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Recent Trend in Friction Stir Welding Process: A Critical Review

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ABSTRCT

Friction Stir Welding (FSW) is a solid-state joining process that offers numerous advantages over traditional welding techniques. This research paper aims to provide a comprehensive review of friction stir welding, covering its history, process parameters, microstructural evolution, mechanical properties, applications, and recent advancements. The paper also discusses the challenges associated with FSW and potential areas for future research. The research is based on an extensive literature review, including scientific journals, conference proceedings, and reputable industry sources. The findings contribute to a better understanding of the FSW process and its potential for various industries.

Keywords: Introduction, Friction Stir welding Process, Welding Parameters, Microstructure of the FSW Joints, Properties of FSW Joints, Summary, References

1. Introduction

Friction-stir welding (FSW) is a solid-state, hot-shear joining process [1–3] in which a rotating tool with a shoulder and terminating in a threaded pin, moves along the butting surfaces of two rigidly clamped plates placed on a backing plate as shown in Fig. 1. The shoulder makes firm contact with the top surface of the work-piece. Heat generated by friction at the shoulder and to a lesser extent at the pin surface, softens the material being welded. Severe plastic deformation and flow of this plasticized metal occurs as the tool is translated along the welding direction. Material is transported from the front of the tool to the trailing edge where it is forged into a joint [7]. Although Fig. 1 shows a butt joint for illustration, other types of joints such as lap joints and fillet joints can also be fabricated by FSW. The half-plate where the direction of rotation is the same as that of welding is called the advancing side, with the other side designated as being the retreating side. Since its discovery in 1991 FSW has evolved as a technique of choice in the routine joining of aluminum components. its applications for joining difficult metals and metals other than aluminum are growing. [1] In friction stir welding, two metal work pieces are joined together by rotating and inserting a cylindrical tool with a specially created profile. It is frequently employed for the fabrication of structural elements like panels, beams, and frames as well as for the mending and joining of intricately shaped parts. Friction stir welding (FSW) is a solid-state joining technology that has proven to be very useful for aerospace aluminum alloys. Although the procedure has been proved to be successful in the welding of a range of alloys, the tensile behavior of friction stir welds in precipitation hardening alloys has yet to be completely investigated. A combination of experimental testing and numerical modelling will be used to better understand the effect of friction stir welding on all precipitation hardening aluminum alloys. The local behavior that underpins the apparent global, mechanical response of the welds, in particular, must be understood. Knowledge of the local behavior is essential for developing a numerical model capable of reliably predicting the reaction of friction stir welds to varied conditions. [5] There is an increasing need to design lightweight structures such as those in aircraft panels and vehicle body shells. Advanced joining technology is an integral part of the manufacturing processes of lightweight structures. Considerable effort has been expended to develop various joining processes and assess their suitability for use in lightweight structures. [2]

1.1 Background

It's utilized to make things like panels, fuselage sections, fuel tanks, heat exchangers, and structural parts. When compared FSW has been used in a variety of industries, including aerospace, automotive, shipbuilding, and railway. to standard welding processes, the approach provides various advantages, including increased joint strength, higher fatigue resistance, and lower weight. FSW has seen developments and refinements over the years. Friction stir spot welding and friction stir processing are two variations of the method that have been developed to suit to specific applications and material kinds. Researchers and engineers are constantly looking for new ways to improve the FSW process, broaden its range of applications, and increase its efficiency and efficacy.

1.2 Objective

FSW's specific goals are as follows:

1. combining different materials: FSW enables the combining of materials that would be difficult to weld using traditional fusion welding procedures. Aluminium, copper, and steel alloys are examples of different materials.

2. Defect reduction: FSW attempts to reduce common fusion welding flaws such as porosity, solidification cracks, and distortions. When compared to fusion welding, the technique runs at lower temperatures, lowering the danger of thermal-induced flaws.

3. Material integrity: Because FSW is a solid-state welding method, the materials being joined do not melt throughout the operation. This helps to preserve the microstructure and mechanical qualities of the material, resulting in stronger and more reliable welds.

4. Increasing welding productivity: FSW delivers faster welding speeds compared to traditional welding techniques, cutting down on overall welding time. Additionally, it requires less clean-up and rework after welding.

5. Improving the quality and strength of the weld: FSW creates weld joints with good mechanical qualities, such as high tensile strength, fatigue resistance, and corrosion resistance. The procedure can produce flawless, continuous welds with a finely tuned grain structure, producing improved weld quality.

1.3 Scope of Research

Friction Stir Welding (FSW) research can cover a broad range of topics pertaining to the procedure, materials, and applications. FSW is a type of solid-state welding that is used to combine metals, typically alloys of. It uses the heat created by friction from a revolving tool to soften the material before manually mixing it together to create a weld.

2. Friction Stir Welding Process

The microstructure, which is in turn governed by the FSW process, determines the characteristics and functionality of the FSW joints. The welding parameters can often be changed to alter the FSW process. Therefore, the best possible microstructure must be achieved by choosing welding parameters. Furthermore, a thorough understanding of the FSW process is a requirement for effective prediction. Of the FSW joints' mechanical characteristics, ultimate microstructure, and weld size. It is quite challenging to acquire insight into the joint during the actual forming process because the FSW process is so complicated. This issue is solved by numerical simulation, which offers a useful method for examining the creation of FSW joints.

2.1 Process Modeling Parameter

The physical connections between mechanics and heat transmission, extremely high deformations, and strain rates in the stirring zone around the pin are all part of the challenging task of simulating the FSW process. Estimation of many process parameters, including tool geometry and speeds, is made possible by numerical simulation of the FSW processes. However, since simulation involves the interaction of thermal and mechanical events, it is not a simple operation. Some well-known numerical modelling methods have been created that can clarify and forecast crucial aspects of the process physics related to the FSW. [3] A number of streamlined numerical models were created to clarify different facets of the intricate thermomechanical processes connected to FSW. [6] Scaling techniques provide a good compromise between simplicity and accuracy. The exact identification of the dominating parameters and their accurate numerical representation form the foundation of scaling approaches. Separate numerical models were used to explore the following phenomena: (i) linked friction heat generation; (ii) slip zone development in plastic flow; and (iii) 3D heat and material flow. Based on data from the linked friction heat production model, a basic 3D heat and material flow model was employed to establish some preliminary understanding. [2]

2.2. Tool Design

materials like AA7039. However, the geometry of the tool shoulder and the concavity of the shoulder surface can have a significant impact on the definition of the Friction stir weld quality attributes. Different shoulder sizes, pin diameters The effects of friction stir welding (FSW) tool geometries on Metal. FSW tools could be beneficial for tougher, and degrees of shoulder surface concavity were used to examine the impact of threaded FSW tools on aluminum alloys. FSW tools with various amounts of threaded pin diameter, shoulder diameter, and shoulder surface concavity were produced using a full factorial design matrix. The impact of various tools on AA7039 welds in terms of weld tensile strength, cross-sectional area, and other factors was investigated through experiments. [38] [3]

Table: Composition of FSW Tool Material by Percentage %. [38]

C	Mn	Fe	Ni	P	S	Si	Cr
0.25	2	48-53	2	.045	.03	1.5	24-26

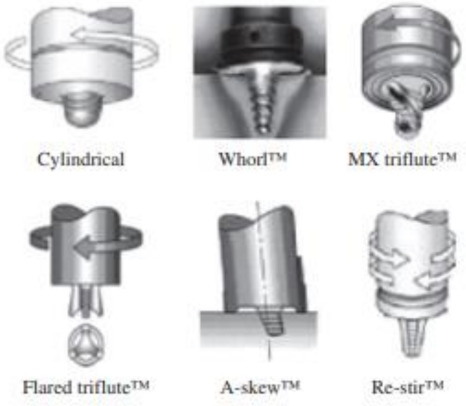

Fig 1: FSW Tool

As shown, there are three different types of FSW/P tools: fixed, adjustable, and self-reacting. The shoulder and probe of the fixed probe tool have been merged into a single component. [40] Heat generation, plastic flow, needed power, and the regularity of the welded junction are all influenced by tool design. Most of the heat

produced by the shoulder, which also keeps the plasticized material from departing the work piece. The tool pin also has an impact on material flow. [8]

2.3 Welding Parameters

The main welding parameters that can be modified in the FSW process for a particular tool are the rotating speed and traverse speed, the axial torque of the tool shoulder on the work piece, and the angle of contact between the tool and work piece. [2] The FSW and Mechanics laboratory at the Pamukkale University Department of Mechanical Engineering served as the site of the study's experiments. Two stainless steel plates with the dimensions of 3 mm x 75 mm x 150 mm were used, and they were butt welded using the FSW process with a 7.5 kW vertical head milling machine. [28] The tests were carried out utilizing a servo-hydraulic Instron 8801 universal uni -axial testing equipment with a load capacity of 50 KN at a stress rate of 12 MPa/sec under stress control. Due to its convenience and efficiency, stress control mode was preferred to stroke or strain mode. Microstructural analysis was done to look for weld flaws such porosity, coarse dendrites, or inadequate welding bead penetration, as well as the grain structure of the heat-affected zone [28].

2.3.1 Tool Geometry

The most important factor in the development of a process is tool geometry. The traverse rate at which FSW may be performed is governed by the tool shape, which is crucial for material flow. [2] The top sheet was excessively thinned when lap welding with a traditional cylindrical threaded pin, which greatly affected the bend characteristics. For situations where fatigue is a major problem, it is especially vital for lap welds to consider the breadth of the weld interface and the angle at which the notch meets the edge of the weld. Where the pin axis is slightly inclined to the axis of the machine spindle with the flute lands flared out, were recently created for enhanced lap welding quality. [40]

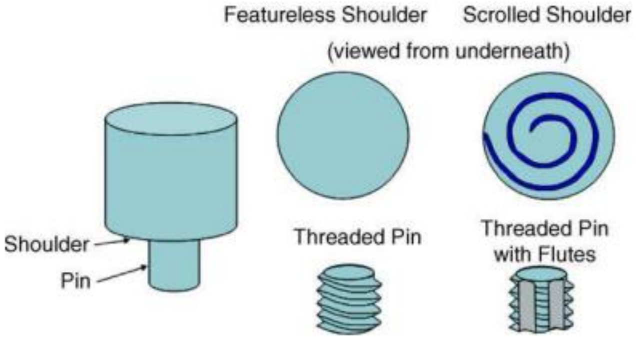

Fig 2: Schematic drawing of FSW Tool Geometry [2]

2.3.2 Joints Design

The butt and lap joints are the most practical joint configurations for FSW. Fig. depicts a straightforward square butt joint. To prevent the abutting joint faces from being driven apart, two plates or sheets of the same thickness are put on a backing plate and secured securely. The tool's first plunge involves rather strong forces, thus extra caution is needed to make sure that the plates in the butt arrangement don't separate. When the rotating tool's shoulder is in close proximity to the surface of the plates, it is inserted into the joint line and moved along it to create a weld along the abutting line. On the other hand, two lapped plates or sheets are used for a straightforward lap junction [1].

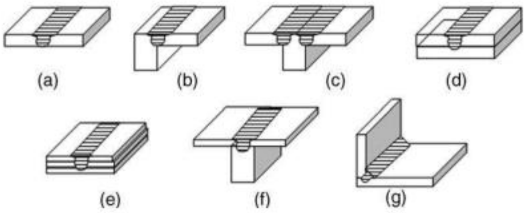

Fig 3: Joint configurations for friction stir welding

(a) square butt

(b) edge butt

(c) T butt joint

(d) lap joint

(e) multiple lap joint

(f) T lap joint

(g) fillet joint

2.4. Tool Wear

The energy input, deformation pattern, plunge force, microstructures, and mechanical characteristics of FSW joints are all considerably influenced by the geometry of the tool, as was before mentioned. [2] The titanium alloy Ti-6Al-4V was stirred by friction and welded (FSW) utilizing three distinct types of tools manufactured of W-1.1%La2O3 and two different grades of WC-Co based materials. Weight loss measurement, pin profile photography, and microscopic inspections were used to analyses tool wear. Bead-on-plate FSW tests were carried out in this study using sheets of Ti-6Al-4V with a thickness of 2.5 mm. The Ti-6Al-4V alloy was delivered with a rolled grain structure made up of an extended phase and a grain boundary phase. [44] Preheating may make it possible to weld more quickly and with fewer tools, in particular. While joining alloys that have greater melting points. To forecast the impact of preheating on the temperature distribution, a transient 3D FE heat transfer model of work pieces was created. And internal heat flow in the work pieces. [44] Preheating may make it possible to weld more quickly and with fewer tools, in particular. While joining alloys that have greater melting points. To forecast the impact of preheating on the temperature distribution, a transient 3D FE heat transfer model of work pieces was created. And internal heat flow in the work pieces [45]

3. Microstructure of FSW Joints

A microstructural analysis of grains and precipitates led to the identification of three different zones. As seen in Fig4. these zones are the stirred (nugget) zone, the thermomechanical affected zone (TMAZ), and the heat-affected zone (HAZ). The mechanical characteristics after welding are significantly impacted by the microstructural changes in the zones. Consequently, a number of researchers [including 8,257] have examined the development of the microstructure during FSW. Reference 18 25 FSW systems with various materials and FSW systems with the same materials. The creation of complex, intercalated vortex and associated flow patterns distinguished the FSW of systems employing different materials from those utilizing the same materials. [2]

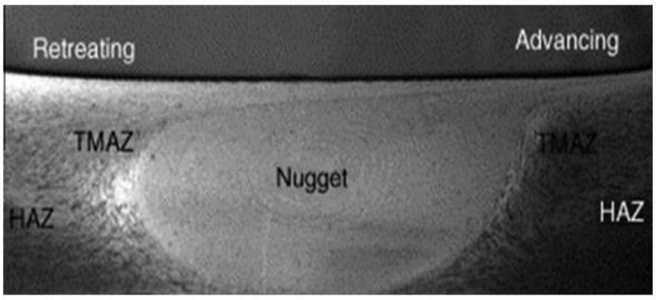

Fig 4: Typical macrograph showing various micro-structural zones in FSP 7075Al-T651 (standard threaded pin, 400 rpm and 51 mm/min)

3.1 Grain Size

Using a mix of extrusion and forging, the work pieces are joined solidly during the FSW process at a temperature below the melting point of the work piece material. FSW results in a significant development of the microstructure. A very fine grain structure in the weld is generated by the continuous dynamic recrystallization (CDRX) phenomenon. Greatly impact the ultimate joint resistance due to nuggets.

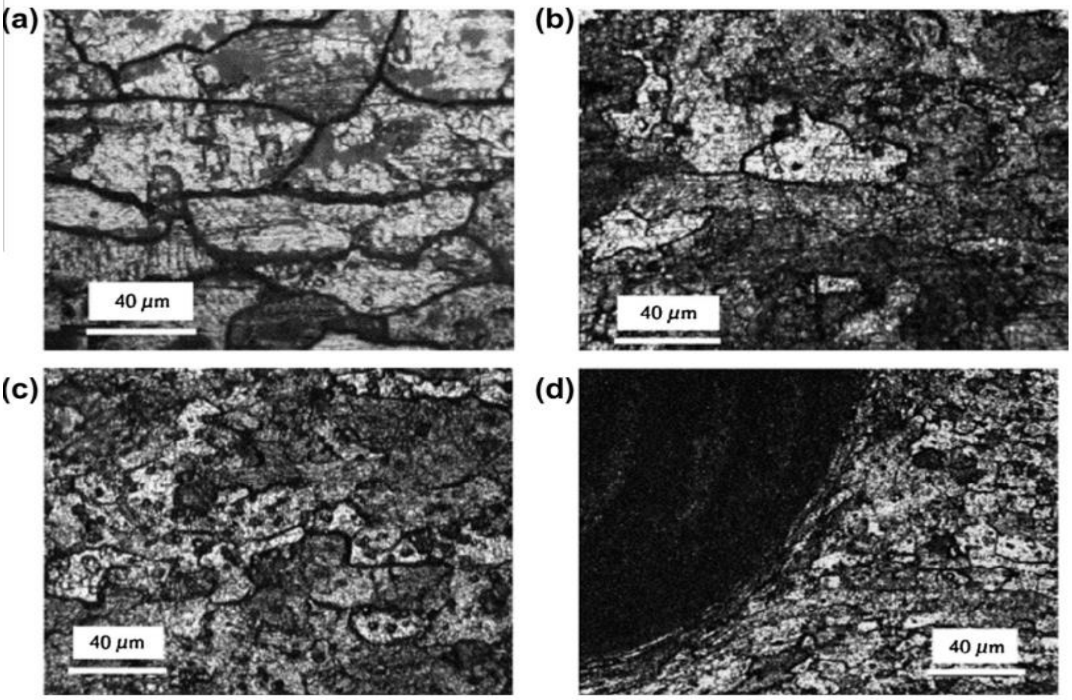

Fig 5: Material microstructures and grain size in a typical joint section (AA 6082-T6). [2]

(a) Parent material.

(b) Heat affected zone.

(c) Thermo-mechanically affected zone.

(d) The nugget transition zone

The study's substance, 6063-t5 aluminium, has the chemical make-up listed in the table. Plates that were 6 mm thick underwent friction stir welding. Vickers hardness measurements were obtained on the cross section next to the welding direction after the welding process, using a Vickers indenter with a 1 kg load for 15 seconds. TED and OIM evaluated the microstructure alterations connected to the hardness profile. [7]

3.2 Nugget Joint

The Gleeble hot compression tests can be used to investigate the microstructure and material constitutive behavior of aluminum alloys. The testing was conducted at high strain rates and at temperatures that were within 5 K of the solidus, which is the innovative component of the experiment. The power may be kept up to almost solidus temperatures, with no appreciable loss in strength seen. [2] Below Fig6. displays EBSD maps of several NCZ sections (T, M, and B) that were produced at various rotational speeds (500, 700, and 900 rpm). Each EBSD map had a 180 180 m area such that more than 500 grains could be measured, resulting in a low zero solution (about 10%). [50]

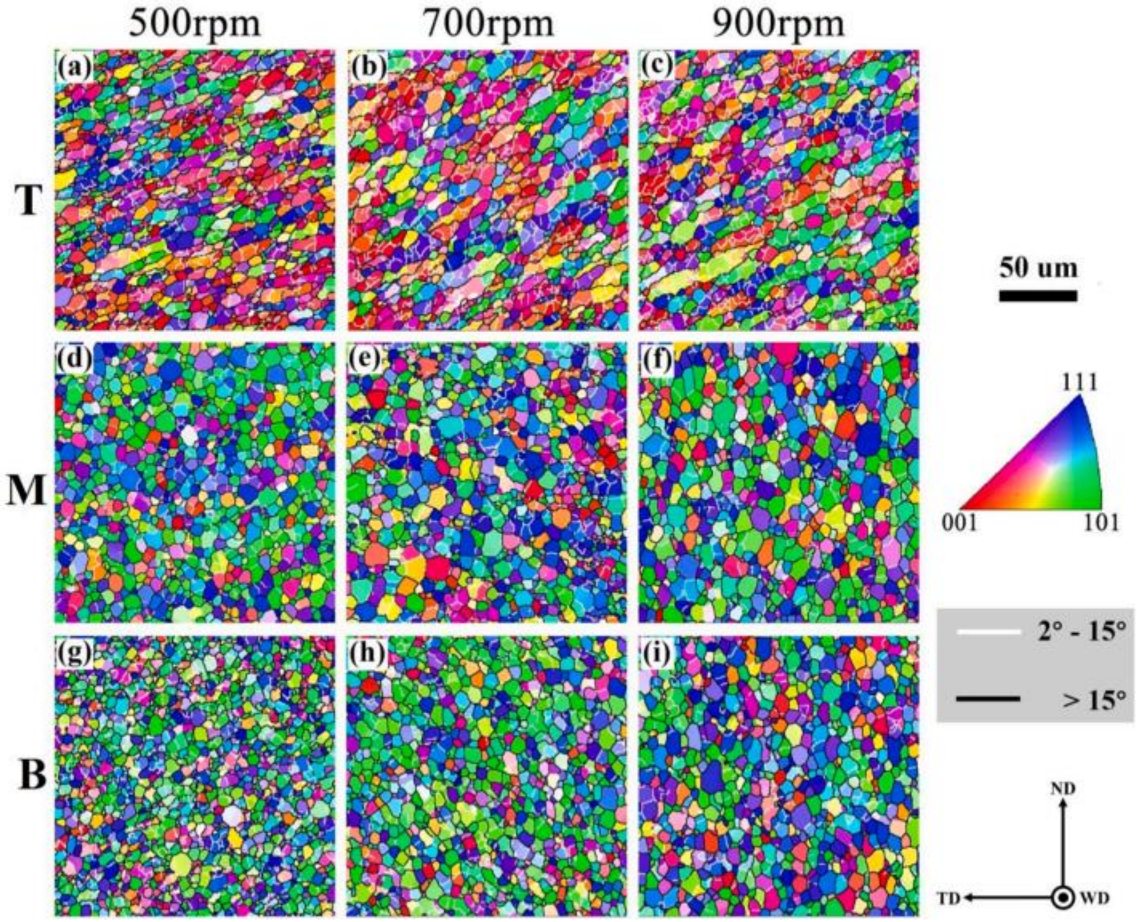

Fig 6: EBSD (Electron backscatter diffraction) maps of different locations in the NCZ (Natural Conservation Zone).[50]

By different rotation speeds: - (a), (b) and (c) Top-500 rpm, 700 rpm and 900 rpm; (d), (e) and (f) Middle-500 rpm, 700 rpm, and 900 rpm; (g), (h) and (i) Bottom-500 rpm, 700 rpm and 900 rpm

At room temperature, the NZ underwent a uniaxial tensile test in the direction of the weld. The engineering stress-strain curves and tensile characteristics of several locations in the NZ, as determined by various rotation speeds, are shown in Fig7. The Fig shows that the NZ stress-strain curves were noticeably irregular and produced certain stress serrations that were distinct from those of the BM (not shown), particularly for the local magnification picture of the stress-strain curve of 900-T. The stress serration phenomenon may be connected to the solute-dislocation interaction, or Portevin-Le Chatelier (PLC) effect. [50]

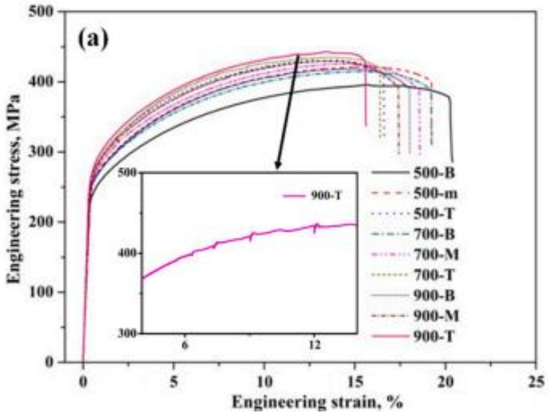

Fig 7: Engineering stress-strain curves [50]

3.3 Heat Effect Zone

The Ti-6Al-4V material found in the HAZ was the subject of the development and parameterization of a microstructure evolution model. This model specifically tackles the issue of how the globular a-phase particles contained within earlier b-phase grains evolved throughout the FSW process. The total structural performance of the weld is then predicted by combining this model with the well-known property versus microstructure correlations in Ti-6Al-4V. The findings indicated that the current computational method may be used to direct the selection of FSW process parameters in order to optimize the structural performance of FSW joints (at least while they are governed by the microstructure/properties of the HAZ-material). For the FSW process, a coupled, implicit 3D Lagrangian rigid-viscoplastic continuum based FE model was presented. [2]

4. Properties of FSW Joints

The mechanical characteristics of the pin tool, which control the heat input in the case of FSW, are directly connected to the torque. Additionally, the thermal history of the weld is directly impacted by the heat produced during FSW. Consequently, the temperature and torque were To investigate the connection between the welding parameters and heat input, both were monitored during the FSW of the Al/Ti lap junction. The fluctuation in spindle torque over time during the FSW of the Al/Ti lap joints, which was carried out under varied welding circumstances, is shown in Fig8. Five steps may be used to categories the variation in spindle torque: [51]

(1) Initiation

(2) Diving

(3) Holding

(4) Welding

(5) Withdraw

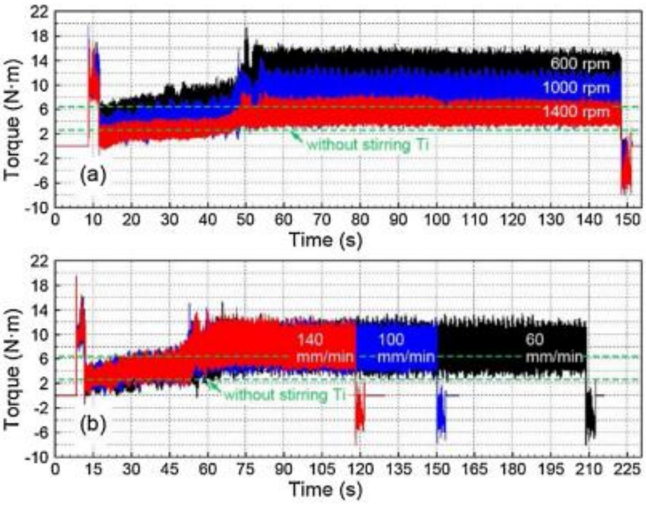

Fig 8: Spindle torques with various welding parameters: (a) v = 100 mm/min, (b) = 1000 rpm

4.1 Residual Stress

One of the most crucial factors affecting how the welds' mechanical characteristics are determined is the residual stress created at the welding zone. According to Anastassiou et al.'s research, residual stresses in the welding area reduce the fatigue and fracture strength of spot-welded welds. [51] During the FSW process, large levels of residual stress are frequently produced, seriously impairing component performance and structural integrity. both 34 X and tensile. Progress in Materials Science 65 (2014) by He et al. The FSW joints have compressive residual stresses ranging from 1 to 66. The HAZ is where the largest residual stresses are, and the advancing side just beyond the weld zone is where the smallest compressive residual stresses are. [2]

The aluminium sheets were fixed in a suitable location using a flexible fixture constructed of stainless steel during the FSW process. As with the traditional FSW technique and underwater friction stir welding (UFSW), the FSW method is carried out under submerging conditions. [52] The aluminium sheets were fixed in a suitable location using a flexible fixture constructed of stainless steel during the FSW process. The underwater friction stir welding (UFSW) and traditional FSW processes both include performing the FSW technique while submerged. Installed on an FSW machine is Plexiglas that encloses the welding equipment that will be submerged in water (Bayer, Berlin, Germany). For the purpose of allowing water to flow while welding, there was just one intake and output valve. The goal of this problem was to maintain a consistent heat transfer coefficient between the water and the weld line. [53] By employing the beamline ENGIN-X facility at the ISIS neutron source at Rutherford Appleton Laboratory, Oxford, UK, residual stress measurements were made using neutron diffraction. As seen in Fig9, a comprehensive diffraction pattern may be observed using a pulsed neutron beam that travels to the sample and scatters onto two banks of detectors that are each cantered at a fixed angle (Bragg angle (20) of 90 to the incident beam). Diffraction peaks happen when Bragg's Law is met at a lattice spacing of d_{dhl}, and are recorded at intervals of t_{hkl} after the original pulse. [54]

Fig 9: Residual stress measurements by neutron diffraction. (a) A picture and schematic top view of sample position on the ENGIN-X beamline and measurement principle, (b) A schematic of the sample position to measure longitudinal strain along the grey shaded area, (c) A schematic of the sample position to measure traverse strain along the grey shaded area, and (d) Cross section showing the positions of measurement points (red squares) and gauge volume.

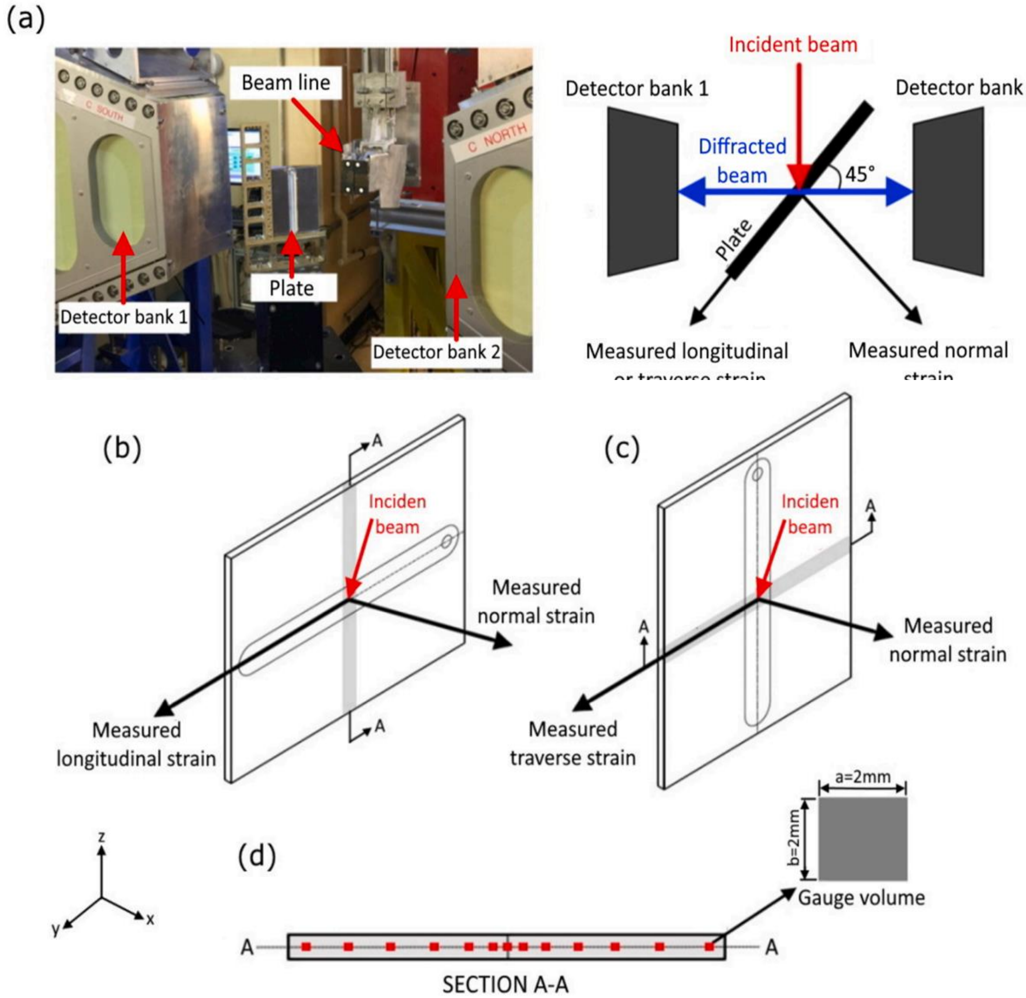

Figure (a) shows the residual stress variation obtained using the thermomechanical model on each side of the weld centerline, whereas Figure (b) shows the residual stress curve derived from XRD data using sin2ψ method.

On the retreating side of samples S8 and S3, the thermomechanical simulation determined the maximum and minimum values of tensile residual stress to be 260 and 199 MPa, respectively. Similar to this, samples S8 and S3 had experimentally determined peak maximum and minimum magnitudes of tensile residual stress of 154 and 94 MPa, respectively. Similar to this, the peak maximum and minimum magnitudes of experimentally measured tensile residual stress in samples S8 and S3 are 154 and 94 MPa, respectively. The observed profile in Fig. (a) closely follows the trend that has been previously described with regard to the location and area of tensile stresses as well as the breadth of the curve. [55]

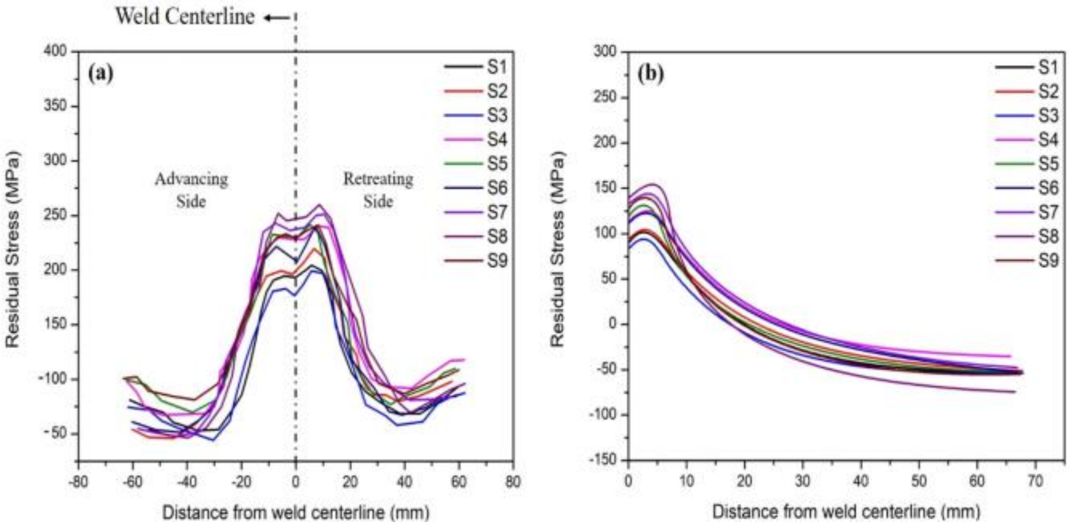

Fig10: Residual stress variation from weld centre line obtained from a simulation and b XRD calculations [55]

4.2. Hardness

Figure displays SEM pictures of the fracture surfaces' microstructures. All fracture surfaces exhibit dimples, demonstrating the ductile fracture process of the joints. Large and deep dimples could be seen on the fracture surface of the joint for FSW with NC produced at an R/T ratio of 1200/100 r/mm (Figure a). The dimples shrank as the R/T ratio dropped to 600/200 r/mm (Figure b). The dimples continue to get smaller and shallower on the fracture surfaces of the FSW joints with FAC, as seen in Figures c,d It is known that the spacing between the precipitates influences the size of the dimple, and a greater dimple results in better plasticity and strength. [57]

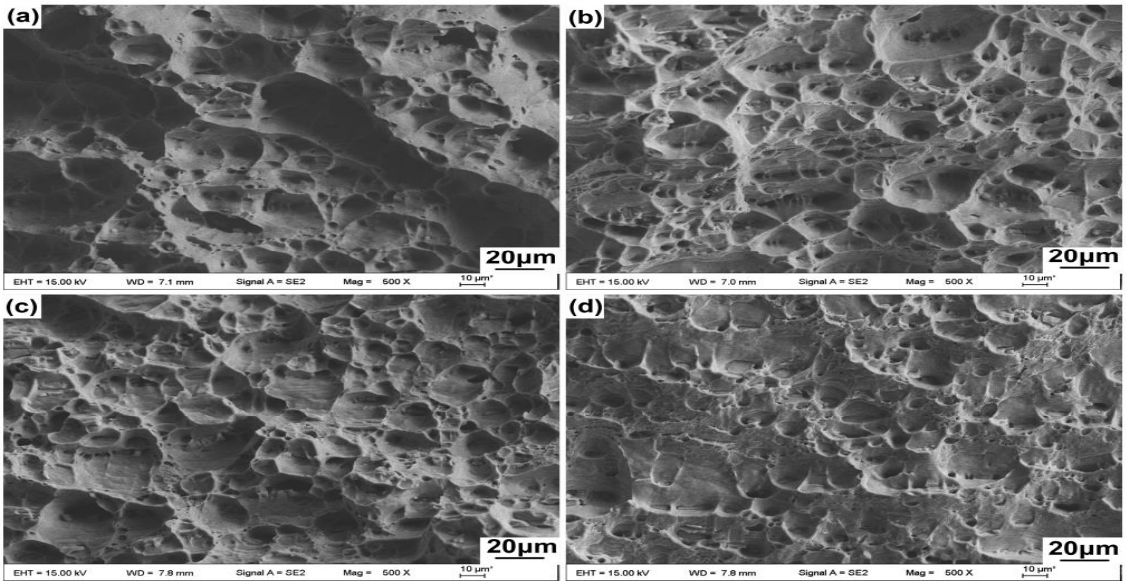

Figure11: Scanning electron microscopy (SEM) images of the fracture surface of FSW specimens obtained at: (a) 1200/100 r/mm with NC, (b) 600/200 r/mm with NC; (c) 1200/100 r/mm with FAC, and (d) 600/200 r/mm with FAC. The fracture surfaces of the FSW joints with FAC tended to have smaller and shallower dimples than those with NC. [57]

Due to their good electrical and thermal conductivity, strong corrosion resistance, and other physical, chemical, and mechanical qualities, both copper (Cu) and aluminium (Al) are now significant metals in the electrical sector. Numerous investigations have been conducted on various welding techniques for joining these two materials. Due to their vastly different chemical and mechanical characteristics and propensity to generate certain brittle Inter-Metallic Compounds (IMCs), they are challenging to combine using existing welding techniques. As a result, several methods for connecting copper and aluminium, such friction stir welding (FSW), have become study topic (1)

5. Summary

Although FSW has been successfully utilized to combine difficult-to-weld materials, it is still in its infancy. The FSW approach has so far been mostly developed empirically for each new application. In order to understand the FSW process, numerical studies that are based on scientific knowledge are highly beneficial. According to the current situation, the dissimilar welding in FSW is mostly preferred by the industry, automobile companies, aerospace etc. They use a variety of FSW tools in their research, including cylindrical, square, rectangle, and conical as needed to convey experiments. Welding parameters are used to regulate FSW tool parameters. We can also quickly determine tool wear, tool hardness, and tool thermal conductivity. The shape and size of this FSW welding tool takes into account a number of factors that have an impact on the drilling process and the work piece strength that the FSW process provides. A single tool pin change might cause several deflections throughout the FSW welding process. With FSW's expanding function and for understanding tool wear in cases of FSW of tougher materials, a deeper knowledge of the plunge phase is crucial. To investigate the thermo-mechanical processes involved during the plunge stage, a 3D ABAQUS FE analysis model was created. When performing FSW welding, the tool and material come into high-speed, high-pressurized contact with one another, which wears down the tool and reduces its lifespan.

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