is created in the welded joint to simulate a defect that needs repairing.

2)Active Filling (AF): This phase involves actively filling the keyhole with material from the surrounding zones of the defect. Pinless tools with different diameters are used to fill the keyhole in multiple steps, starting with a smaller diameter tool and progressively increasing;

3)Passive Filling (PF): Following active filling, the process moves to passive filling, which involves using additional filling material of the same type as the base material (BM). The filling material is placed in the defect area and worked with the pinless tool to fully integrate it into the joint;

4)Surface Friction Stir Repairing (SFSR): This final phase entails moving the tool along the weld to improve the surface formation and reduce the possibility of adhesion defects (kissing bond defects);

Here in Table 8 are shown all the available parameters about the process:

No.	Tool Rotational Speed (rpm)	Dwell Time (s)	Shoulder Diameter [mm]	Pin Diameter [mm]	Pin Lenght [mm]
1	1000	5	11, 15, 18	4	5
2	1000	10	11, 15, 18	4	5
3	3000	5	11, 15, 18	4	5
4	3000	10	11, 15, 18	4	5

Table 8: Process Parameters and tool geometry.

The A-PFFSR technique has been successfully employed to repair 4 mm deep defects in friction stir welded (FSW) joints of the 7N01-T4 aluminum alloy.

1) The use of pinless tools with different diameters and additional filling material has enabled the achievement of defect-free joints, avoiding issues such as cavities or incomplete bonds.
2) Increasing the rotational speed during the A-PFFSR process has improved material flow and joint quality, eliminating defects and enhancing mechanical properties.

3) The mechanical properties of the repaired joints, such as tensile strength and elongation, reached maximum values at a rotational speed of 1600 rpm, equivalent to 82.1% and 95.8% of a defect-free FSW joint, respectively.

Drilling-filling friction stir repairing of AZ31B magnesium alloy [17]

The aim of this study is to assess the effectiveness of the friction drilling-fill repair technique for addressing volume defects near the structural surface of metal, utilizing AZ31B magnesium alloy as the test material. The experiment was conducted using a Friction Drilling-Fill Repair (D-FFSR) technique, involving the use of two pinless tools with different shoulder diameters and an additional filling material. The microstructural evolution, material flow, hardness, and tensile properties of the AZ31B magnesium alloy D-FFSR joints were investigated. The base material used was a hot-rolled AZ31B magnesium alloy sheet with a thickness of 3 mm, a width of 180 mm, and a length of 200 mm. Microstructural and mechanical tests were prepared to evaluate the properties of the repaired joint.

Here in Table 6 are reported the process parameters:

Fase	Kind of tool	Shoulder Diametrer [mm]	Rotational Velocity [rpm]	Dwell Time [s]	Plunge Depths [mm]	Width of Groove [mm]	Depth of Groove [mm]
Drilling Stage	Pinless	10	1600	-	1.5	-	-
Filling Stage	Pinless	14	1600	20	0.2, 0.3, 0.4, 0.6	1	0.5

Table 9: Summary of the experimental details.

Below are Huang and Ji's final considerations:

1)The volume defect characterised by the keyhole was successfully repaired and the sound joint without obvious thickness reduction was achieved.

2) The microstructures at the FAZ and DAZ were featured by fine and equiaxed grains that were larger than 10 μm, thereby resulting in the flat hardness distribution of the repaired joint.

3) The tensile strength and elongation of the D-FFSR joint using the plunge depth of 0.4 mm reached the maximum values of 217 MPa and 8%, which were quasi equal to the tensile properties of the superior conventional FSW joint. The fracture surface morphologies of the repaired joint exhibited the typical ductile fracture feature.

Microstructures and mechanical properties of 7N01-T4 aluminium alloy joints by active-passive filling friction stir repairing [18]

The purpose of the study is to introduce a friction stir repair method called active-passive filling friction stir repairing (A-PFFSR) to address the disadvantages induced by volumetric defects in friction stir welding. This aims to enhance the metallurgical aspects and mechanical properties of the welded joints. The experiment was conducted using a 4 mm thick plate of 7N01-T4 aluminium alloy as the base material. Repair experiments were carried out using an FSW-3LM-4012 machine. The inclination angle relative to the Z-axis was 2.5°. All holes were produced in the sound FSW joint of the 7N01-T4 aluminium alloy at a rotation speed of 2000 rpm and a welding speed of 30 mm/min. The constant plunge speed was 2 mm/min, and the dwell time was 5 s. The rotation speeds were varied, namely 1000 rpm, 1200 rpm, 1400 rpm, and 1600 rpm, respectively. The study results have demonstrated that the A-PFFSR repair method can significantly enhance the metallurgical welding and mechanical properties of the repaired FSW joint. Additionally, it has been shown that the rotational speed of the friction stir device has a significant effect on the microstructure and mechanical properties of the repaired joint. Specifically, a higher rotational speed led to increased plastic deformation and higher tensile strength of the repaired joint. The study's conclusions suggest that the A-PFFSR repair method can be successfully employed to repair FSW joints in 7N01-T4 aluminium alloys and may provide an effective alternative to traditional repair methods.

New technique of radial-additive friction stir repairing for exceeded tolerance holes [19]

The purpose of the study is to assess the mechanical properties and surface morphology of regions repaired through the radial additive friction stir repair technique (R-AFSR). The study focuses on analysing material flow behaviours, microstructures, material hardness, and mechanical properties of the repaired regions to evaluate the effectiveness and potential of this innovative repair technique. The radial additive friction stir repair technique (R-AFSR) has been developed to repair holes with excessive tolerances. During the process, a rotating tool consisting of a cylindrical threaded pin and a grooved shoulder is utilized. The technique involves drilling, filling, repairing, and withdrawing phases. Initially, the pinless tool is plunged into the workpiece, creating a cylindrical-shaped hole. Subsequently, filling material is inserted into the hole, and the rotating tool is gradually immersed into the workpiece to a predetermined depth. Finally, after the withdrawal of the rotating tool, the hole with excessive tolerance is repaired, resulting in high-quality repair interfaces.

Rotation Speed [rpm]	Plunge Speed [mm/min]	Dwelling time [s]	Shoulder diameter [mm]	Pin length	Pin diameter[mm]
1200, 1400, 1600	2	20	14	2,8	8

Table 10: Tool geometries and features for R-AFSR process.

Mechanical tests such as tensile and compressive shear tests, microhardness tests of the repaired region, and optical microscope inspections were conducted. The experiment results indicate that the "radial-additive friction stir repairing" (R-AFSR) technique was successful in repairing out-of-tolerance holes caused by wear and corrosion. During the R-AFSR process, high-quality repaired regions were obtained without thickness reduction. The microstructures of the thermomechanically affected zone (TMAZ) in the repaired region exhibited fine and equiaxed grains, while the heat-affected zone (HAZ) consisted of coarse grains. Additionally, black lines were detected at the interface between the filling metal (FM) and the base metal (BM) in samples at different rotation speeds (1400 and 1600 rpm). The presence of black lines was attributed to strong thermomechanical flow. The microhardness of the repaired region was measured, revealing a grain size distribution that increases and then decreases from the SZ to the BM. Microstructures in different zones were analyzed in detail, revealing significant differences between BM, HAZ, TMAZ, and SZ.

The study's conclusions indicate that the R-AFSR technique has the potential to successfully repair out-of-tolerance holes, relying on atomic diffusion induced by severe thermomechanical behaviors. Furthermore, it was highlighted that the choice of the pin rotation direction significantly influences the repair outcome. The results indicate that defects at a heat-affected interface can be reduced by selecting the appropriate pin rotation direction. The proposed repair methodology offers advantages such as the formation of a repaired region without reduced thickness and the elimination of the "kissing bond" defect at the interface between FM and BM. The microstructure and mechanical properties of the repaired regions were evaluated in detail, demonstrating the success of the proposed technique in repairing out-of-tolerance holes.

Solid-State Repair of Casting Defects in ZL210 Aluminium Alloy [20]

The objective of this study was to investigate the effects of plunge speed on the microstructures and mechanical properties of repaired joints in ZL210 aluminium alloys using the active-passive filling friction stir repairing (A-PFFSR) method. The aim was to determine the optimal plunge speed that would eliminate interfacial defects and improve the tensile strength of the repaired joints. In the study, metallurgical samples were used, cut from repaired joints. During the repair process, different immersion speeds were used to evaluate the effect on the formation of repaired joints. The repair process was performed using the active-passive friction stir filling repair (A-PFFSR) method:

1) Active filling phase (AF): During this phase, the pinless rotating tool is plunged into the conical hole and then withdrawn. The surrounding materials are continuously compressed into the keyhole by the pinless tool, filling the hole to a certain depth.
2) Passive filling phase (PF): During this phase, additional filling material is inserted into the enlarged hole with a relatively small depth produced by the AF phase. The filling material is heated and softened and transferred under the action of heat and material flow.
3) Surface friction stir stretching phase (SFSR): In this phase, the rotating tool moves in a straight line for 15 mm after a 5-second pause. This phase is used to complete the repair of volume defects such as the keyhole.

Here below in Table 11 are shown the main parameters that remain constant for each weld while varying the plunge speed:

Parameter	Plunge speed [mm/min]	Shoulder diameter [mm]	Repair depth[mm]	Height of filling material (PF) [mm]	Rotation speed [rpm]	Inclination angle (Z-axis) [°]
AF - First phase	1, 2, 4, 6	6	1	2	1600	2.5
AF - Second phase		10	1.5			
PF- Passive fase		14	1.5			

Table 11: Process parameters.

Additionally, temperatures were measured during the repair process using K-type thermocouples to analyse the thermal cycle in the filling zone. The microstructures of the repaired joints were characterized using a scanning electron microscope (SEM), while microhardness was measured using a microhardness tester.

The conclusions of the study are as follows:

1) Casting defects were successfully eliminated using the A-PFFSR method, effectively avoiding shrinkage defects, porosity, and cavities associated with the fusion welding process.
2) The formation of joints is influenced by the immersion speed. At lower immersion speeds, the surface appears relatively smooth, while at higher immersion speeds, a waveform morphology with large burrs is observed.
3) The mechanical properties of the repaired joints depend on the immersion speed. Joints repaired at the lower immersion speed (1 mm/min) exhibit a maximum tensile strength almost equivalent to that of the base alloy. Conversely, at higher immersion speeds, interfacial defects and welding thinning are observed, significantly reducing the mechanical properties.
4) The microstructures of the repaired joints show good interfacial integrity at lower immersion speeds, while at higher immersion speeds, interfacial defects and welding thinning are observed.

In summary, the A-PFFSR method has proven effective in repairing casting defects in ZL210 aluminium alloys, with better results achieved at lower immersion speeds. This has led to the elimination of interfacial defects and improved tensile strength of the repaired joints.

New technique of filling friction stir welding [21]

The experiment involves using a semi-consumable joining tool to repair the keyhole left at the end of a friction stir welding seam. The material used is Al-Cu-Mg aluminium alloy sheet with a thickness of 7-8 mm, and the initial heat treatment is T6. The FFSW processing involves joining by friction, stirring, and cutting, and the FFSW processing is finished using an FSW machine. In addition, friction stir processing (FSP) smoothed and reprocessed the FFSW joint with a non-consumable tool consisting of only a steel shoulder without protruding pin. the three mentioned activities (friction, stirring, and joining) are part of the same FFSW (Filling Friction Stir Welding) process and are carried out sequentially. During the FFSW process, the aluminium alloy joining bit is first rubbed against the inner wall of the keyhole (friction), then immersed into the keyhole to mix the material (stirring), and finally the joining bit is consumed as filler material to join the bit and the keyhole (joining). Here, in table 12 are reported the process parameters of the different activity:

Process	Tool geometry	Tool material	Shoulder diameter [mm]	Pin Diameter [mm]	Pin Lenght [mm]	Pin Conicity [°]	Rotation rate [rpm]	Plunge speed [mm/min]	Traverse speed [mm/min]	Deep indentation depth [mm]	Tilt angle [°]
FSW	Conical pin with thread	Steel		9.8	7.6	15	80000	3	200	0.2	2.5
FFSW	Conical pin without thread	Shoulder: steel	22	10	10	12	800	0.5	200	0.1	2.5
		Pin: aluminium									
FSP	Only shoulder	Steel	22	---	---	---	800	0.5	200	0.1	2.5

Table 12: Process Parameters.

At the end of process, the material will have a solid joint without defects. The relative tensile strength of the FFSW joint is 84.3% compared to the base welding without a keyhole, while the relative elongation is 98.9% compared to the base welding. Furthermore, the FFSW joint exhibits better mechanical properties compared to conventional fusion welds.

AA7075 bit for repairing AA2219 keyhole by filling friction stir welding [22]

The authors have set the goal of exploring the use of friction stir welding to repair parts made of AA2219 aluminum alloy. In particular, the study focuses on the use of a specific semi-consumable tool and investigates the effects of the tool geometry and plunge speed on the mechanical properties of the joints. The objective is to evaluate the potential of this technique in producing defect-free joints with high strength and elongation. The entire FFSW process was divided into three parts: previous FFSW, shoulder further effect (SFE), and friction stir processing (FSP). Over here in table 13 and table 14 are resumed the principal process condition:

Tool Parameters	Units
Shoulder Diameter [mm]	22
Probe Diameter [mm]	9.8
Probe Length [mm]	7.6
Probe Conicity [°]	15
Material of Tool	HSS
Rotary Speed [rpm]	800
Welding Speed [mm/min]	500
Plunge Speed [mm/min]	3.0
Deep Indentation Depth [mm]	0.2
Tilt Angle (forward) [°]	2.5

Table 13: Friction stir welding conditions

Tool Parameters	Units
Shoulder Diameter [mm]	22
Bit Diameter [mm]	10
Bit Length [mm]	10, 11, 12
Bit Conicity [°]	11, 12
Material of Tool	HSS, AA7075
Rotary Speed [rpm]	800
Welding Speed [mm/min]	500
Plunge Speed [mm/min]	0.5, 2, 5, 8
Deep Indentation Depth [mm]	0.1
Tilt Angle (forward) [°]	2.5

Table 14: Filling Friction stir welding conditions.

Tensile tests, hardness tests, and optical microscope inspections were conducted, and specifically, the results indicated that the use of the AA7075 bit effectively reduced the tool material loss. In the tensile tests, the maximum tensile strength and maximum elongation of the joint were 179.6 MPa and 13.7%, respectively, equivalent to 96.6% and 99% of the original defect-free friction stir welding joint. Defect-free FFSW joints were produced at lower plunge speeds, and the fracture locations were in the softened region within the thermomechanically affected zone (TMAZ) on the return side.

Self-refilling friction stir Welding (SRFSW)

Is a relatively new welding technique that aims to overcome a limitation of conventional friction stir welding (FSW).

In standard FSW, a rotating tool is used to generate heat and plasticize the material to be welded, creating a solid joint. However, FSW can sometimes leave a void or "keyhole" at the end of the weld. SRFSW was developed to address this issue.

Here's how SRFSW works:

- A special tool with a geometry that gradually changes during welding is used.
- The tool heats and mixes the material around the keyhole.
- The deformed material fills the void and creates a solid joint.

Some articles will be illustrated here where various aspects of this repair process are seen.

Parametric study of two-stage refilled friction stir spot welding [23]
The purpose of this study is to conduct a parametric analysis on two-phase friction spot welding with filler (TFSSW) to determine the effect of welding parameters on the tensile strength and maximum deformation of the welded joints. The experiment was conducted using 2-millimeter-thick sheets of aluminium Al 1100. Three welding parameters were selected: the tool rotation speed, the penetration depth of the conventional tool, and the total dwell time. Conventional welds were first performed using a conventional tool, followed by the use of a filler tool in the second phase of the welding process. Three samples were tested for each parameter configuration. Process Parameters are shown in table 15:

tool rotational speed [rpm]	dwell time [s]	tool plunge depth at first step [s]	feed rate
1000, 2000	6, 12	3.7, 3.8	0.3

Table 15: Conventional welding parameters.

Tensile strength and maximum deformation of the welded joints were evaluated using a tensile testing machine. Results were analysed using the ANOVA method to determine the effect of welding parameters on the strength and deformation of the joints.
The results of the study indicate that the most influential welding parameters on joint strength are the tool rotation speed and the diameter of the filler tool shoulder. A lower tool rotation speed and a larger diameter of the filler tool shoulder resulted in stronger joints. Dwell time had a negligible effect on joint strength. The strongest joint, with a tensile strength of 6.96 kN, was achieved with a tool rotation speed of 1000 rpm, a conventional tool penetration depth of 3.8 mm, a total dwell time of 6 s, and a filler tool shoulder diameter of 14 mm.

The study's conclusions suggest that the two-phase friction spot welding with filler (TFSSW) process can enhance the strength and maximum deformation of welded joints. Tool rotation speed and filler tool shoulder diameter are key parameters to consider for achieving stronger joints. The filling process with the filler tool may reduce joint strength compared to conventional welding, but increasing the filler tool shoulder diameter can compensate for this decrease. In general, a lower tool rotation speed and a larger filler tool shoulder diameter are preferable for obtaining stronger joints.

Passive filling friction stir repairing AZ31-B magnesium alloy by external stationary shoulder [24]

The study aims to examine the application of passive filling friction stir repair (PFFSR) with an external stationary shoulder to address variously shaped volume defects near metal structure surfaces, specifically in AZ31-B magnesium alloy plates. It seeks to outline a model of material flow during the repair process, elucidate the role of the stationary shoulder in enhancing the repaired area's quality, and establish correlations between microstructures and microhardness. The experiment involves employing PFFSR on 3mm thick AZ31B-H24 magnesium alloy plates using a friction stir welding (FSW) machine. Utilizing a rotating tool system with an inside pinless rotating tool and an external stationary shoulder, a hole with a depth of 1.5mm is drilled in the AZ31B alloy plate using a pinless tool with a 10mm shoulder diameter, serving as the targeted defect for repair. A filler material, 10mm in diameter, is placed in the hole, and the rotating tool system, in contact with the top surface of the filler material, descends toward the repaired plate.

For this process are chosen rotating velocity of 2000 rpm, dwell time of 20 s, and plunge rate of 2 mm/min. The experiment is conducted with and without the stationary shoulder to examine its impact on the quality of the repaired region. Specimens for metallographic analysis and microhardness testing are obtained by cutting across the center of the repaired region, and the cross-section is observed using an optical microscope. Vickers microhardness testing is employed to assess the repaired region's hardness. In figure 4 is schematically shown the process.

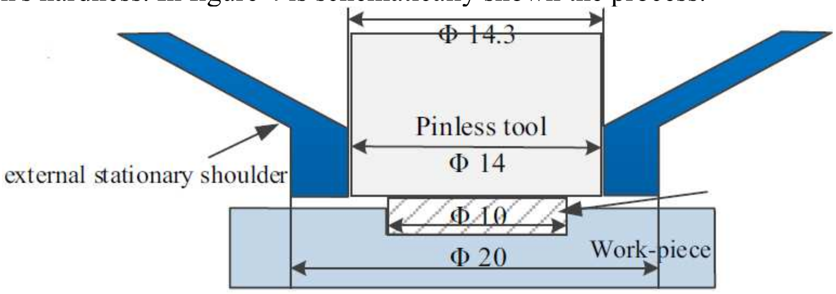

Figure 4: Schematic representation of the process.

Here some consideration obtained after experiments:

1. The use of an external stationary shoulder during the PFFSR process improves the quality of the repaired region, resulting in a more uniform microstructure and higher microhardness values.

2. The decrease of the temperature during the AZ31 alloy PFFSR process attains smaller grains, which verifies that the effect of temperature change on the grain size greatly exceeds the effect of material flow change in this study;

3. The microhardness distributions under different tool systems are quite different. For the pinless tool, the microhardness values are relatively uniform not only parallel but perpendicular to the top surface of the repaired region. So, in this study, the remarkable change of the grain size has no significant influence on the hardness distribution of the PFFSR region;

4)The microhardness distribution law of the repaired region with the stationary shoulder is similar to the region without the stationary shoulder. Moreover, the microhardness of the AZ31 magnesium alloy is insensitive to the grains size variation when the grain size of AZ31 alloy is bigger than 10 μm, and the Hall-Petch relation could be followed under the grain size smaller than 8 μm.

New technique of self-refilling friction stir welding to repair keyhole [25]

The aim of this research is to introduce a novel welding technique called "self-refilling friction stir welding" (SFFSW) to repair keyhole defects in AISI 316L welding. This technique employs a non-consumable welding tool with a gradual geometry that creates a solid-state filled joint step by step. During the process, the material is heated and mixed without reaching a liquid state, eliminating issues of porosity and grain boundary cracks associated with conventional fusion welding. The high-temperature retention period is relatively short, preventing the formation of sigma phases in the affected area. For this set of experiments were used tools with same geometry but different dimensions and process parameters that you can see in table 11 (further the friction stir processing FSP):

Process	Geometry	Shoulder diameter [mm]	Pin diameter at tip [mm]	Pin length[mm]	Pin conicity[°]	Rotation speed [rpm]	Axial force [kN]	Plunge Rate [mm/min]	Dwelling time [s]
FSP	Threaded conical pin	22	4	5	30	300	30	20	--
SFFSW	Threaded conical pin	22	4.3	5	30	1200	30	--	5
	Threaded conical pin	22	5.4	4.6	30	1200	30	--	5
	Threaded conical pin	22	7.2	4.2	30	1200	30	--	5
	Threaded conical pin	22	10.1	4	30	1200	30	--	5
	Threaded conical pin	22	13	3.7	30	1500	30	--	5
	Threaded conical pin	22	14,8	3.3	30	1500	30	--	5
	Threaded conical pin	22	0	1.9	80	1500	30	--	5
	Only shoulder	22	--	--	--	1500	30	--	5

Table 16: Tool geometries and features for FSP and SRFSW.

Keyholes in 316L stainless steel plates were effectively repaired using the SRFSW technology, employing a non-consumable tool. The significant observations are as follows:

1) A refilled joint was successfully achieved without noticeable macro defects when appropriate tool design and processing parameters were applied. The microstructure in the refilled zone displayed a considerably refined structure, showcasing an approximately equiaxed grain formation with an average size of a few micrometres.
2) The microhardness within the refilled zone of the joint, absent of visible macro defects, was marginally higher compared to that of the base metal.
3) The absence of sigma phase in the refilled zone was due to a relatively brief high-temperature retention period. Limited precipitation of chromium carbides in the refilled zone did not cause evident chromium depletion, which could have otherwise impacted the corrosion resistance of the austenitic stainless steel.

1.2 Process customization based on the type of tool used.

Friction stir spot welding (FSSW) process customization heavily relies on the specific tool design and features. Here's how tool variations influence the customization process:

Tool Pin Profile:

- Cylindrical Pin: Offers a balance between heat generation and material mixing. Suitable for general-purpose FSSW applications.
- Threaded/Fluted Pin: Enhances material mixing and creates a larger nugget (weld zone). Ideal for thicker materials or situations requiring high joint strength.
- Tapered Pin: Provides a self-centering effect and reduces stirring resistance during plunge. Useful for joining materials with varying thicknesses or for automation.

Shoulder Geometry:

- Flat Shoulder: Offers a simple design suitable for general applications.
- Wavy/Lobed Shoulder: Creates a larger contact area, increasing heat generation and improving material mixing. Beneficial for thicker materials or high-strength joints.
- Scroll Shoulder: Enhances material stirring and refines the nugget microstructure. Useful for materials prone to solidification cracking.

Additional Customization Techniques:

- Tool Material Selection: Using tool materials with higher thermal conductivity (e.g., Diamond) can be beneficial for materials with high melting points.
- Shoulder Features: Incorporating features like backing pins or auxiliary holes can influence material flow and heat distribution.

Some applications will be illustrated here where the variety of results based on the type of tool used is evident.

2. Aim of the Thesis

The objective of this thesis is to understand how the Friction Stir Welding process (specifically addressing (Active (AF-FSR) and Passive Filling Friction Stir Repairing (PF-FSR)) can be employed to fill and repair material defects, focusing on gap filling, improvement or deterioration of mechanical properties, and changes in welding process characteristics such as axial force and torque. Before activating the machine, a plug is inserted into the specimen with the aim of performing friction repair with passive filling. The objective of the research is to evaluate the effectiveness of surface defect repair, there are two overlapping sheets, the top one drilled with increasing diameters (0, 2, 4, 6 mm) to gradually test the sheltering capabilities of the process with bigger holes. mechanical properties (tensile strength and elongation) and macroscopic areas will be evaluated to understand how the material flow of this series of processes is distributed .

How Friction Stir Repair (FSR) works:

1) Preparation of the repair area: The damaged area is prepared and cleaned to remove any impurities or damaged material (was used Alcohol or Acetone);
2) Tip placement: The rotating tip is positioned over the repair area;
3) Initiation of the repair process: The tip begins to move through the damaged area, generating heat and mixing the material to fill any voids or defects;
4) Cooling and solidification: After the tip passes through, the material cools and solidifies, repairing the damaged area.

Advantages of FSR:

- No fusion: There is no material fusion, reducing the risk of defects associated with rapid cooling.
- Low distortion: The low heat generation limits distortion of the parts during the process.
- Versatility: It can be used to repair a lot of materials, including those difficult to weld using conventional methods.

3. Material and Experimental Methods

The material chosen for the specimens is AISI 304 as it has an excellent compromise between mechanical properties and workability. Below is a summary table of the chemical composition of this material.

Amount of Alligants (Casting Analysis) %	C max	Si max	Mn max	P max	S max	N max	Cr	Ni
	0.07	1	2	0.045	0.03	0.1	17.5÷19.5	8.0÷10.5

Table 17: The chemical composition of AISI 304 steel, the material used in the test specimens [28].

Considering the JIS G 3136 [27] (figure 5) regulations and selecting the thickness a priori, the other dimensions of the test specimen were then consistently determined:

Nominal thickness [mm]	2
plates width [mm]	40
Length of the sheets to overlap [mm]	40
Length of the sheets [mm]	125
Distance between camps [mm]	100

Table 18: typical size of chosen specimen.

Fig. 7 Configuration of Weld Test Specimens (JIS G 3136)

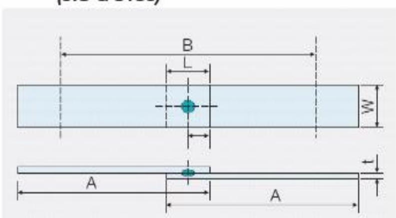

Table 19 Size of Weld Test Specimens (JIS G 3136) (unit: mm)

Nominal thickness (t)	Width (W)	Lap allowance (L)	Test specimen length (A)	Distance between clamps (B)
0.3≦t<0.8	20	20	75	70
0.8≦t<1.3	30	30	100	90
1.3≦t<2.5	40	40	125	100
2.5≦t≦5.0	50	50	150	110

Figure 5. Geometry of the tensile test specimens used in the joints. Dimensions taken from the regulations JIS G 3136.

The chemically composition of the tool is W-Re25%. Rhenium helps maintain mechanical properties at higher temperatures, thus preventing softening.

The tool used for the various tests, whose geometric characteristics are illustrated in Figure 6, possesses a highly advantageous feature from both a technological and process quality perspective: the contact surface of the shoulder exhibits an internal taper (in the specific case, it is 3°). As the tool rotates and moves through the material, the taper collects the molten material and pushes it into the joint area between the two parts being welded, consequently limiting the generation of protruding excess material (referred to as FLASH), this is significant both aesthetically (if important for the application) and functionally.

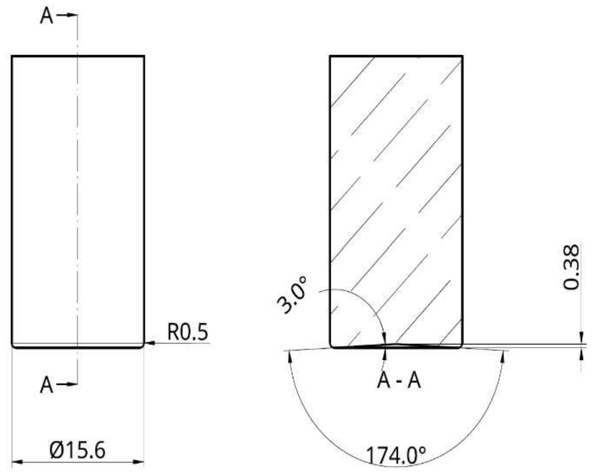

Figure 6. Geometry of the tool used for the experiment.

The welds were carried out by implementing certain precautions:

- Three different dwell times were used: the series with a 20-second dwell time was aimed at closing the holes; in fact, a longer process duration corresponds to a greater amount of flow;
- High plunge rate in order to reduce cycle-time;
- Rotation speed set at a typical value for steels;
- The upper plates of the specimen had a hole each, measuring 0, 2, 4, 6 mm in diameter, respectively;
- The penetration depth was chosen by initially conducting preliminary tests with plunge depths of -1, -1.25, and -1.5 mm. The 1mm plunge depth (Figures 8a and 8b at the top) was discarded as the joint appeared weak; in fact, it required modest effort to separate them. The 1.5mm plunge depth (Figures 5a and 5b at the bottom) generated excessively large flashes. Thus, the best compromise was slightly more than the central joint at 1.25mm: 1.3mm
- For passive friction stir repairing process, a 2,5 mm thick plug made of AISI 304 (the same material of test sample) is used, and the dwelling time are 10, 15 and 20s.

Figure 7: Image depicting the joint creation during the dwell phase.

Figure 8a: Frontal view of the sample
obtained from the preliminary tests.

Figure 8b: Sample obtained from the preliminary
tests, mechanically separated after the junction.

It was essential to perform simple P-FSSW (Pinless Friction Stir Spot Welding) tests at the beginning to understand how as the parameters change, the process of defect joining and/or repair occurs, and how the final microstructure, mechanical properties, and forces at play throughout the process, (totally or partially filled) change. Here in Table 19 all the process series are given.

<table>
<tr><th>FSSW process</th><th>Pre-hole diameter [mm]</th><th>Dwell time [s]</th><th>Rotational speed [rpm]</th><th>Plunge depth [mm]</th><th>Plunge speed [mm/min]</th></tr>
<tr><td>P-FSSW</td><td>-</td><td rowspan="2">10, 15</td><td rowspan="4">1000</td><td rowspan="5">1.3</td><td rowspan="5">50</td></tr>
<tr><td>AF-FSR</td><td>2, 4, 6</td></tr>
<tr><td rowspan="3">PF-FSR</td><td>4</td><td rowspan="2">15, 20</td></tr>
<tr><td rowspan="2">6</td></tr>
<tr><td>20</td><td>1500</td></tr>
</table>

Table 21: Summary of all process parameters.

In the case of AF-FSR (Active Filling-Friction Stir Repair) the total or partial filling of the Pre-hole occurs only thanks to the flow generated by the rotation of the tool without the contribution of extra material.

In the case of PF-FSR (Passive Filling-Friction Stir Repair) the filling of the Pre-hole takes place thanks to the contribution of extra material (in the specific case, a disk of AISI 304 with a slightly larger diameter than the hole was used).

The processes (where the differences can be seen) are schematized in Figure 9:

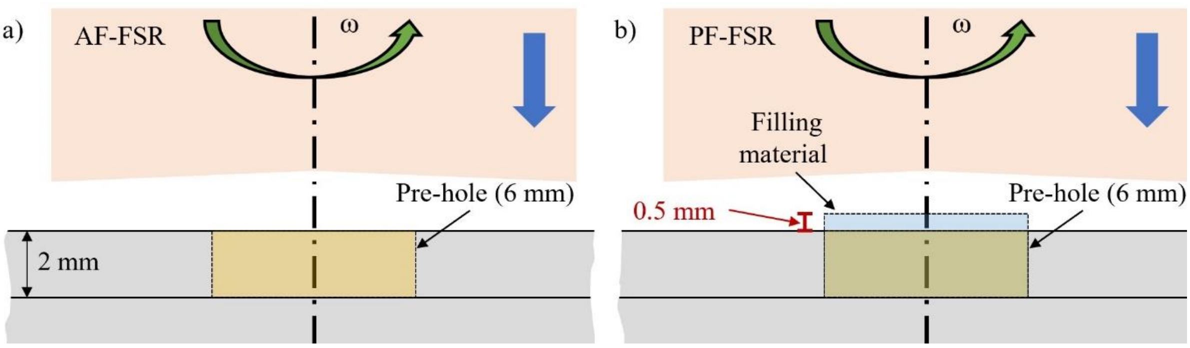

Figure 9: Schematic illustration of the selected processes (example for the 6 mm diameter pre-hole): a) AF-FSR and b) PF-FSR.

4. Discussion and Results

In Figure 10, it can be observed the tool's condition before and after the activities: the internal taper of the tool reduced due to natural wear on one side, and on the other side, traces of base metal attached to the shoulder base.

Figure 10. Dwelling time10 s: Tool before (left) and after (right) the set of trials.

4.1 Analysis of the variation of force and torque

The figure 11 displays the trends of the axial force and applied torque over time for all arranged specimens. Figure a show the test series for P-FSSW, AF-FSR.

In particular, the test series for dwell times of 10 s and 15 s are distinguished. In particular, in the former case (dwell time 10 s) each process lasts 15.9 s, of which:

- In the first 1.6 s, the tool goes from the part zero to a depth of -1.3mm where it reaches the peak of the axial force;
- subsequently, there is the dwell time (in this case, 10 s), during which there is a progressive decrease in torque;
- in the remaining 4.3 s, the tool returns to the initial position.

In the latter case (dwell time 15s) each process lasts 20.9 s, of which:

- In the first 1.6 s, the tool goes from the part zero to a depth of -1.3mm where it reaches the peak of the axial force;
- subsequently, there is the dwell time (in this case, 15 s), during which there is a progressive decrease in torque;
- in the remaining 4.3 s, the tool returns to the initial position.

Observing the graphs, there is a noticeable variation in the applied axial force concerning the specimen hole diameters: indeed, transitioning from D6 to D0 shows a 10 kN variation, approximately 29%. Moreover, it is noticed that in specimens with a 4 mm hole, the axial force in action increases only by 2-3 kN, and the actual torque does not vary. Meanwhile, in specimens with a 6 mm hole, there seems to be a more significant increase in the forces at play, approximately 10 kN, and the peak torque is slightly elevated. This is attributed to the fact that the plug's diameter was slightly interfering with that of the hole and because the material flow is greater.

Figure b, on the other hand, shows the same kind of graph for PF-FSR (dwell time of 15 and 20s) where it also shows the variation of forces as the number of revolutions changes. For dwell time=15s the timing of the process steps are the same of case “a”, for dwell time=20s each process lasts 25,9s in particullary:

- In the first 1.6 s, the tool goes from the part zero to a depth of -1.3mm where it reaches the peak of the axial force;
- subsequently, there is the dwell time (in this case, 20 s), during which there is a progressive decrease in torque;
- in the remaining 4.3 s, the tool returns to the initial position.

What is noticeable here is that in the series of tests with a rotational speed (of the tool) of 1500 rpm, compared with the 1000rpm series is the following:

- the vertical load remains almost constant;
- the torque goes from a maximum of 43Nm to 32Nm (about 26% reduction) and from a minimum of 18Nm to 14Nm (about 23% reduction);

This is because increasing the number of revolutions increases the temperature at the interface between the tool and the specimen; this implies that the material becomes softer and less mechanical effort from the tool will be needed to mix the flow and penetrate the specimen for the full Plunge Depth

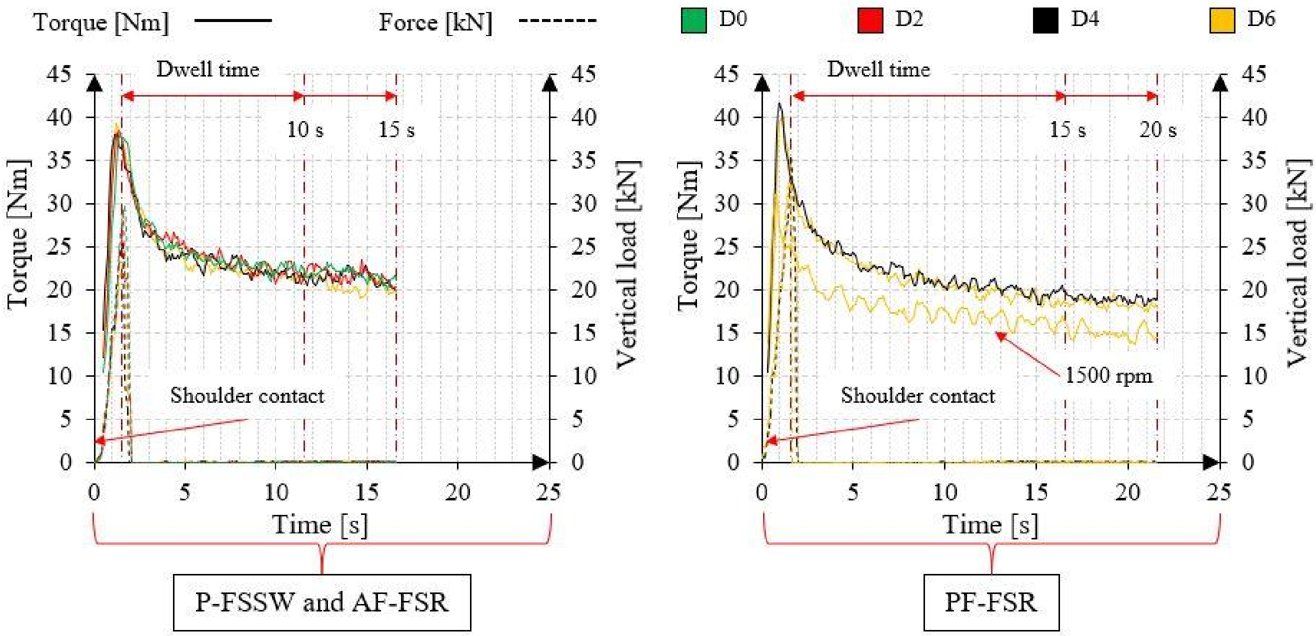

Figure 11: variation of the applied torque and vertical load throughout the process, for P-FSSW, AF-FSR(a) and PF-FSR(b).

4.2 Microstructure Analysis

After performing the various test sets for a portion of specimens, embedding, acid attacks (to improve the contrast between the different phases and make the defects more visible) and microstructure observation under the microscope were performed in chronological order.

Metallographic analysis of the weld joint makes it possible to verify that following a friction stir repair process the material undergoes a deep refinement of the crystalline grain to the point where each pass of the tool through the material can be likened to a heat treatment cycle.

Figure 12 shows a comparison of the macros of a defect-free specimen joined with P-FSSW and specimens with the presence of a pre-hole (with a diameter of 2.4 and 6 mm, respectively) joined with AF-FSR (all at a rotation speed of 1000rpm and a dwell time of 10s).

Looking at the macrographs, three characteristic zones can be easily identified:

- **Base metal (BM):** The BM is the unaffected material on either side of the weld;
- **Thermo-Mechanically Affected Zone (TMAZ):** it's a crucial zone within the weld. It surrounds the stir zone (SZ), which is the central, most heavily deformed region of the weld. The TMAZ is created by the combined effects of heat and mechanical stirring from the tool. It exhibits a microstructure that's transitional between the fine-grained, equiaxed structure of the SZ and the coarser grains of the base material;
- **Stir zone (SZ):** is the region of the weld that has been directly affected by the heat and stirring action of the tool. The SZ has a fine-grained, equiaxed microstructure. The grains in the SZ are typically much smaller than the grains in the base metal.

It can be seen that:

- The 4 mm and 6 mm holes were not completely filled;
- The 2 mm hole that also thickened compared to the specimen without the hole, this explains why it was not deemed necessary to proceed with the friction stir repair even in the specimens with a 2 mm hole;
- Comparing the four macrographies , it is noticeable that the stir zone (the blackened circular crown at the center) decreases as the diameter increases;
- The material structure around the SZ in samples with 0 and 2 mm prehole and is finer and inhomogeneous, while in samples with 4 and 6 mm prehole, the material structure is coarser and more uniform.

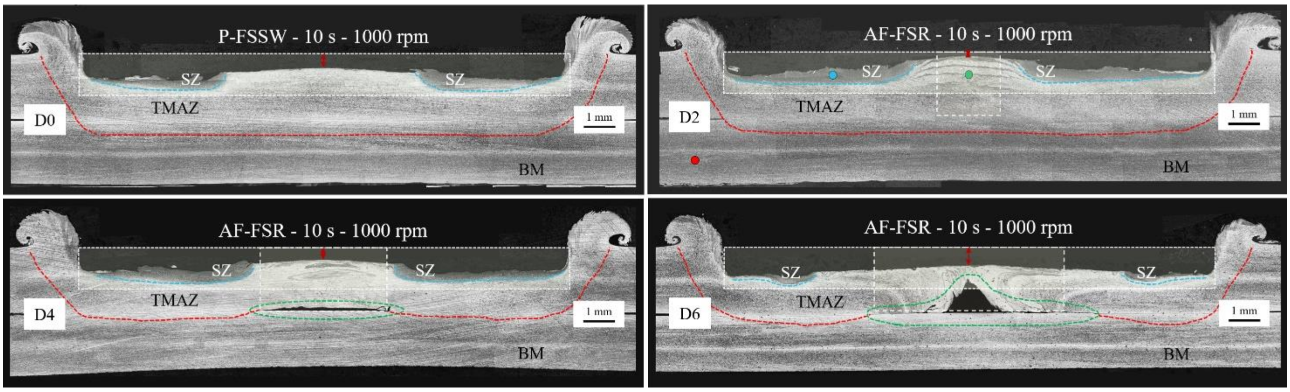

Figure 12: Macrography of welded joint with dwelling time 10 s.

A comparison of the two repair techniques (for a dwell time of 15 s and a rotation speed of 1000 rpm) for 4- and 6-mm pre-holes is shown in figure 13. This is what is observed:

- For AF-FSR compared with the dwell time of 10s in this case the filling was greater (although not total) as expected;
- Compared the two techniques we can see that for PF-FSR filling was almost completed for both diameters and the macrostructure is more homogenous than AF-FSR specimen (this because as mentioned earlier in the PF-FSR process there is extra material input that will contribute to the total material flow involved by the process);

Moreover, comparing the two series, it is noticeable that SZ is thicker in the case with a longer dwell time, as this involved a greater flow of material. Additionally, in the case of AF-FSR compared with the case of PF-FSR this has a larger size and a more symmetrical and regular shape of the SZ and a finer and more uniform material structure.

Regarding TMAZ, it is observed that in the case of AF-FSR (left) compared with the case of PF-FSR (right) this has a larger size, a more symmetrical and regular shape, and a finer and more uniform microstructure than TMAZ.

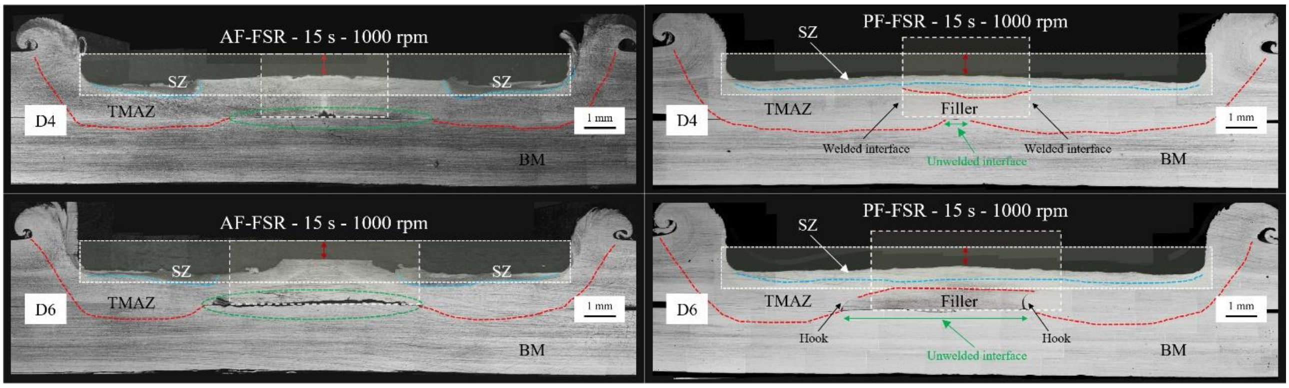

Figure 13. Compare between Macrography of welded joint with dwelling time 15 s for AF-FSR and PF-FSR.

Instead, below in Figure 14 a comparison is shown to see if increasing the rpm can close the specimens with a 6mm diameter pre-hole.

The tests were performed with a dwell time of 20 s for a rotational speed of 1000 and 1500 rpm. It can be seen that:

- In the top image as can be observed that there is a small area left that is not involved in the process, the so-called unwelded zone" but still the stir zone (the black circular crown) is extended across the entire width;
- In the bottom image there is a more extensive and penetrating filler zone in the specimen, this is because the higher rotational speed bringing the material to higher temperatures allowed for better mixing;
- As the rotational speed increases, is observable an enlargement of the TMAZ zone, from this embrittlement may result;

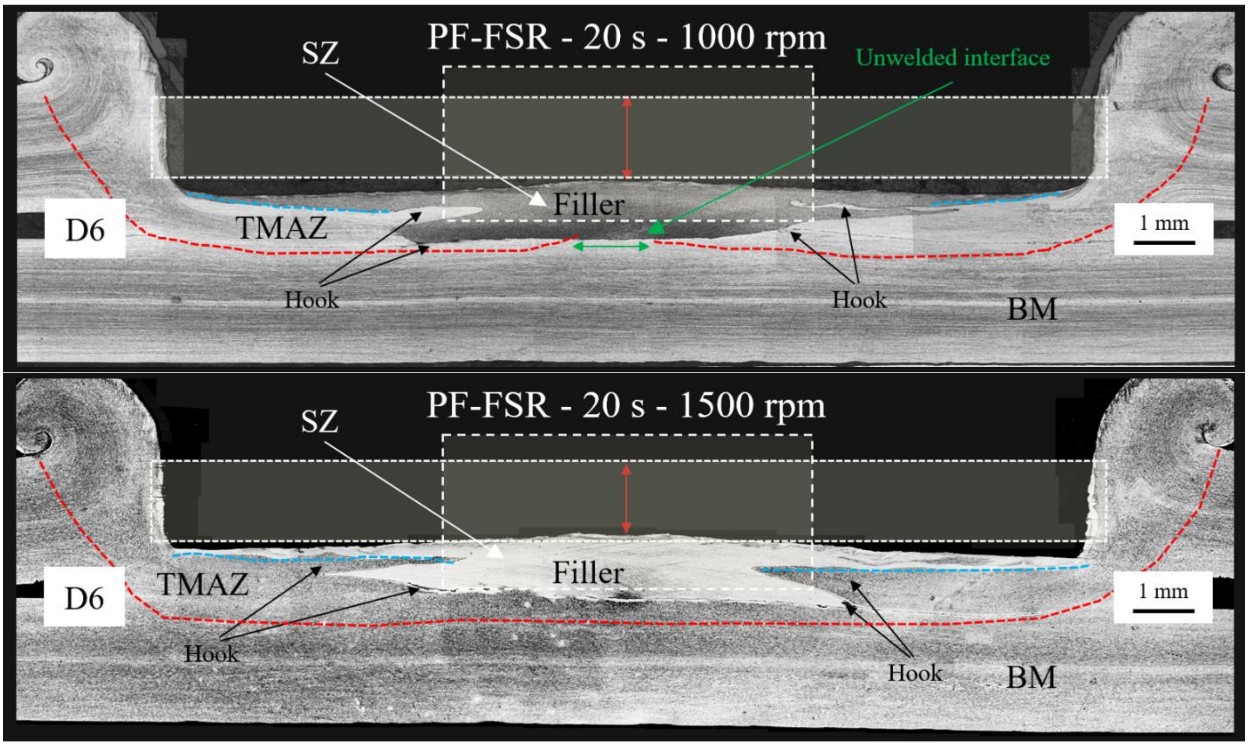

Figure 14. Compare of Macrography of welded joint with dwelling time 15 s with a variable rotation speed.

Considerations resulting from the tensile tests shown in figure 15:

- The test sample with no hole exhibits compared to all other tests performed, it possesses average tensile strength (a symptom of how customizable the mechanical properties are by changing the process parameters) and shows very low data variability;
- As the hole size increases, the load exhibits a negative trend and data variability increases, thus resulting in higher uncertainty in the obtained values. However, with increasing process dwell times, the load values tend to become more uniform compared to the values with D0 (resulting from increased hole filling)
- With a longer dwelling time, in the case of the 4 mm hole, it is better closed, allowing to achieve a maximum load close to 25 kN, which is not equally true for the 6 mm hole.
- Progressively as dwelling time increases, there are better mechanical properties consequent to better homogenization of the macrostructure;
- All experiments performed exceed the minimum value of Shear Tension Strength imposed by the AWS standard [28] indicated for the automotive field, applied to the joined joints by RSW;
- As observed in the case of PF-FSR compared with the AF-FSR process consequently to a larger amount of material and a smaller cross-sectional area discontinuity, there is an even higher value of Shear tension strength than the simple case of P-FSSW.
- As dwelling time increases, the elongation at the peak load also tends to increase from 2-4 mm (for a dwelling time of 10 s) to 6-8 mm (for a dwelling time of 20 s) a symptom of the fact that a greater amount of material flow has made the specimens gradually less structurally brittle;

- The repair tests seem to have been performed correctly by looking at the graphs since the ratio of Shear Tension Strength to Elongation is almost constant.

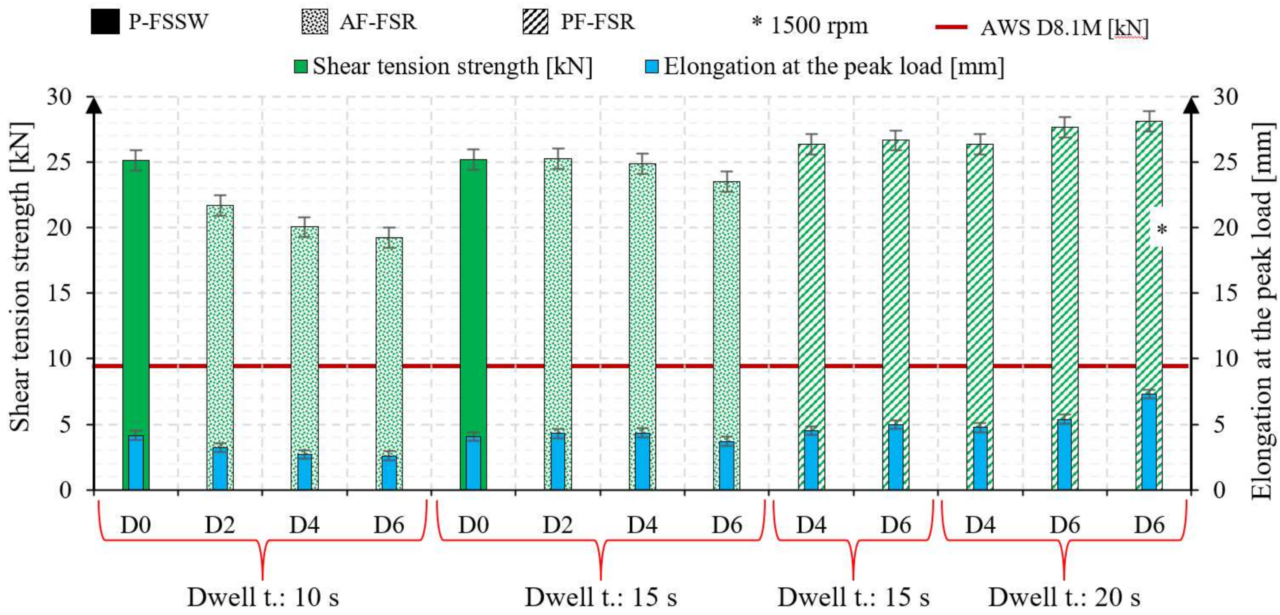

Figura 15. Tensile test.

5. Conclusion

- With a longer dwelling time, a qualitatively better specimen is obtained, as the holes are more thoroughly filled.
- Breakage loads with less variability reach a maximum value of 28 kN in the flat sample. In the repaired sample, a little bit more (about1-2 kN), probabilily due to the friction between sample-hole and the plug. What is noticeable is the trend of mechanical properties increasing as dwelling time increases, which almost completely offsets the worsening due to the growth of the initial defect due to hole enlargement.
- It seems that in general with PF-FSSR is obtained mechanically better-performing finished product, but combining both processes gives an even better result.

The obtained results indicate what was hoped for indeed, with an increase in dwelling time, the closure of the defect improves. Furthermore, by performing the repair process, even better mechanical characteristics are achieved compared to the flat sample.

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