ASSESSMENT OF FRICTION STIR WELDING: AN OVERVIEW

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Article history
Received
19th July 2022
Revised
28th July 2022
Accepted
28th November 2022
Published
5th January 2023

ABSTRACT

Friction stir welding (FSW) has an advanced technique in solid-state conditions that joins from different materials compared to the fusion welding process and is eco-friendly. This significant advancement involves aluminium (Al) alloys which facilitate the FSW of distinguished flow patterns in the weld zone. Technically, heat energy and stirred material resulted in softening areas, affecting joint efficiency, mechanical properties, and metallurgical characterisation. This paper has concerns comprehensively covering and summarising the development and application of the topic in different aspects of the performance and quality of the FSW welded joint. The proper tools can create sufficient heat under the shoulder for excellent performance to deal with the welding parameter. All these tools have their literature and journal, which extensive discussion.Furthermore, alloy positioning, defect formation, rotational speed and transverse feed are essential analytical tools for FSW to control the significant weld quality. Furthermore, the mechanical properties associated with microstructural evolution highly dependent on welding technique have remarkably contributed to product development. Finally, a previous study has shown the interest in the topic to enhance the knowledge for further investigation with emerging technology for future recommendations in the FSW discipline.

Keywords: *Friction stir welding, aluminium, process parameter, welding strategies, review*

1.0 INTRODUCTION

The Welding Institute (TWI) developed a new method that engaged with the joining of material in which a solid-state welding process, friction stir welding (FSW) [1], which may be used to join any sort of comparable material, such as alloys, steel, or even composite materials. FSW processes may be applied for similar and dissimilar materials welding joints configuration. However, it has been generally documented that joint efficiency can improve mechanical properties and microstructure characteristics using FSW processes of dissimilar materials to those of the base materials [2]. Figure 1 shows that the FSW process employs a non-consumable rotating tool comprised of a shoulder, pin, or probe. During FSW, heat generation is caused by friction between shoulder surface and parent material and localised plastic deformation. Because of the combined action of the rotating tool and shearing, the shoulder has plasticised material through transverse motion generating a butt-welded joint [3].

 DOI: https://doi.org/10.11113/jm.v45.456

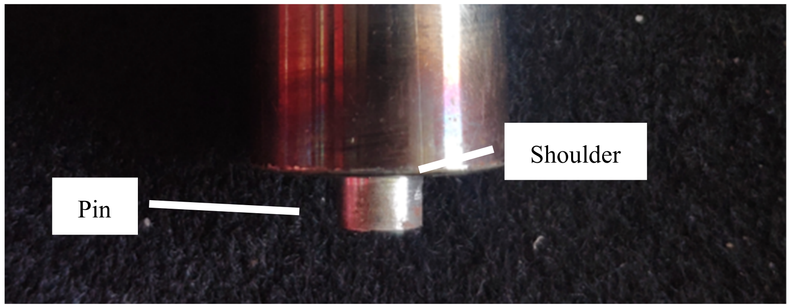

Figure 1: Parts of the FSW tool

Generally, FSW is controlled by several process parameters into consideration for performing the welding. In addition, numerous studies were carried out on the influence of these variables on the properties of dissimilar aluminium alloys upon underwater friction stir welding (UFSW) joints. Meanwhile, the workpiece heats up during the friction stir; the temperature does not achieve the melting point [4]. The peak temperature and melting points were ~ 511◦C and 638 ˚C, respectively [5]. Despite that, an interface curved by a coarse grain structure is caused by the increased input and subsequent reduction of the cooling rate. The temperature effect on material behaviour on AA7075-T6, owing to uneven temperature changes after the temperature distribution near the welded zone, led to crucial conditions and very fine to improve the accuracy of coarse grain structure [6].

Due to its favourable strength, aluminium alloy is a viable candidate to replace steel in getting an effective weld and the critical contributions of this study in a few defence applications. Furthermore, the development utilised to weld various aluminium was improved to some extent regarding the mechanical properties of the joints. Friction stir welding has multiple advantages over traditional fusion welding processes. Fusion welding techniques are classified based on a heat source, such as electric arc welding, gas welding, electrical resistance welding, and high-energy welding. Furthermore, compared to fusion welding, FSW processes are far more energy-efficient, environmentally friendly, and versatile. Aluminium alloy joints are commonly found in various applications, such as marine structures, pipelines, and storage tanks [7].

During FSW, the bottom part of the tool, known as the tool pin, is completely inserted between adjoining surfaces until the upper part of the tool, known as the shoulder, contacts the base plate material near the bottom of welded joints. In addition, the geometry of the FSW tool shoulder and tool pin profile is an essential factor that influences the weld strength stirring effect also in the welded zone [8] Because the frictional heat created by rubbing between the tool shoulder softens the parent metal during the FSW process, the surface of the metal becomes plasticised, allowing bonding to occur [9]. The combined effect of two forces (plunge force and forward motion) causes the plasticised material around the pin inside the stir zone [10]. In most FSW joints, three unique zones are identified: the stir zone (SZ), the thermo-mechanically affected zone (TMAZ), and the heat-affected zone (HAZ). The basic schematic diagram of FSW processes is shown in Figure 2.

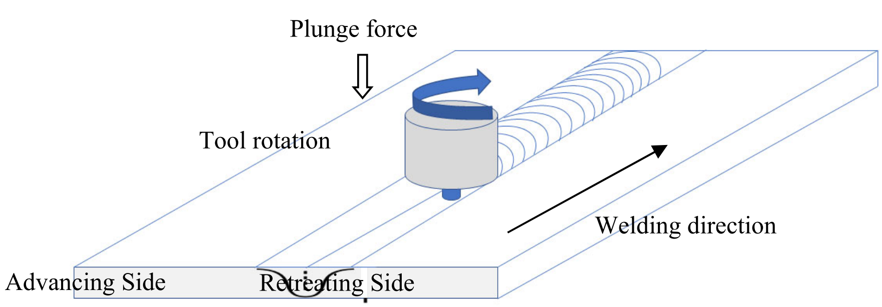

Figure 2: Schematic diagram of FSW processes.

DOI: https://doi.org/10.11113/jm.v45.456

In contrast, the welding line creates a sound joint with defect-free and more homogenous welds produced by the underwater FSW technique. At higher rotational speeds, microstructure evolutions and mechanical characteristics significantly affect the maximum weld efficiencies recorded for underwater FSW [11]. Weld joint quality revealed onion ring patterns exclusively in underwater FSW, and the tensile strength and the micro-hardness of both TMAZ and SZ were roughly higher than the conventional ones [12]. Increased rotational speed reduced weld efficiency to several percent on the weld strength. Because of the cooling effect and decreased heat input revealed finer grain structure in the underwater FSW [13]. The general characteristics of this welding process are analysed to suggest the needed input parameters by focusing primarily on the process parameter, the effect of rotational speed and welding speed, welding strategy, mechanical and microstructural analysis and the defect creation and characteristics of the welded materials [14].

It is critical to have a good comprehension of this crucial topic of friction stir welding. Understanding how to use the FSW method is essential to process development. The influence of process parameters, welding effects, and process monitoring on joint qualities are continuously being studied. However, a significant effort remains research to be done to completely gather and integrate the understanding of mechanical properties and the microstructure analysis process has been extensively studied. This review was created by reviewing several published studies on various FSW techniques of experiments. The assessment was carried out to map numerous features during the process of FSW and underwater FSW, link these factors and emphasise continuity and gaps in this discipline. This manuscript also includes the previous study for interested scholars in the additional field of the FSW technique utilised to material similar and dissimilar welded joints. The following section discusses the effect of the FSW parameters on material as reported by the researchers.

2.0 PROCESS PARAMETERS

The welding performance of this friction stir welding type is determined by primary process parameters such as tool material, tool design and geometry, tool shoulder and tool pin, welding speed, and rotational speed. Various studies have explored these process parameters to determine the influence on FSW processes to achieve sound welded and defect-free.

2.1 FSW Tool

The FSW tool is a crucial process parameter developed by surface grinding and lathe machine whose primary role is to soften the base material through frictional force between the tool and the workpiece. The mechanical stirring effect occurred plastically deformed material extruded the base materials around the tool in plunge force and traversed along the weld axis, after which the softened material solidified during the operation [15]. The choice of FSW tool is influenced by two factors: tool material, tool design, geometry and tool shoulder and tool pin.

2.1.1 FSW Tool Material

Material selection and process parameters play a significant role in determining the FSW's success depending on the material's properties to be connected [16]. For example, AA7075 and AA5083 are widely used for the sample and are often needed in shipping and aerospace. In addition, the pin is made up of high-strength materials required during the stirring process, such as tungsten carbide [17]. The shape and characteristics of tool material have been developed for high integrity casting performance to unwanted effect mixing that influences the outcomes joint interface. The tool is designed to create composites, remove casting defects, and refine microstructure with excellent toughness and strength [18]. However, the fabrication of such a tool is significantly challenging and how the FSW process influences the various mechanical effects and associated product defects, especially component material joining, for utilising both high melting temperature and high strength alloys [19]. The most regularly used FSW tool materials are listed below in Table 1.

Table 1: FSW tool material used during FSW

Alloy	Thickness (mm)	Tool Material	Reference
Aluminium	<12	Tool steel,WC-Co	
Aluminium	2.5	AA5083	4
Aluminium	6	7075-T6	6
Aluminium	6	AA 5383/AA 7075	7
Aluminium	6	AA5083-H111 and AA6351-T6	8
Aluminium	4	7055	20
Aluminium	5	AA 5086–AA 6061	21
Aluminium	6	AA6061–AA5086	22
Aluminium	5	A6061-AA7075	23
Aluminium	10 & 16	AA7075–T651	24
Aluminium	8	AA6082–AA7075	25
Aluminium	6.3	AA6061-AA7075	26
Aluminium	4	7055	27
Aluminium	6	AA7075/AA5083	28
Aluminium	19	AA2519-T87	29

Various studies successfully attempted to fabricate FSW joints utilising heat-treated high-speed steel and hardened tool steels from HRC 45 to HRC 62 [30]. Most FSW processes have primarily used tool steel during the experimental work. Because it is a solid-state process, rather than melting the base material, heat generation resulting from the frictional force was joined to the working material using the FSW tool [14]. The rotating tool helps soften the material with an adequate temperature closer to the melting point subjected to the welded joint by FSW. No defect existed during the material deformation and joint strength and consequently improved weld quality owing to increased material flow of solidified material [31]. As previously said, manufacturing a high-quality FSW necessitates the selection of the best tool material for the experimental work. Microstructural analysis and mechanical properties were performed to establish the best technique for joining the base material plates. The study showed that excellent welded connections might be formed when a tool is coated with AlTiN [32].

2.1.2 FSW Tool Design And Geometry

The solid-state nature of FSW was influenced by tool design and material; welding parameters with the joint design were performed to assess the effect of process parameters on weld joint quality. A specially designed rotational pin as the non-consumable tool is mounted on the chuck to weld materials; generated heat from frictional heat leads to plastic deformation in the welded zone [33]. The tools are essential in getting the best FSW/UFSW process results. Friction creates heat between the tools and material plasticised under sufficient axial force to complete the joining process influenced by the tool design. Generating heat and mixing material by stirring and developing joint, tool pin and shoulder is very helpful. As the friction occurs between the tools and the plastic deformation, there is no melting during the phase and heat generation occurs internally. The influences of tool profile variation on mechanical were tested in 6 mm thickness AA5083- H111 joints [34].

The localising heating and material flow behaviour is primarily influenced by the FSW tool design of the pin and shoulder; this relates to controlling critical components on the strength of the welds [35]. Before welding, the parent materials must be fastened and clamped at the jig and fixture to prevent the parent material from moving throughout the experimental work. The tool shoulder then forges the plastic deformation. Material flow behaviour under the operation of a spinning tool influences the formation of a friction stir processing zone. The findings reveal that different types of welding process parameter combinations design affect the mechanical characteristics and of joints due to changes in suitable heat generation and sufficient material flow and microstructure homogeneity of composites [36]. The effect of different tool geometries and shoulder and pin design on FSW experimental work is discussed below.

DOI: https://doi.org/10.11113/jm.v45.456

2.1.3 FSW Tool Shoulder

A study of tool shoulder considers various profiles in which essential aspects for given material and welding parameter. Figure 3 showed that the different tool shoulder surface features [27]. The tool's flat shoulder design is simple, yet flowing material under the surface must be avoided. The adjustment strategy of welding parameter using concave 10 mm diameter shoulder for spray formed AA7055 UFSW joint studied by [37]. Type of conical probe on concave shoulder tool stirred with three grooves resulted in significant rather than other tools on investigating the effect of tool geometry contributed the be-behavioural on mechanical and microstructure such tensile strength, hardness, the grain size of the welded joint on AA5086 and AA6061 [20]. Along with the tool shoulder geometry on material, flow obtained small grain size at the top of the weld resulted from high friction input provided more heating during the welding across the temperature of recrystallisation formed the joint comprising FSP zone, TMAZ, HAZ, and base metal regions lead to optimum result for mechanical properties.

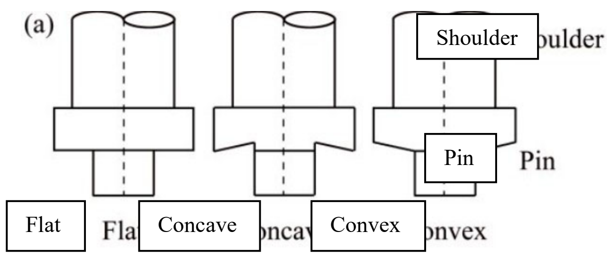

Figure 3: Different tool shoulder profiles, reproduced from review on underwater friction stir welding: A variant of friction stir welding with great potential of improving joint properties, [27].

Tool shoulder diameter is a critical FSW feature to achieve a high-quality connection without defects and should be optimised. The tool shoulder has two functions: it initiates the force down (plunge force) and transverse welding line, which most of the frictional heat. During FSW, the heat generation, plastic flow, and plastic deformation are affected by shoulder diameter [38]. According to [39], the shoulder diameter provides heat generation due to the frictional force of the workpiece and shoulder surface, which influences welded joint qualities and defect development. The tool that is used affects the deformation of the material, the variation of the plunging load, microstructure, and the mechanical features of the FSW processes. The significant accumulation of compound fragments surrounding the joint scratched from the composite bulk, the formation of the intermetallic compound layer is thickened at the weldment joint interfaces.

Consequently, 600 r/min achieved a value of 124 MPa, which was the greatest tensile strength possible [40]. Furthermore, according to the findings that were presented in [41], the Ultimate Tensile Stress (UTS) of the welds increased with bigger tool shoulder diameter sizes resulting from characteristic sections and the size weldment that was being stirred [42]. For this reason, optimising the process parameters of selecting a tool shoulder is vital for achieving a good weld and lowering the number of welding defects. The tool shoulder profile and geometry considerably impact the material flow mechanism. External heating proved critical in enhancing weld nugget shape and size, boosting welding mechanical strength and microstructural characteristics, and producing FSW processes by softening the material to be welded [35]. In addition, a tool with a shoe shoulder enabled the creation of stronger bond welds with acceptable surface appearances [43]. The author [44] achieves complete and high-quality weld sound and defect-free weld lines in the FSW of thermoplastic pipe joints. The imparted downward force and a double shoulder and threaded pin allowed for proper material flow, resulting in good welds. The workpiece thickness, parent materials and the tool profile contribute to the compressive effects characteristics of shoulder geometry. As a result of many research articles, designing the most appropriate tool shoulder characteristic during experimental works of the FSW process is still an area of research interest.

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2.1.4 FSW Tool Pin

During welding, the tool's extended portion after the shoulder's surface, known as the probe or pin, is the component inserted into the workpiece by applying axial force [45]. The tool pin travels forward along the metal surface (shoulder) and is shoved inside the workpiece, closely clamped and mounted on a backplate. During the process, shearing the tool shoulder provides a stirring friction action of the plasticised parent metal and consolidating the joint are the primary functions of the revolving tool pin [46]. The pin profile and welding speed contribute to the determining peak temperature of the welding process and the ensuing mechanical characteristics and joint structure [47]. There are several vital elements to consider in the geometry of the tool pin profile, including the surface shape, the tool pin's length, and the tool pin's diameter to produce refined grains in the stir zone. In addition, the FSW process requires a proper contact surface slide between the workpiece and the shoulder. The length of the pin is yet another essential component of the FSW process. If the length of the pin is more than the thickness of the workpiece, otherwise will be destroyed parent material can cause damage to the fixture. Therefore, tool pin length should be selected at an appropriate rate so that it corresponds to the thickness of the workpiece [48].

The geometry pin profile and the pin diameter significantly impact the material flow pattern, the characteristics of the stir zone, mixing and joining, and the grain microstructure. For example, Nazarlou et al. [49] used three tool pins: cylindrical, square, and triangle. The effect of processed superplasticity of AA7075 alloy under variation of polygonal pin profile on FSW weld joint as shown in Figure 4 [50].

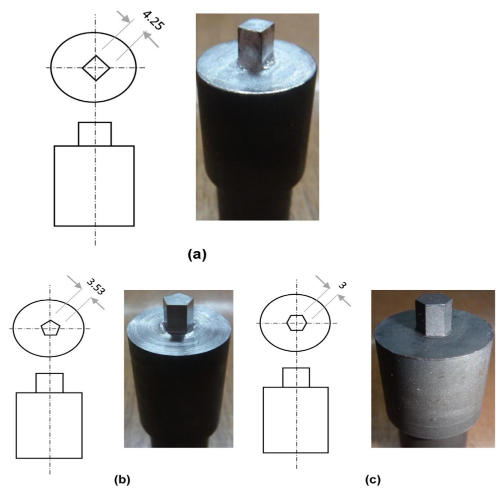

Figure 4: Variation of pin profile tools on friction stir processed superplasticity of AA7075, reproduced from [50].

The type of pin profiles like threaded cylindrical, taper cylindrical and straight cylindrical is used to analyse FSW, AA6061- AA5086 joints [22]. They analysed the strength hardness, microstructure and material flow behaviour of dissimilar aluminium alloys and found that the threaded cylindrical profile resulted in good flowability and produced free sound weld. On the other hand, the significant relationship resulted in the behaviour of the tool pin thread with interruption on the surface [51]. The primary function is to form a weld joint from the tool shoulder, a pin plunged into the joint, traverses along the line, and contact under depth penetration [50,23,24]. During friction stir welding, stirring produces higher heat input and higher temperature from the conical pin with three grooves that reduce the stir zone region and obtain quality joint compared to other tools [25]. After the welded joint using the pin with three flats resulted in the thickness of onion ring sub-layers provided from the material flow waves pattern in the nugget centre line [26].

To conclude, associated stirring with the pin eventually produced a high plasticity impact, and the parent metal was deformed [4,52]. The conical helical shape is best at the mechanical properties due to the cyclical material oscillations transfer from stirrer pins and the hardness value comparable to the rotational speed of the pin profile in the weld centre [53]. The penetration depth related to severity defect

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at weld nugget due to failure behaviour in joints contributed from inadequate and mixed flow materials are subject to low penetration due to unwanted alteration of the material flow with the flow profile during welding [34].

2.2 Rotational Speed And Welding Speed Effect During Dissimilar FSW

Welding speed, also known as feed rate and traverse speed, is the rate at which the tool moves longitudinally along the surface of the weld line being operated on the FSW. The rotational speed, welding speed, tool shape, and tilt angle are all essential design aspects that must be considered [49]. It was deduced that welding speed contributes considerably to weld quality during the FSW experimental works. The ideal welding speed depends on several criteria after the optimal level of process parameter has been chosen. This is all about developing and improving the welding quality of the FSW process. Krishnan and Subramaniam [54] researched and established the best values for the process parameters of tool rotation speed, welding speed, and tool plunge depth. Their result indicated that the percentage contribution of the welding speed was 40.5 percent, influencing numerous answers considerably. Following it in order of importance was the plunge depth, which contributed 25.84 percent, and the rotational speed, which contributed 18.13 percent. The FSW process was fabricated successfully, and it is essential to have complete control over the process parameter to determine the optimal welding speed.

The production of the intermetallic compound on parent metal in the FSW process greatly influences the welding speed followed by rotational speed [55]. In addition, the FSW process proved the effectiveness of heat input by producing metallurgical bonding grain in the stir zone, which resulted from material flow mixing. Therefore, it was possible to get a relatively sound welding result with welding settings of the high rotational speed (2085 rpm) used to generate the proper amount of heat input from mechanical mixing and the associated high welding speed (762mm/min) [56]. Therefore, welding parameters such as rotating speed, tool penetration, and welding speed are critical to a successful welded joint. In addition, fabricated joints can be reinforced and strengthened by adding nanoparticles to the weldment, which can also be used to generate a metal matrix composite [57]. Afterwards, the qualities of the parent material, such as hardness, strength, ductility, fatigue life, wear resistance, and corrosion resistance, improved due to this treatment [58].

A large part of the hardness profiles is influenced by precipitation behaviour, which is governed by the amount of heat generated by frictional force. Because the heat input increases with high rotational speed while welding at a constant speed, the TMAZ's width constantly grows [59]. As a result of too much heat input, the grain becomes coarser, and the hardness is relatively low. Lower hardness values can be attained in the TMAZ and HAZ because the coarsening and dissolving of precipitate particles are facilitated [60]. The welding temperature can be reduced by reducing both the rotational speed and the axial force by increasing the welding speed. The remaining stresses were symmetrically at the tool shoulder edge along the welding line. It was found that the increased residual tensile and axial force stress was caused by increasing welding speed [61]. Welding speed is the following list of factors influencing the weldment product's properties [62]. Welding and rotational speed contribute to a significant responsible impact on heat generation during the FSW process [56]. The high temperature reached during the FSW process relies on the welding speed value [41]. Another investigation found that a high velocity of welding speed produced less heat, which resulted in an inadequate mixing material flow of the parent material. Consequently, the weldment joint surface turns imperfect, creating poor quality and joint strength [63]. In contrast to the high welding speed, according to the experimental work by Dewangan et al.[64] they observed the best-achieved weld strength on dissimilar joining of AA7075 and AA5083 at a welding speed of 20 mm/min.

In FSW, defect such as tunnel defect, kissing bond, lack of fill, and flashes occurs because of the excessive heat generated by the improper material mix flow of rotational tool speed and welding speed. Whenever the tool shoulder fails to retain the plasticised material within the shoulder's diameter, the material dries up and accumulates due to the lack of heat consumed during welding. The quality of the weld and material flow is influenced by tool design and tool speed, controlling the frictional heat generated during welding. Consequently, welding speed significantly impacts grain structure formation with superior mechanical properties values during the FSW process. The rotational tool speed and feed

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rate greatly influence better flowability and weld nugget formation at the joining centre [65]. Several process parameters contributed to the FSW of dissimilar alloy. Many studies were carried out on the effect of these variables on parameters of the FSW joints of dissimilar aluminium (Al) alloys. The result of rotational tool speed (700,800, 900 rpm) and transverse speeds (40, 60, 80 mm/min) on the FSW of Al-alloy showed that there is a correct combination of the weldment caused by strength and hardness in metallurgical bonding [66]. Two parameters significantly affected the joints between strength and microstructure resulting from the influences of the rotational tool speed and tool pin profile on the strength and microstructure of FSW AA5083-H11 and AA6351-T6 Al-alloys [67].

3.0 WELDING STRATEGY FOR DISSIMILAR FSW

The FSW method utilised to acquire the welded joints directly contributes to the welding quality that was produced. However, many weld defects can be caused by selecting insufficiently accurate parameters for the welding process or employing an improper welding strategy. Weld strategies include parametric optimisation, tool design and geometry selection, heat treatment, type hole design and reinforcement particles [68]. It was discovered that the spindle motor had the strongest association with the stress and ductility of the material due to identifying defect-free welds and welding quality [69]. For monitoring of the FSW process, welding set parameters must be employed, such as controlling tool speed, welding speed and plunge depth. Besides that, a successful technique for the stirring mechanism is often influenced by the material mixing and plastic deformation to impact the weld quality significantly. The mechanical mixing in the stir zone during the FSW process results from a combination of the effect of several different welding strategies. Heat is generated through frictional force between the shoulder, and the surface of the parent material, leading to softening impact and dynamic recrystallisation at the weldment [70. To this point, sound welding of the FSW process has been achieved by employing combinations to enhance the welding strategies. Research has also attempted to adopt improvement strategies on the material thickness and workpiece position. The finding of these studies is summarised in the section that follows.

3.1 Workpiece Material Thickness

Choosing appropriate process parameters is heavily influenced by the thickness of the sheet material. The length of the tool pin should be within the thickness of the weld plate; otherwise, the tool can break after being shoved into the weld plate. Poor mechanical mixing (interlayer) along the weld plate thickness resulted from an improper approach to selection process inputs [56]. Regardless of tool design or material weld plate thickness, that is the essential mechanics of material flow. For dissimilar material, underwater FSW of 1 mm thick Al-Cu, would be beneficial results from more systematic experiments, partly because the weld zone in FSW dissipates heat more rapidly than in FSW [71]. Heat loss and surface stirring also increase at the weld zone, reducing the weld's thickness and requiring improved downward direction control [72]. In future, additional research is needed in the material FSW process with a plate thickness of more than 12.7 mm [73].

3.2 Workpiece Position And Placement

The relative workpiece position and placement of the tool profile and parent material are essential aspects determining the welding quality during the FSW process. Placement of workpiece indicates rotation speed and affects the mixing levels for both low and high rotation as low speed will result in intense mixing, whereas high spin speed can produce a smooth onion ring pattern during mixing during weld joints [74]. The location of the advancing side (AS) and retreating side (RS) could significantly affect the material flow and weld quality. The hardness level of the retreating side is relatively higher than that of the advancing side [33]. The position of base plate aluminium alloys can significantly impact the peak temperature and the heat dispersion. According to the findings, the parent material with the most impact can be reached peak temperature on the advancing side than when the harder alloy is on the retreating side [75]. Aluminium alloys 6061- T6 to T2 copper of 1 mm in thickness FS welds with comprehensively

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investigate the placement of workpiece in which the aluminium alloys sheet can be placed on the advancing side to facilitate the flow of nugget material increased and expand the volume of the mixing zone due to thermal cycle effect [76]. In the stirring process during the FSW of dissimilar alloys, the position and arrangement of parent material considerably influence the material flow pattern and the welding quality. The only part of the tool pin that sees a considerable temperature differential is right around the surface shoulder [77]. The FSW is distinguished by the uneven temperature distribution of the material plate resulting from the material flow produced by advancing and retreating sides. To successfully the FSW process, it is advised to consider the positioning of parent material in welding arrangements since the thermal conductivity of alloys material flow increases and produces defect-free [78].

4.0 MECHANICAL PROPERTIES OF DISSIMILAR FSW

During the FSW process, different temperatures at different stages will produce the material flow behaviour and differences in the mechanical property [37]. However, generally, it something hard to define the effect of temperature along with the FSW process's material flow behaviour and mechanical properties. However, there were differences in tensile strength of these dissimilar weld alloys on behaviour material flow, effect between the elimination of cold working and heat-affected zone (HAZ) of AA5083, precipitation of second phase dissolution in AA6351 alloy and imperfections bonding formation in weld zone between two plate welded zones. Yet, it is crucial for developing the quality of welding joints. For example, the material transfer displacement in the middle of the weld is upward while the material near the bottom of the weld transfer to nearly zero and the material transfer downwards when the material is near the surface [6].

Focusing on the hardness and tensile properties of FSW AA5083- and AA6111-T4 Al alloys showed comparable strength to the base material (BM) of welded zone AA6111 alloy [79]. However, noticeably, the weld zone is softer than the base material in the AA5083-H18 alloy. This softening is related to the heat generated from the FSW process due to porosity and kissing bonds being formed with the increase in the welding speed when the position is on the retreating side [80]. Improvement of hardness strength was attributed to the joint strength and deformation behaviour remarkably affected on dissimilar FSW aluminium alloy [81]. The hardness measurement of three depths from the top is shown in Figure 5. Besides the effect of tool pin profile on the micro-hardness distribution of the FSW of high zinc brass, it was confirmed that in the correlation between temperature and hardness which noticeably heat generation resulted from frictional forces and material flow stirring supplementing effect on hardness scale for different tool pin profiles during FSW of brasses [82].

FSW on joining of non-weldable AA7075 and weldable AA6061 aluminium alloy sheet contributed the lowest hardness under the pin across stir zone was found further in the TMAZ regions were defect-free was observed to occur [83]. The hardness measurement of three depths from the top is shown in Figure 5. The effects of welding heat input and post-weld ageing time on welding parameters in dissimilar FSW of AA7075 and AA5086 aluminium alloys are considered. The reprecipitation enhances higher hardness due to solid solutions during rapid cooling of welds joint for natural ageing on the AA7075 side [84].

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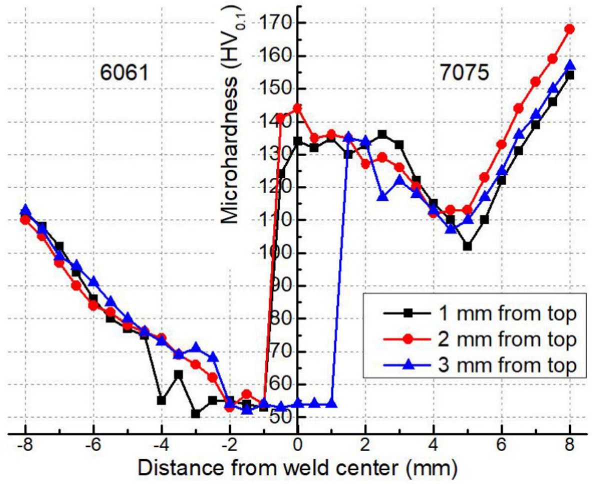

Figure 5: Cross-sectional hardness distribution at three depths from the top (17mm/min by feed rate), reproduced from [83].

The beneficial effect of preheating on the A7075 aluminium alloy specimen was a successful weld joint for output in tensile strength and joint efficiency during process control [85]. Before welding a joint, add preheating process with a selection of the tool pin profile and the appropriate combination of parameters; it provides the presence of a microcavity that indicates ductility failure for joints [65]. However, the tool rotating at high speed along the joint line could lead to failure such as breakage and brittle on the contact surface. The preheating process significantly affects the specimen as it will affect the behaviour and pattern of the mixing and the grain stirring zone where the grain size is slightly coarser, and the tensile strength and bending are slightly better than the specimen without preheating [86]. While stirring AA2024 and pure commercial copper, higher ultimate stress results from flat shoulder tool and 2° tilt angle rather than the specimen welded without tilt angle, and the 1mm pin offset offered higher strength upon the samples welded [87].

The experiment on dissimilar AA6082-T6 and AA5083-H111 FSW weld joints are under investigation of the mechanical properties. The joint efficiencies were obtained for different aluminium alloys compared to similar weld joints resulting in the process parameter getting better mechanical properties, as shown in Figure 6 [88].

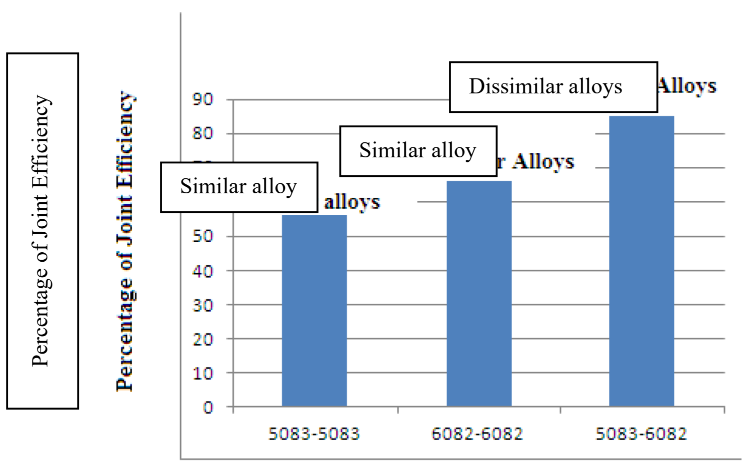

Figure 6: Optical micrographs in various processing conditions of the different samples., reproduced from [88]

DOI: https://doi.org/10.11113/jm.v45.456

5.0 MICROSTRUCTURAL ANALYSIS OF DISSIMILAR FSW

The study reviewed that these sub-processes had a comparable impact on the material movement and temperature generated over the UFSW welded process, resulting in the material's microstructure [89]. Band density and the travel speed gave significant results from the effect of travel speed even on the FSW of the brass plate (CuZn30) [90]. Comparable water-cooled results led to a better cooling rate in the air-cooled environment due to the affected weld zone during the rotational speed of 600 rpm and traverse speed of 30 mm/min for a successful weld joint [91]. Cooling medium submerging underwater produced cooling capability that influenced the parent material up to a hundred degrees Celsius [5]. Decreasing the temperature enhances metal-matrix formation that could be affected by grain structural refinement in weld zone as affected behaviour such as hardness resistance and tensile strength mechanism. Arguably, the cooling medium did not significantly affect the fine-grained and balanced orientation of the stir zone measured from the average grain diameter [92].

In addition, the larger grain size of the FSW joint than the UFSW joints shows the coarsened grain of the microstructure view. A proper flow of material could strengthen the FSW weld joint around the pin, but material friction would result in severe plastic deformation at elevated temperatures and smaller grain size within the nucleation site [93].

Again, at stir zone region could contribute to fine recrystallised equiaxed grain in both base materials welded joints [92]. The grain size variation is significant in UFSW joining process compared to FSW due to lower pin-influenced regions being the finest size. The width of TMAZ resulted from the increased rotational speed on both aluminium alloy sides, which noticeably affected the material flow of the mixing pattern across welded joints [74]. On the other hand, the dissimilar joining of the brass plate (CuZn30) to 1050 Al-alloy gives better joints created owing to higher material flow and metallurgical bonding, significantly affecting heat input on recrystallisation at the welded stir zone [94].

6.0 WELDING DEFECTS OF DISSIMILAR FSW

The study used UFSW on aluminium alloy AA5052, a weldability material that produces quality joint welds and found that certain rotational speed and welding speed could lead to tunnel defects and excess plasticised issues [34]. During the welding process, the initial cavity shaped in AS shaped the flowing materials short fill in filament as incomplete welds and tunnel defects appeared inner the weld [95]. Furthermore, high friction during welding leads to increased heat input on the aluminium surface and dissolved excessively, which causes a defect in the HAZ region [96]. In addition, the precipitate is dissolved in the aluminium matrix due to high heat friction. Therefore, the weld strength will be affected collectively due to defects. However, the study proposed that the cooling medium can be used to surround the weld zone so that defects can be resolved due to grain refinement control of the welding defects [27,96].

Theoretically, high heat generation results from high rotation of the tool and will release the stirred material to the upper surface, resulting in a micro void in the nugget zone [4]. On the other hand, the tool's speed causes a low cooling rate and results in the formation of coarse grains on the welded surface. Besides, the welding process in air-cooled conditions leads to large voids rather than underwater welds showing dimples with small voids. Differences in porosity comparably the grain refinement in cooling medium weld compared to ambient condition weld [97]. However, reducing the heat input by cooling medium helps the material's grain structure be continuously refined [5]. Due to cracking in the solidification process, this alloy does involve the melting materials, which rely on melting to join material; otherwise, it would degrade the mechanical properties of the joint. However, AA7075 aluminium alloy is practically used in aerospace components because of the composition material like high strength and lightweight [85]. However, the dispersion of fractured surface energy contributes to surface cracks and causes brittle fractures and failures, resulting in a loss of strength from oxide formation.

 DOI: https://doi.org/10.11113/jm.v45.456

7.0 CONCLUSION

This article aims to provide insight into the current study of the information connected to the FSW process by presenting the review and complete analysis of previous literature on FSW of parent materials. Most of the research publications cited comprehensively studied the various process parameters, considering their effect on the FSW joints' process parameters, welding strategies, microstructure, and mechanical properties. Welding design is essential in optimising process parameters such as rotational tool speed, traverse speeds, and tool pin profiles of the FSW formed. Also, added heating in FSW improves flow, reducing tool and welding forces. Moreover, to achieve good quality joint with optimum strength and minimum defect, it can be helpful, especially during FSW of dissimilar aluminium alloys, to analyse the impact of process parameters such as rotational tools, traverse speed, and effect on the tool pin profiles and preheating. The FSW and UFSW optimisation process must be performed for good quality welding joining. The development of this method is an essential field of research for using this process to incorporate different materials with industrial applications. The researchers have mentioned the defect discovered during the various FSW processes of varying parent materials. The researchers have also explored the potential sources of these defects and potential solutions to fix them. In addition, a discussion is held on various possible variations of FSW utilised by researchers for a microscopic study. Despite the significant research interests, different research has to give more attention to this area. Hopefully, this overview could better understand essential information and help them orientate future development for the FSW process.

ACKNOWLEDGMENTS

This material is based upon work supported by the Ministry of Higher Education (MOHE), Malaysia and the Research Management Centre of UTM for the financial support through the RUG funding R.J130000.7851.5F382.

REFERENCES

1. Thomas, W.M., Nicholas, E.D., Needham, J.C., Murch, M.G., Temple-Smith, P., and Dawes, C.J., 1991. Friction Stir Butt Welding. International Patent Application No. PCT/GB92/02203; GB Patent Application No.9125978.8, U.S.Patent Application., 460 (5) .
2. Sengupta, K., Singh, D.K., Mondal, A.K., Bose, D. and Ghosh, B., 2021. Analysis of mechanical property of electrically assisted friction stir welding to enhance the efficiency of joints. *Materials Today: Proceedings*, *38:*2263-2270.
3. Verma, M., Ahmed, S. and Saha, P., 2021. Challenges, process requisites/inputs, mechanics, and weld performance of Processes, *68*:249-276.
4. Thube R., (2014). Effect of Tool Pin Profile and Welding Parameters on Friction Stir Processing Zone, Tensile Properties and Micro-hardness of AA5083 Joints Produced by Friction Stir Welding. *International Journal of Engineering and Advanced Technology (IJEAT)*, 3(5): 2249 – 8958.
5. Derazkola H. and Khodabakshi F., 2019. Underwater submerged dissimilar friction-stir welding of AA5083 aluminium alloy and A441 AISI steel, *The International Journal of Advanced Manufacturing Technology*., 102:4383–4395.
6. Ji, S. D., Jin, Y. Y., Yue, Y. M., Gao, S. S., Huang, Y. X. and Wang, L., 2013. Effect of temperature on material transfer behaviour different stages of friction stir welded 7075-t6 aluminium alloy, Journal Material Science Technology, 29(10):955-960.
7. Tamjidy, M., Baharudin, B.H.T., Paslar, S., Matori, K.A., Sulaiman, S. and Fadaeifard, F., 2017. Multi-objective optimisation of friction stir welding process parameters of AA6061-T6 and AA7075-T6 using a biogeography based optimisation algorithm. *Materials*, *10*(5):533.
8. Muhayat, N., Triyono, R.D.R. and Zubaydi, A., 2018. Effect of Tool Plunge Depth and Pin Profile on Mechanical Properties of Friction Stir Spot Welded AA5052 Joints. *Journal of Mechanical Engineering (JMechE)*, *15*(1):181-191.
9. Sucharitha, M., Sankar, B.R. and Umamaheswarrao, P., 2020, October. A Review on Submerged Friction Stir Welding of Light Weight Alloys. In *IOP Conference Series: Materials Science and Engineering* IOP Publishing, 954(1): 012014)..
10. Yuqing, M., Liming, K., Fencheng, L., Yuhua, C. and Li, X., 2017. Effect of tool pin-tip profiles on material flow and mechanical properties of friction stir welding thick AA7075-T6 alloy joints. *The International Journal of Advanced Manufacturing Technology*, *88*(1):949-960.
11. Chandran, R. and Santhanam, SKV, 2018. Submerged friction stir welding of 6061-T6 aluminium alloy under different water heads. *Materials Research*, *21*.

 DOI: https://doi.org/10.11113/jm.v45.456

12. Ethiraj, N., Sivabalan, T., Meikeerthy, S., Kumar, KLVR, Chaithanya, G. and Reddy, G.P.K., 2019, July. Comparative study on conventional and underwater friction stir welding of copper plates. In *AIP Conference Proceedings* AIP Publishing LLC.,128(1):030003.
13. Zhang, G., Xiao, C. and Ojo, OO, 2021. Dissimilar friction stir spot welding of AA2024-T3/AA7075-T6 aluminum alloys under different welding parameters and media. *Defence Technology*, *17*(2):531-544.
14. Anand, R. and Sridhar, V.G., 2020. Studies on process parameters and tool geometry selecting aspects of friction stir welding–A review. *Materials Today: Proceedings*, *27*:576-583.
15. Ramnath, B.V., Elanchezhain, C., Vignesh, C., Sudharsan, V. and Ganesh, C.S., 2020, September. A Review On Friction Stir Welding And It's Processes. In *IOP Conference Series: Materials Science and Engineering*., 923, (1):012030.
16. Shojaeefard M. H., Behnagh R. A., Akbari M., Givi M. K. B. and Farhani F., 2013. Modelling and Pareto optimisation of mechanical properties of friction stir welded AA 7075/AA5083 butt joints using neural network and particle swarm algorithm, Materials & Design., 44:190-198.
17. Chaudhary, A., Mishra, R., Anshari, M.A.A., Imam, M. and Chintapenta, V., 2022. Experimental and numerical investigation of laser-FSW hybrid welding technique for high strength materials. *Materials Today: Proceedings*.
18. Hoyos, E. and Serna, M.C., 2021. Basic tool design guidelines for friction stir welding of aluminum alloys. *Metals*, *11*(12):2042.
19. Singh, V.P., Patel, S.K., Ranjan, A. and Kuriachen, B., 2020. Recent research progress in solid state friction-stir welding of aluminium–magnesium alloys: a critical review. *Journal of Materials Research and Technology*, 9(3):*.6217-6256.*
20. Wang, Q., Zhao, Y., Yan, K., & Lu, S., 2015. Corrosion behaviour of spray formed 7055 aluminium alloy joints welded by underwater friction stir welding, *Materials & Design*, 68: 97–103.
21. Aval H. J., Serajzadeh S., Kokabi A. H. and Loureiro A.., 2011. Effect of tool geometry on mechanical and microstructural behaviours in dissimilar friction stir welding of AA 5086-AA 6061, *Science and Technology of Welding and Joining*., 16(7):597–604.
22. Ilangovan, M., Boopathy, S.R. and Balasubramanian, V., 2015. Effect of tool pin profile on microstructure and tensile properties of friction stir welded dissimilar AA6061-AA5086 aluminium alloy joints, *Def. Technol*., 11: 174–184.
23. Rhodes C. G., Mahoney M. W., Bingel W. H., Spurling R. A., Bampton C. C., 1997. Effects of friction stir welding on the microstructure of 7075 aluminium, *Scripta Materialia*, 36 (1): 69-75, 1997.
24. Chandrashekar, A., Reddappa, H.N. and Ajaykumar, B.S., 2016. Influence of Tool Profile on Mechanical Properties of Friction Stir Welded Aluminium Alloy 5083, *World Academy of Science, Engineering and Technology International Journal of Materials and Metallurgical Engineering.,*10(1).
25. Aval H. J., 2015. Influences of pin profile on the mechanical and microstructural behaviours in dissimilar friction stir welded AA6082-AA 7075 butt Joint, *Materials & Design*., 67: 413-421.
26. Guo, J. F., Chen, H. C., Sun, C. N., Bi, G., Sun, Z. and Wei, J., 2014 Friction stir welding of dissimilar materials between AA6061 and AA7075 Al alloys effects of process parameters, *Materials and Design*., 56:185–192.
27. Zhao, Y., Wang, Q., Chen, H. and Yan K., 2014. Microstructure and mechanical properties of spray formed 7055 aluminium alloy by underwater friction stir welding, *Material and Design*, 56: 725–30.
28. Shojaeefard M. H., Behnagh R. A., Akbari M., Givi M. K. B. and Farhani F., 2013. Modelling and Pareto optimisation of mechanical properties of friction stir welded AA 7075/AA5083 butt joints using neural network and particle swarm algorithm, *Materials & Design*., 44:190-198.
29. Sabari, S. S., Malarvizhi, S., Balasubramania,V. and Madusudhan R.G., 2016. Experimental and numerical investigation on under-water friction stir welding of armour grade AA2519-T87 aluminium alloy, *Defence Technology*.,12: 324–333.
30. Hou, W., Shen, Z., Huda, N., Oheil, M., Shen, Y., Jahed, H. and Gerlich, A.P., 2021. Enhancing metallurgical and mechanical properties of friction stir butt welded joints of Al–Cu via cold sprayed Ni interlayer. *Materials Science and Engineering: A*, *809*:140992.
31. Isa, M.S.M., Moghadasi, K., Ariffin, M.A., Raja, S., bin Muhamad, M.R., Yusof, F., Jamaludin, M.F., bin Yusoff, N. and bin Ab Karim, M.S., 2021. Recent research progress in friction stir welding of aluminium and copper dissimilar joint: a review. *Journal of Materials Research and Technology, 15:2735-2780.*
32. Bozkurt, Y. and Boumerzoug, Z., 2018. Tool material effect on the friction stir butt welding of AA2124-T4 Alloy Matrix MMC. *Journal of materials research and technology*, *7*(1):29-38.
33. Naik, L. S., Hadya, B. and Murahari, K., 2018. Experimental Study On AA7075 Its Effect Of Rotational Speed And Tool Pin Profile On Friction Stir Welding Process, *International Journal of Innovations in Engineering and Technology (IJIET)*, 9(3): 88-93.
34. Shanavas S., Dhas J.E.R. and Murugan N., 2018. Weldability of Marine Grade AA 5052 aluminium alloy by underwater friction stir welding, *The International Journal of Advanced Manufacturing Technology*., 95: 4535–4546.
35. Pereira, M.A., Amaro, A.M., Reis, P.N. and Loureiro, A., 2021. Effect of Friction Stir Welding techniques and parameters on polymers joint efficiency—A critical review. *Polymers*, *13*(13):2056.
36. Zhang, C., Huang, G., Cao, Y., Zhu, Y., Li, W., Wang, X. and Liu, Q., 2019. Microstructure and mechanical properties of dissimilar friction stir welded AA2024-7075 joints: Influence of joining material direction. *Materials Science and Engineering: A*, *766*: 138368.
37. Fourment, L. and Guerdoux, S., 2008. 3D numerical simulation of the three stages of Friction Stir Welding based on friction parameters calibration, *International Journal of Material Forming* 1(S1),:1287–1290.
38. Wahid, M.A. and Siddiquee, A.N., 2018. Review on underwater friction stir welding: A variant of friction stir welding with great potential of improving joint properties. *Transactions of Nonferrous Metals Society of China*, *28*(2):193-219.

 DOI: https://doi.org/10.11113/jm.v45.456

39. Chu, Q., Hao, S.J., Li, W.Y., Yang, X.W., Zou, Y.F. and Wu, D., 2021. Impact of shoulder morphology on macrostructural forming and the texture development during probeless friction stir spot welding. *Journal of Materials Research and Technology*, *12*: 2042-2054.
40. Muhammad, N.A. and Wu, C., 2020. Evaluation of capabilities of ultrasonic vibration on the surface, electrical and mechanical behaviours of aluminium to copper dissimilar friction stir welds. *International Journal of Mechanical Sciences*, *183*: 105784.
41. Lambiase, F., Paoletti, A. and Di Ilio, A., 2017. Effect of tool geometry on mechanical behavior of friction stir spot welds of polycarbonate sheets. *The International Journal of Advanced Manufacturing Technology*, *88*(9): 3005-3016.
42. Jafari, H., Mansouri, H. and Honarpisheh, M., 2019. Investigation of residual stress distribution of dissimilar Al-7075-T6 and Al-6061-T6 in the friction stir welding process strengthened with SiO2 nanoparticles. *Journal of Manufacturing Processes*, *43*: 145-153.
43. Eslami, S., De Figueiredo, M.A.V., Tavares, P.J. and Moreira, P.M.G.P., 2018. Parameter optimisation of friction stir welded dissimilar polymers joints. *The International Journal of Advanced Manufacturing Technology*, *94*(5): 1759-1770.
44. Mosavvar, A., Azdast, T., Moradian, M. and Hasanzadeh, R., 2019. Tensile properties of friction stir welding of thermoplastic pipes based on a novel designed mechanism. *Welding in the World*, *63*(3): 691-699.
45. Shunmugasundaram, M., Kumar, A.P., Sankar, L.P. and Sivasankar, S., 2020. Optimisation of process parameters of friction stir welded dissimilar AA6063 and AA5052 aluminum alloys by Taguchi technique. *Materials Today: Proceedings*, *27*: 871-876.
46. Cabibbo, M., Forcellese, A., Santecchia, E., Paoletti, C., Spigarelli, S. and Simoncini, M., 2020. New approaches to friction stir welding of aluminum light-alloys. *Metals*, *10*(2): 233.
47. El-Sayed, M.M., Shash, A.Y., Mahmoud, T.S. and Rabbou, M.A., 2018. Effect of friction stir welding parameters on the peak temperature and the mechanical properties of aluminum alloy 5083-O. In *Improved performance of materials Springer, Cham:*11-25.
48. Khan, N.Z., Siddiquee, A.N. and Khan, Z.A., 2018. Proposing a new relation for selecting tool pin length in friction stir welding process. *Measurement*, *129*:112-118.
49. Delir Nazarlou, R., Nemati Akhgar, B. and Omidbakhsh, F., 2021. Optimisation of friction stir welding parameters with Taguchi method for maximum electrical conductivity in Al-1080 welded sections. *Scientia Iranica*, *28*(4): 2250-2258.
50. Patel, V., Badheka, V. and Kumar, A., 2017. Effect of polygonal pin profiles on friction stir processed superplasticity of AA7075 alloy, *Journal of Materials Processing Technology.,* 240: 68–76.
51. 51 Reza-E-, R. M., Tang, W. and Reynolds A.P., 2018. Effects of thread interruptions on tool pins in friction stir welding of AA6061', *Sci. Technol. Weld. Join*, 23: 114–124.
52. Tiwari S., Chelladurai H. and Shukla A. K., 2014. Parametric Analysis of Friction Stir Welding", AIMTDR.: 1-6.
53. Heirani, F., Abbasi, A. and Ardestani, M., 2017. Effects of processing parameters on microstructure and mechanical behaviours of underwater friction stir welding of Al5083 alloy, *Journal of Manufacturing Processes*., 25:77–84.
54. Krishnan, M. and Subramaniam, S., 2019. Multi-response optimisation of friction stir corner welding of dissimilar thickness AA5086 and AA6061 aluminum alloys by Taguchi grey relational analysis. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *233*(11):3733-3742.
55. Pourali, M., Abdollah-Zadeh, A., Saeid, T. and Kargar, F., 2017. Influence of welding parameters on intermetallic compounds formation in dissimilar steel/aluminum friction stir welds. *Journal of Alloys and Compounds*, *715*:1-8.
56. Zhang, C., Qin, Z., Rong, C., Shi, W. and Wang, S., 2020. The preliminary exploration of micro-friction stir welding process and material flow of copper and brass ultra-thin sheets. *Materials*, *13*(10):2401.
57. Fouladi, S. and Abbasi, M., 2017. The effect of friction stir vibration welding process on characteristics of SiO2 incorporated joint. *Journal of Materials Processing Technology*, *243*:23-30.
58. Sharma, V., Prakash, U. and Kumar, B.M., 2015. Surface composites by friction stir processing: A review. *Journal of Materials Processing Technology*, *224*:117-134.
59. Zhang, C., Huang, G., Cao, Y., Zhu, Y. and Liu, Q., 2019. On the microstructure and mechanical properties of similar and dissimilar AA7075 and AA2024 friction stir welding joints: effect of rotational speed. *Journal of Manufacturing Processes*, *37*:470-487.
60. Fathi, J., Ebrahimzadeh, P., Farasati, R. and Teimouri, R., 2019. Friction stir welding of aluminum 6061-T6 in presence of watercooling: Analysing mechanical properties and residual stress distribution. *International Journal of Lightweight Materials and Manufacture*, *2*(2):107-115.
61. Nie, L., Wu, Y.X. and Gong, H., 2020. Prediction of temperature and residual stress distributions in friction stir welding of aluminum alloy. *The International Journal of Advanced Manufacturing Technology*, *106*(7):3301-3310.
62. Węglowski, M.S., 2018. Friction stir processing–State of the art. *Archives of civil and Mechanical Engineering*, *18*(1):114-129.
63. Kumar Rajak, D., Pagar, D.D., Menezes, P.L. and Eyvazian, A., 2020. Friction-based welding processes: friction welding and friction stir welding. *Journal of Adhesion Science and Technology*, *34*(24):2613-2637.
64. Dewangan, S.K., Tripathi, M.K. and Manoj, M.K., 2020. Effect of welding speeds on microstructure and mechanical properties of dissimilar friction stir welding of AA7075 and AA5083 alloy. *Materials Today: Proceedings*, *27*:2713-2717.
65. Saeidi, M., Barmouz, M., and Givi, M. K. B., 2015. Investigation on AA5083/AA7075+Al2O3 Joint Fabricated by Friction Stir Welding: Characterizing Microstructure, Corrosion and Toughness Behavior. *Materials Research*., 18(6):1156–1162.
66. Sivachidambaram S. S., Rajamurugan G., Amirtharaj. and Divya., 2015. Optimising the parameters for friction stir welding of dissimilar aluminium alloys AA 5383/AA 7075, *ARPN Journal of Engineering and Applied Sciences*., 10: 5434-5437.

 DOI: https://doi.org/10.11113/jm.v45.456

67. Palanivel R., Mathews P. K, Murugan N., and Dinaharan I., 2012. Effect of tool rotational speed and pin profile on microstructure and tensile strength of dissimilar friction stir welded AA5083-H111 and AA6351-T6 aluminium alloys, *Materials & Design*., 40: 7–16.
68. Ogunsemi, B.T., Abioye, T.E., Ogedengbe, T.I. and Zuhailawati, H., 2021. A review of various improvement strategies for joint quality of AA 6061-T6 friction stir weldments. *Journal of Materials Research and Technology*, *11*, pp.1061-1089.
69. Mishra, D., Gupta, A., Raj, P., Kumar, A., Anwer, S., Pal, S.K., Chakravarty, D., Pal, S., Chakravarty, T., Pal, A. and Misra, P., 2020. Real time monitoring and control of friction stir welding process using multiple sensors. *CIRP Journal of Manufacturing Science and Technology*, *30*:1-11.
70. Abioye, T.E., Zuhailawati, H., Anasyida, A.S., Yahaya, S.A. and Dhindaw, B.K., 2019. Investigation of the microstructure, mechanical and wear properties of AA6061-T6 friction stir weldments with different particulate reinforcements addition. *Journal of Materials Research and Technology*, *8*(5):3917-3928.
71. Mao, Y., Ni, Y., Xiao, X., Qin, D. and Fu, L., 2020. Microstructural characterisation and mechanical properties of micro friction stir welded dissimilar Al/Cu ultra-thin sheets. *Journal of Manufacturing Processes*, *60*:356-365.
72. Ahmed, S. and Saha, P., 2020. Selection of optimal process parameters and assessment of its effect in micro-friction stir welding of AA6061-T6 sheets. *The International Journal of Advanced Manufacturing Technology*, *106*(7):3045-3061.
73. Garg, A., Raturi, M., Garg, A. and Bhattacharya, A., 2020. Microstructure evolution and mechanical properties of double-sided friction stir welding between AA6061-T6 and AA7075-T651. *CIRP Journal of Manufacturing Science and Technology*, *31*:431-438.
74. Zhang, C., Huang, G., Cao, Y., Zhu, Y., and Liu, Q., 2019. On the microstructure and mechanical properties of similar and dissimilar AA7075 and AA2024 friction stir welding joints: Effect of rotational speed, *Journal of Manufacturing Processes*., 37: 470–487.
75. Ghiasvand, A., Kazemi, M., Mahdipour Jalilian, M. and Ahmadi Rashid, H., 2020. Effects of tool offset, pin offset, and alloys position on maximum temperature in dissimilar FSW of AA6061 and AA5086. *International Journal of Mechanical and Materials Engineering*, *15*(1):1-14.
76. Zhang, H., Sun, S., Liu, X., Song, J. and Chen, X., 2022. Effect of Tool-Workpiece Relative Position on Microstructure and Mechanical Properties of Al-Cu Dissimilar Friction Stir Weld. *Journal of Materials Engineering and Performance*, *31*(3):2457-2465.
77. Dhanesh Babu, S.D., Sevvel, P., Senthil Kumar, R., Vijayan, V. and Subramani, J., 2021. Development of thermo mechanical model for prediction of temperature diffusion in different FSW tool pin geometries during joining of AZ80A Mg alloys. *Journal of Inorganic and Organometallic Polymers and Materials*, *31*(7):3196-3212.
78. Wei, Y., Chen, Y., Niu, R., Yang, Q., Luo, Y. and Zou, J., 2022. Study on the Thermal Conductivity of Cu/Al Joints with Different Interfacial Microstructures. *Advances in Materials Science and Engineering*, *2022*.
79. Hamed J. A., 2017. Effect of welding heat input and post-weld ageing time on microstructure and mechanical properties in dissimilar friction stir welded AA7075AA5086, *Trans. Nonferrous Met. Soc. China.*, 27: 1707-1715.
80. Raturi, M., Garg, A. and Bhattacharya A., (2019) Joint strength and failure studies of dissimilar AA6061-AA7075 friction stir welds: Effects of tool pin, process parameters and preheating, *Engineering Failure Analysis.*, 96:570–588.
81. Garg A., Raturi M. and Bhattacharya A., 2019. Metallurgical behaviour and variation of the vibroacoustic signal during preheating assisted friction stir welding between AA6061-T6 and AA7075-T651 alloys, *Transactions of Nonferrous Metals Society of China*., 29 (8): 1610-1620.
82. Heidarzadeh, A., Paidar, M., Güleryüz, G. and Vatankhah Barenji, R., 2020. Application of nanoindentation to evaluate the hardness and yield strength of brass joints produced by FSW: microstructural and strengthening mechanisms. *Archives of Civil and Mechanical Engineering*, *20*(2):1-9.
83. Yoon J., Kim C., and Rhee S., 2019. Performance of plunge depth control methods during friction stir welding, *Metals.,* 9(283).
84. Muhayat, N. and Rahmanto, R. D., 2018. Effect of Tool Plunge Depth and Pin Profile on Mechanical Properties of Friction Stir Spot Welded AA5052 Joints, *Journal of Mechanical Engineering Vol SI.*, 5(1): 181-191.
85. Poongkundran, R., and Senthilkumar, K., 2016. Preheating Effect on Microstructure and Tensile Properties of Friction Stir Welded AA7075 Aluminium Alloy Joints, *Brazilian Archives of Biology and Technology*., 59.
86. Kaushik, P. and Dwivedi, DK, 2021. Induction preheating in FSW of Al-Steel combination. *Materials Today: Proceedings*, 46:1091-1095.
87. Tolephih, M. H., Mahmood, H. M and Esam, H. H., 2013. Effect of tool offset and tilt angle on weld strength of the butt joint friction stir welded specimens of AA2024 aluminium alloy welded to commercial pure copper, *Chemistry and Materials Research*., 3(4): 49-55.
88. Kumar, H. M. A., Venkata, R. V. and Pawar M., 2018. Experimental Study on Dissimilar Friction Stir Welding of Aluminium Alloys (5083-H111 and 6082-T6) to investigate the mechanical properties, *IOP Conf. Series: Materials Science and Engineering*., 330.
89. Wahid M.A., Khan Z.A. and Siddiquee A.N., 2018. Review on underwater friction stir welding: A variant of friction stir welding with great potential of improving joint properties, *Transactions of Nonferrous Metals Society of China (English Edition)*., 28(2):193–219.
90. Moghaddam, M., Zarei-Hanzaki, A., Pishbin, M. H., Shafieizad, A. H., and Oliveira, V. B. 2016. Characterisation of the microstructure, texture and mechanical properties of 7075 aluminium alloy in the early stage of severe plastic deformation, *Materials Characterization*, 119:137–147.
91. Khodir S.A. and Shibayanagi T., 2008. Friction stir welding of dissimilar AA2024 and AA7075 aluminium alloys, *Materials Science and Engineering: B.,* 148: 82–87.

 DOI: https://doi.org/10.11113/jm.v45.456

92. Patel, V., Badheka., Li, W. and Akkireddy, S., 2019. Hybrid friction stir processing with the active cooling approach to enhance superplastic behaviour of AA7075 aluminium alloy, *Archives of Civil and Mechanical Engineering I9*,19, pp. 1368-1380.
93. Emamikhah A., Abbasi A., Atefat A. and Givi MK, 2013. Effect of tool pin profile on friction stir butt welding of high-zinc brass (CUZN40), *The International Journal of Advanced Manufacturing Technology.*, 71: 81–90.
94. Kovacs, Z. and Hareancz, F., 2018. Joining of non-weldable AA7075 and weldable AA6082 aluminium alloy sheets by Friction Stir Welding, *IOP Conf. Series: Materials Science and Engineering*., 448.
95. Bayazid S. M., Farhangia, H. and Ghahramania, A., 2015. Effect of Pin Profile on Defects of Friction Stir Welded 7075 Aluminium Alloy, *School Procedia Materials Science*., 11:12 – 16.
96. Mahto, R. P., Gupta, C., Kinjawadekar, M., Meena, A., and Pal, S. K., 2019. Weldability of AA6061-T6 and AISI 304 by underwater friction stir welding, *Journal of Manufacturing Processes*.,38: 370–386.
97. Rouzbehani, R., Kokabi, A. H., Sabet, H., Paidar, M and Ojo, O. O., 2018. Metallurgical and mechanical properties of underwater friction stir welds of Al7075 aluminium alloy, *Journal of Materials Processing Tech.,* 262: 239–256.

 DOI: https://doi.org/10.11113/jm.v45.456