International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XVI, No. 1 / 2024
https://doi.org/ 10.54684/ijmmt.2024.16.1.88

COMPARATIVE STUDY OF JOINING HETEROGENEOUS STRUCTURES MADE BY SOME ALUMINIUM ALLOYS USING FSW PROCESS

Eliza Roxana Oprescu, Alexandru Toma, Daniela Monica Iordache, Eduard Laurențiu Nițu

Manufacturing and Industrial Management Department, National University of Science and Technology Politehnica Bucharest, Pitești University Center, Pitesti, Romania
Str. Târgul din Vale no. 1, Pitești, 110040

Corresponding author: Eliza-Roxana Oprescu, eliza.oprescu@upit.ro

Abstract: Friction Stir Welding (FSW) is an economic and ecological process (the use of additive materials and shielding gas is unnecessary, does not emit harmful gases, uses less energy), which offers important advantages, such as the possibility of joining materials with different properties (e.g., Al - Cu) and making several types of structures. This article aims to carry out a short comparative analysis between end-to-end structures and overlapping structures obtained from some aluminium alloys: AA2024, AA6061, and AA7075. A comparison is presented between the types of tools used to obtain the mentioned structures, between the values of the process parameters, as well as their other particularities. The characteristics of FSW joint structures are analyzed based on the macro and microstructure of the joint and its mechanical properties. Finally, conclusions are presented that allow the orientation of future studies and research.

Key words: FSW, aluminium alloys, end-to-end joints, overlapped joints, comparative study.

1. INTRODUCTION

Light weight, corrosion resistance, machinability and good appearance are the most economical and attractive features that make the aluminium to become a great choice of material for many applications, in various industries (e.g., aerospatial, aircraft, maritime, automobiles, shipbuilding industries etc.). The aluminium alloys are used for a variety of applications, from foil to superstructures [1]. Since some aluminum alloys are not suitable to be joined by conventional welding processes, the development of the friction stir welding (FSW) process has enabled not only the joining of challenging-to-weld alloys but also the fabrication of structures possessing desired properties.

1.1 FSW process description

Given that the joining process takes place at temperatures below the melting point of the base materials, friction stir welding (FSW) is categorized as a solid-state welding technique. Thus, the FSW is used to join non-weldable materials, such as copper, titanium, magnesium, etc., and some aluminum alloys. It occurs in four stages: plugging, dwelling, welding and retracting (Figure 1). In the plunge stage the tool penetrates the workpieces with a specific rotational speed and stand still until it softens the material due to plastic deformation as well as friction (dwelling stage). The tool stirs the soften material and traverse the weld path. Through that is generated the weld seam in the welding stage. The last stage entails that the tool to be retracted from the workpieces when welding is fulfilled [2].

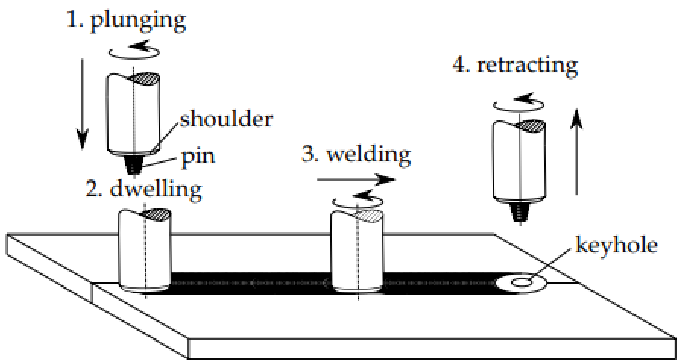

Fig. 1. FSW stages (adapted from [3])

1.2 Types of aluminium alloys joined by FSW

Pure aluminium has lots of good properties, but it doesn't have very high tensile strength. To obtain superior properties of the material it is necessary to combine it with various alloying elements. The aluminium alloys series and their properties are presented in Table 1, and in Figure 2 are illustrated the series of aluminium obtained with different alloying elements and their weldability.

Table 1. Aluminium alloys properties [1]

Material	Properties			
1xxx	Suitable for strain hardening	High formability, Electrical conductivity, Corrosion resistance	Typical ultimate tensile strength domain: 70 to 185 [MPa]	Joined by welding, soldering and brazing
2xxx	Suitable for heat treatment	At room and elevated temperatures present high strength	Typical ultimate tensile strength domain: 190 to 430 [MPa]	Commonly joined mechanically
3xxx	High formability, Medium strength, Corrosion resistance	Typical ultimate tensile strength domain: 110 to 285 [MPa]	Joined by all conventional procedures	
4xxx	Suitable for heat treatment	Medium strength, Satisfactory flow characteristics	Typical ultimate tensile strength domain: 175 to 380 [MPa]	Simply joined
5xxx	Suitable for strain hardening	Average strength high corrosion resistance, toughness, weldability;	Typical ultimate tensile strength domain: 125 to 350 [MPa]	Used in building and construction, automotive, and marine applications
6xxx	Suitable for heat treatment	High corrosion resistance, very good extrudability, average strength	Typical ultimate tensile strength domain: 125 to 400 [MPa]	Welded by gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW)
7xxx	Suitable for heat treatment	Significant strength; special high-toughness versions	Typical ultimate tensile strength domain: 220 to 610 [MPa]	Joined mechanically
8xxx	Suitable for heat treatment	Significant conductivity, strength, and hardness	Typical ultimate tensile strength domain: 120 to 240 [MPa]	

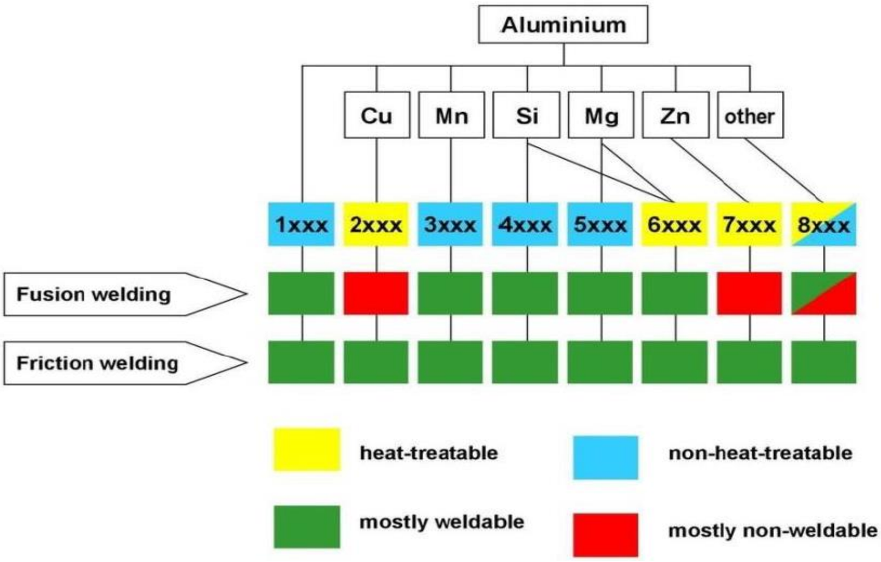

Fig. 2. Aluminium alloys weldability [4]

The 2xxx and 7xxx series of aluminium alloys, whose properties recommend their use in aircraft parts and structures [1], are hard to weld by conventional welding (see Figure 2), but they could be joined mechanically (Table 1). These series are considered as non-weldable alloys due to their defective solidification microstructures obtained by conventional welding techniques [5]. Because no melting takes place in FSW, no re-solidification problems occur.

1.3 Structure configurations of aluminium alloys joined by FSW

Friction stir welded structures can be made in several configurations (Figure 3), but the most common configurations of the FSW structure are end-to-end (butt) and lap joints, as they do not require special preparation.

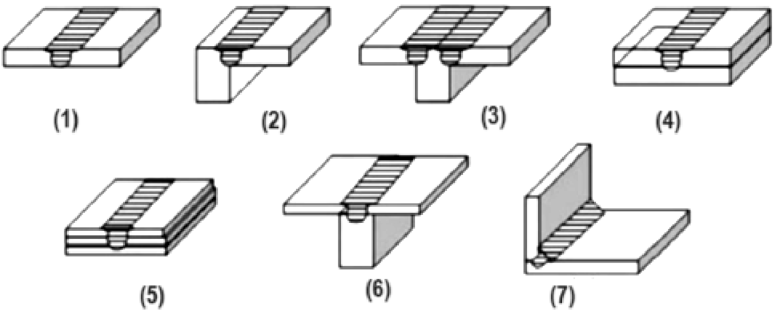

Fig. 3. FSW joint configurations: (1) square end-to-end, (2) edge end-to-end, (3) T end-to-end joint, (4) lap joint, (5) multiple lap joint, (6) T lap joint, and (7) fillet joint [5]

The friction welding process represents a viable solution to create both end-to-end and lap structures, with superior characteristics compared to those obtained by conventional welding processes, which makes it applicable in many industrial fields, the field of machine construction, the aeronautical field or the railway, fields that involve the assembly of metals or hard-to-weld alloys [6].

The end-to-end structure implies that the two workpieces to be placed end to end and the rotary tool, having specific rotation and advance movements, penetrates between the two, mixing the material and transferring it behind the pin of the active element, thus making the weld bead, Figure 4 [7].

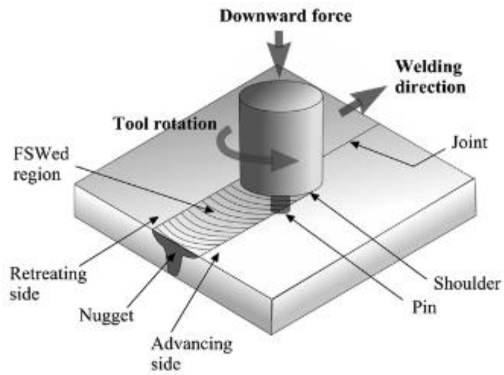

Fig. 4. End-to-end FSW joining process [7]

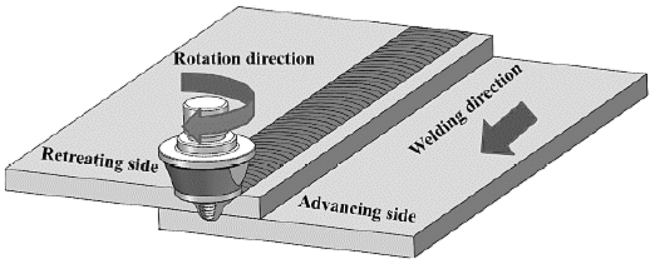

Fig. 5. Schematic principle of FSLW [8]

Friction stir lap welds (FSLW) are obtained by embedding the adjoining edges of the workpiece on a well-designed fixture, then inserting a specific rotary tool into the materials to be welded, penetrating them both and then moving the tool across the joint path. In particular, the joining edges need a suitable backing as a means to avoid that the blanks material to suffer a forward extrusion due to the action of tool pin. Furthermore, the upper sheet must be supported in the proper way to avoid any bending movements during the joint process, Figure 5. While the material softening is hit, the tool moves along the joint path; it should be known that a single point of the tool contact surface moves circumferentially on a plane normal to the tool axis for a given tilt angle and on the basis of the actual values of the tool pin rotation speed and the tool feed speed. The tool moves with respect to a fixed referring system [9].

The first differences between these two types of structures that can be easily observed are the positioning of the workpieces (which requires the use of clamping devices specific to each type of structure) and the length of the tool pin (which, in the case of lap or multiple lap joint, must penetrate all structure plates).

2. MATERIALS AND METHODS

The quality of friction stir welding (FSW) welded joints is heavily impacted by both the geometry and dimensions of the tool, as well as the parameters of the technological process. The optimized process parameters and tool design lead to the fine quality of joints, satisfactory material mixing in the different heating zones and surface with no defects. They are enhancing the mechanical performance of the weld surface as well. However, the improper selection of these factors deteriorated the surface quality of the joint structure, leading to the formation of defects [10]. Over time, there were many studies regarding these issues. This is the reason why we focus in this article only on process parameters and tool designs used for obtaining end-to-end and lap FSW joints.

2.1 Tools used in the FSW process

The tool used in the FSW process is a rotational tool, with a pin and a shoulder, see Figure 6, and its geometry is given by the shape and dimensions of the pin, respectively, the shape and dimensions of the shoulder. The flow of material and the heat released during the process are determined by the two geometric elements of the tool, they significantly influence the quality of the joint [8].

As well, is also important to know that the tool pin is characterized by a rather small tilt angle to restrict the contact between the tool shoulder and the workpieces to almost one-half of the shoulder surface [11]. During FSW, tilting the tool towards the joint line provides an additional forging action on the weld region. It was considered that this additional pressure enlarges the interaction of the tool with the workpiece and minimizes the formation of weld defects [12].

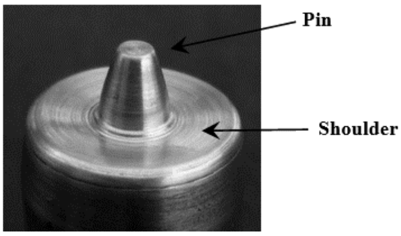

Fig. 6. Tool geometry [13]

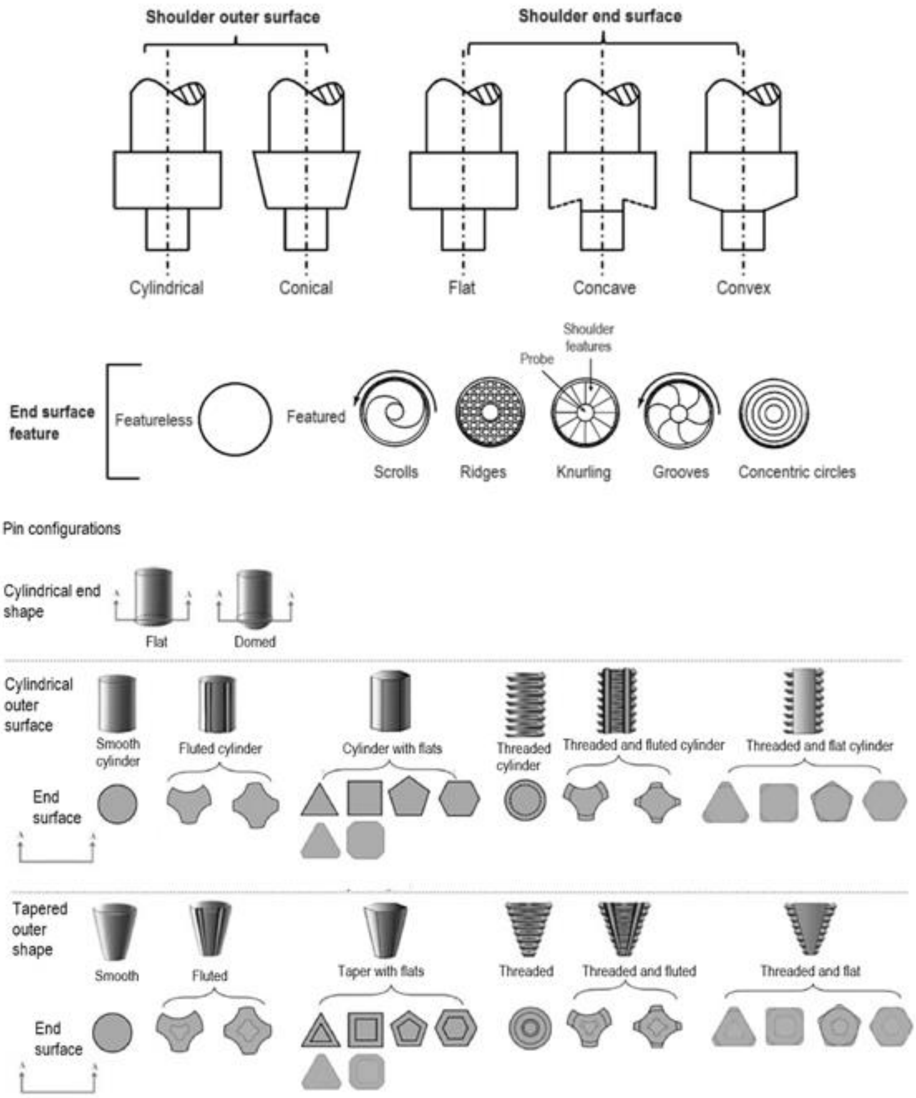

Fig. 7. Types of shoulder and pin used in FSW (adapted from [5] and [14])

Over the years, there have been many studies concerning the effect of the tool material and geometry on the microstructure, mechanical properties, the behavior of the FSW structures [11, 13 – 19]. The tool materials and characteristics used for obtaining end-to-end structures are described in Table 2 and Table 3 describes the tools used for obtaining lap structures.

Table 2. Tool configurations used in FSW, end-to-end structures

Workpiece material	Tool Material	Shoulder characteristics		Pin Characteristics		Ref.
		Shape	Dimensions [mm]	Shape	Dimensions [mm]	
AA2024-T351 AA7075-T651		concave	Ø15 mm	threaded	M6	[15]
AA2024-T3 AA7075-T6		cylindrical	Ø20 mm	threaded	M5	[16]
AA2024-T4 AA7075-T6	AISI H13	cylindrical		cylindrical		[17]
AA2024-T3 AA7075-T6		cylindrical	Ø20 mm	cylindrical	Ø6 x 2.5 mm	[18]
AA2024-T3 AA7075-T6		cylindrical		threaded		[19]
AA2024-T351 AA7075-T651		cylindrical	Ø15 mm	conical threaded	M5 ÷ Ø3.76 mm	[20]
AA2024-T3 AA7075-T6	AISI H13	cylindrical	Ø15 mm	conical threaded	M5 x 3,76 mm	[21]
AA2024-T351 AA7075-T651		concave shoulder end profiles with concentric circle shoulder (CCS)	Ø15 mm	conical threaded	M3.76 x 5 mm	[22]
AA2024-T351 AA7075-T651		Cylindrical three-helix shoulder (THS)	Ø18 mm	conical threaded	M4.52 x 5 mm	[22]
AA2024-T351 AA7075-T735		concave shoulder end profiles with concentric circle shoulder (CCS)	Ø18 mm	conical threaded	M3,76x5 mm	[23]
AA7075-T651		cylindrical	Ø18 mm	conical left threaded	M8 ÷ Ø6 mm	[24]
AA7075-T651	AISI H13	Cylindrical three-helix shoulder (THS)	Ø18 mm	conical threaded	M6 x 5.7 mm	[25]
AA2024-T351 AA7075-T651	HDS (Hot Die Steel)	cylindrical		conical threaded	M7.5 ÷ Ø6 mm	[26]
AA2024-T4 AA7075-T6	AISI H13			cylindrical	Ø3 x 2.8 mm	[27]
AA2024-T3 AA7075-T6				cylindrical	Ø6 x 2.5 mm	[28]
AA2024-T3 AA7075-T6	AISI H13	cylindrical	Ø12 mm	conical threaded	M4	[29]
AA2024-T3 AA7075-T6		cylindrical	Ø18 mm	conical threaded	M6 x 5,7 mm	[30]
AA2024-T3 AA7075-T6		cylindrical	Ø12 mm	cylindrical	Ø4 x 2.85 mm	[31]
AA2024-T3 AA7075-T6	AISI H13	cylindrical	Ø25 mm	square	Ø5 x 4.85 mm	[32]
AA2024-T3 AA7075-T6		cylindrical	Ø17,5 mm	conical threaded	M5 x 4.65 mm	[33]

The previous tables show that the most utilized FSW tool material for joining the aluminium alloys, both end-to-end and lap structures, is H13 steel. The H13 steel is a tool steel with good properties like wear resistance, thermal fatigue, and high strength (at elevated temperatures) and it's easy to fabricate and not so expensive [34].
Also, the most utilized FSW tool for joining the aluminium alloys, both end-to-end and lap structures, has a cylindrical shoulder and threaded pin. The threaded pin is used in FSW because the pin has the role of moving and mixing the plasticized material. Better mixing is favored by the presence of threads on the tool pin [35].

Table 3. Tool configurations used in FSW, lap structures

Workpiece material	Tool material	Shoulder characteristics		Pin characteristics		Ref.
		Shape	Dimensions [mm]	Shape	Dimensions [mm]	
AA6061-T6	AISI H13	Flat	Ø12 mm	Threaded Pin	Ø 5 x 3 mm	[36]
AA6061-T6	AISI H13	Cylindrical	Ø20 mm	Left-handed screw cylinder with sub-conical headpin	Ø8 x 5 mm with Ø8 x 3 mm	[37]
AA7075-T6	-	Cylindrical with concentric circles	Ø18 mm	Conical threaded pin	T1: Ø4.5 - Ø7 (top -bottom) x 5 mm T2: Ø4.1 - Ø7 (top -bottom) x 5 mm T3: Ø3.8 - Ø7 (top -bottom) x 5 mm	[38]
AA7075-T6 AA2024-T3	AISI H13	Concave	Ø15 mm	threaded taper cylindrical pin	top – bottom Ø4 – Ø6 mm x 5 mm	[39]
AA7075-T6 AA2024-T3	AISI H13	Scroll	Ø19 mm	cylindrical left hand threaded pin	Ø6.3 mm and 2 mm pitch	[40]

Regarding the limitations imposed by the construction of the tool on FSW welded structures, it was found that:
- for end-to-end friction stir welded structures, plates ranging in thickness from 3 mm to 6 mm are commonly employed due to their practical utility, with the tool used not imposing restrictions in this regard;
- in the case of FSW welded structures by overlapping, plates with a wider range of thicknesses are used, from 1.5 mm to 6 mm, but those with smaller thicknesses prevail, due to the limitation of the dimensions of the pin.

2.2 Technological parameters

Since the welding parameters have a great influence on the FSW joint quality, many researches have focused on establishing this influence. Thus, the influence of these parameters (especially of the tool strength and the welding speed) was studied in relation to the microstructure or defects in the joint, but also in relation to the mechanical behavior of the structure in different types of tests. A synthesis including the characteristics of the workpieces, tool, and FSW parameters is presented in Table 4 for end-to-end joints, respectively, in Table 5 for lap structures.

Table 4. Process parameters used in FSW, end-to-end structures

Workpiece material	Plate thickness	Tool	Process parameters		Ref.
			Rotational speed [rot/min]	Feed speed [mm/min]	
AA2024-T4 AA7075-T6	3 mm	cylindrical Ø3 x 2.8mm	1040	104	[27]
AA2024-T3 AA7075-T6	2,5mm	unindicated	unindicated	160	[28]
AA2024-T3 AA7075-T6	3 mm 4mm	threaded M4	120 1140	42÷198 32	[29]
AA2024-T3 AA7075-T6	4mm	unindicated	1600	120	[41]
AA2024-T3 AA7075-T6	3mm	cylindrical Ø4 x 2.85	400/ 1000/ 2000	254	[31]
AA2024-T3 AA7075-T6	5mm 6,5mm	square Ø5 x 4.85	710/ 1000/ 1400	80/ 112	[32]
AA2024-T3 AA7075-T6	5mm	threaded M5	900/ 1050/ 1200	10/ 15/ 20	[33]
AA2024-T3 AA7075-T6	4mm	unindicated	1000/ 1500/ 2000	10/ 35/ 60	[42]
AA2024-T3 AA7075-T6	6mm	unindicated	1200/ 1300/ 1400/ 1500/ 1600	22/ 45/ 75/ 100/ 135	[30]
AA2024-T3 AA7075-T6	6mm	cylindrical Ø6x2.7	1000/ 1100/ 1200/ 1400	20/ 30/ 40	[43]

The values frequently used for the rotation speed of the tool are over 1000 rpm in both cases of joining, and the feed speed varies between 20 and 135 mm/min for end-to-end structures and 20-700 mm/min for lap structures.

Depending on the results of the FSW process analyzed, several types of approaches were carried out:
- only some of the technological parameters were varied [11, 34, 49];
- all technological parameters were varied, sometimes using techniques for planning experiments (design of experiments - DOE or Taguchi) and even optimization methods (response surface method) [9, 37];
- some of the technological parameters were varied together with other input elements in the process (often the thermal treatments applied to the plates in the structure) [43, 44, 48, 50].
Some conclusions derived from these studies are exemplified in the following.

Table 5. Process parameters used in FSW, lap structures

Workpieces			**Tool**		**Process parameters**			**Ref.**
Material	**Dim. L x l x H [mm]**	**Overlapped dimensions [mm]**	**Pin shape & dimensions D x L [mm]**	**Tilt angle [°]**	**Plunge depth [mm]**	**Rotation speed [rpm]**	**Feed speed [mm/min]**	
AA6061-T6	100 x 100 x 2	35 x 100	Threaded pin Ø5 x 3 mm	0 °	0.2	1200 1500 1800	20	[33]
AA6061-T6	220 x 140 x 5	unindicated	Screw cylinder Ø8 x 5 with sub-conical headpin Ø8 x 3	3 °	0.15	900 1000 1200	40	[34]
AA7075-T6	100 x 70 x 6	30 x 70	Conical threaded pin T1: Ø4.5 - Ø7 (top -bottom) x 5 T2: Ø4.1 - Ø7 (top -bottom) x 5 T3: Ø3.8 - Ø7 (top -bottom) x 5	2,5 °	0.2	1000	70	[35]
AA7075-T6 AA2024-T3	200 x 150 x 5	50 x 150	Threaded taper cylindrical pin Ø4 – Ø6 (top - bottom) x 5	2.5 °	0.2	1500	50 150 225 300	[36]
AA7075-T6 stringer AA2024-T3, skin	450 x 50 x 1.5 450 x 190 x 1.5	-	Cylindrical left hand threaded pin Ø6.3 and 2 mm pitch	un-indicated	un-indicated	700	700	[37]

Regarding the effect of rotation speed on the weld bead, Amatullah M. et all. [45] concluded that:
- for 2XXX series aluminium alloys, the increase in rotational speed is felt in the increase of the nugget zone; to understand what happens in the nugget zone, rotations of 150 rot/min, 200 rot/min, 300 rot/min, 450 rot/min, 600 rot/min, 800 rot/min were used;
- for 7XXX series alloys, the values of mechanical properties increase proportionally with decreasing rotational speed.
Studies carried out in the field of friction stir welding of AA2024 with AA7075, have revealed an increased possibility of cracks, which is why J. Jayapriyaa, welds these materials by varying the parameters to locate cracks as accurately as possible. The parameters he proposes are 700 rpm, 1000 rpm and 1400 rpm respectively, and the feed rates used are 80mm/min and 110mm/min respectively [44].
The research presented in recent articles, summarized in the previous paragraphs, results that for the FSW structures of AA2024-AA7075 joined end-to-end, the values of the parameters that generate a maximum hardness of the structure are 1400 rpm and 31.5 mm/min, while parameter values of 900 rpm and 60 mm/min led to structures with maximum tensile strength. These parameter values were obtained when the boards were 4 mm thick and pine conical in shape. Depending on the thickness of the boards as well as the shape of the pin these values may change [45].
Regarding the lap joints, Zhang G. et. al. [46] studied the temperature evolution on different rotational speeds (630 rpm, 1000 rpm, respectively 1400 rpm) in the friction stir welds of the AA2024-T3 and AA7075-T6. Raising the temperature results in an escalation of heat input, facilitating the mixing of materials and flow within the nugget zone of the joint. The increase in tensile-shear force is due to the width in the stir zone and can be obtained by the increase in rotational speed and the plunge depth. The maximum tensile-shear force was obtained at the rotational speed of 1400 rpm.

3. CHARACTERISTICS OF JOINED STRUCTURES

It is known that some aluminium alloys and other lightweight alloys are “un-weldable” materials (hard to weld) because through conventional welding processes can be obtained joints with mechanical performances lower than 60% or even 50% of the blank material ones. Using FSW, any melting of the material is avoided, therefore it can be obtained an effective structure (from metallurgical perspective). Thereby, joints with mechanical performances undergoing tensile tests even up to the 90% concerning the blank material can be produced [9]. The quality of structures fabricated through the FSW process hinges on the quality of the weld joint, which essentially depends on the mixing of the welded materials in the joint bead. Therefore, in this study, we will address aspects related to the microscopic structure of the joint and its mechanical properties.

3.1 Structural analysis

It is a consensus that the microstructure of FSW joints of aluminum alloys consists of four regions: the base material (BM), the thermally affected zone (HAZ), the thermo-mechanically affected zone (TMAZ), and the nugget zone (NZ) or stir zone (SZ). Nonetheless, their shape and specific attributes are contingent on various factors, beginning with the properties of the welded plates, the type of structure (end-to-end or lap), the technological regime used, etc., which determines the weight of the effect of heating and plastic deformation within the joint bead and adjacent areas. The common general characteristics of these regions are briefly presented below:

- Base material (BM): it is the region where the microstructure is the initial one, of the materials to be welded, not affected by heating or plastic deformation. It is the region farthest from the weld bead line;
- The heat-affected zone (HAZ) refers to the area solely influenced by the heat generated during the FSW process, without undergoing plastic deformation, and where any microstructure alterations are minimal;
- Thermo-mechanically affected zone (TMAZ): it is the region affected by both the heat generated during the FSW process and the plastic deformation of the joined materials, resulting in alterations to the original microstructures;
- Nugget zone (NZ): it is the zone most affected by temperature and plastic deformation, which are the most intense here, the zone is located around the line of the weld bead (pin axis). Most of the time, dynamic recrystallization of grains occurs in this region, and the structure of the onion ring characterizes this region.

The factors that have a great influence on the microstructure of the FSW joints are the values of welding parameters, like feed speed and welding speed, but in the case of overlapping structures, the way of positioning the joined plates within the structure was also analyzed. Khodir S.A. et. al. [28] studied how the microstructure of dissimilar aluminium alloys AA2024 and AA7075 end-to-end joints are affected by the values of feed speed, Figure 10. The microstructure of overlapping aluminum alloy structures has been analyzed in numerous studies [7, 8, 13, 36, 37, 38, 39, 45]. For example, the influence of feed rate on the microstructure and mechanical properties of different aluminum alloys AA2024 and AA7075 was studied by Song Y. et al. [36], and the influence of the positioning of the joined plates within the structure was analyzed by Maji P. et al. [38], Figure 11.

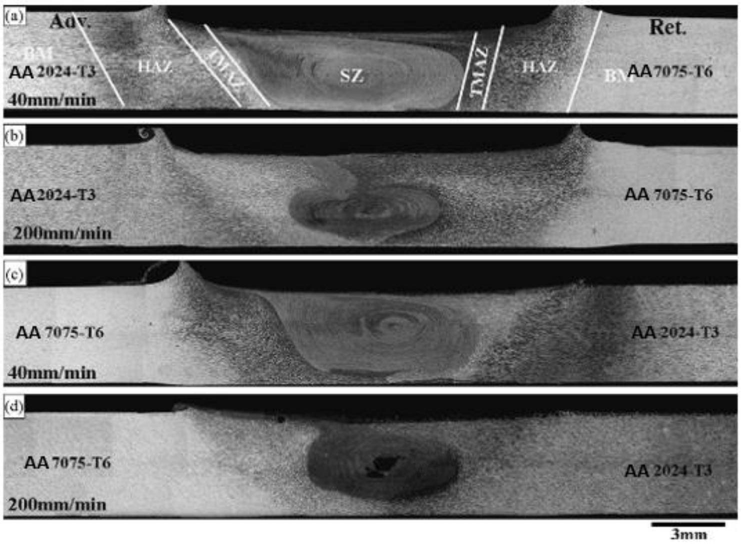

Fig. 10. Effect of the feed speed on end-to-end joints microstructure [29]

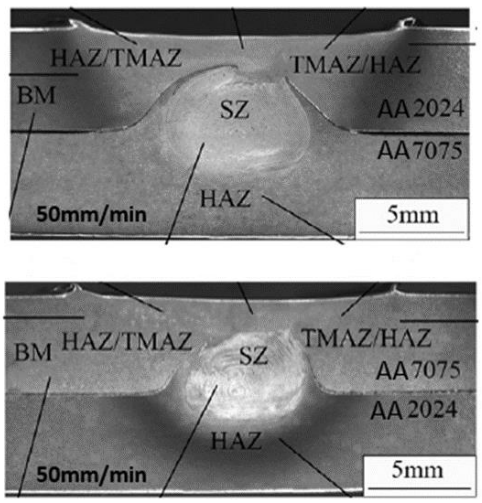

Fig. 11. Effect of the feed speed on lap joints microstructure [38]

The notation from figure 10 and 11 are as follows: BM - Base material; HAZ - Heat-affected zone; TMAZ - Thermo-mechanically affected zone and SZ - Stir zone.
Mechanical deformation, heat generated by friction and the post-weld cooling rate are factors that can affect the microstructure of the base material in both FSW end-to-end and lap structure. The region of the material that was exposed to the highest temperature and plastic deformation shows a different microstructure compared to another region that was exposed to less heat and deformation [47].

3.2 Mechanical properties

The mechanical properties of FSW welded structures, including microhardness and tensile strength, are affected by various parameters of the FSW process, such as tool geometry, tool tilt angle, and welding parameters. This aspect is often a focus of research due to its significance.
The influence of the rotation speed on the tensile strength and the elongation of end-to-end joints made of FSW-welded AA7xxx series aluminum alloys was studied by Jayapriya, J et. al. [48]. They showed that the two mechanical characteristics of the welded structure have a similar behavior, Figure 12, increasing with the increase of the rotation speed up to a certain value, after which they decrease due to the increase of the thermally affected area.

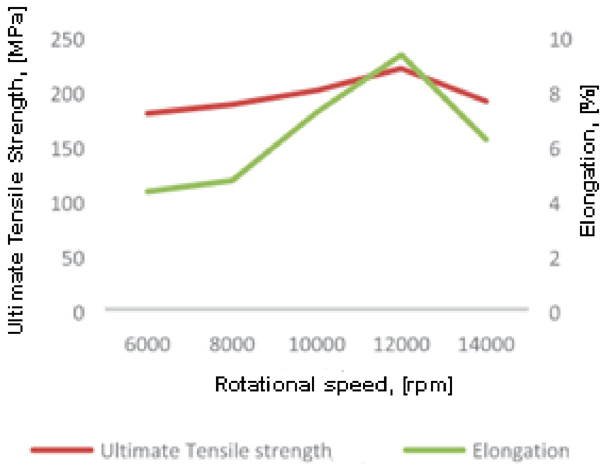

Fig. 12. Example of the influence of tool rotation speed on the ultimate tensile strength and elongation of the 7XXX aluminum series alloy [48]

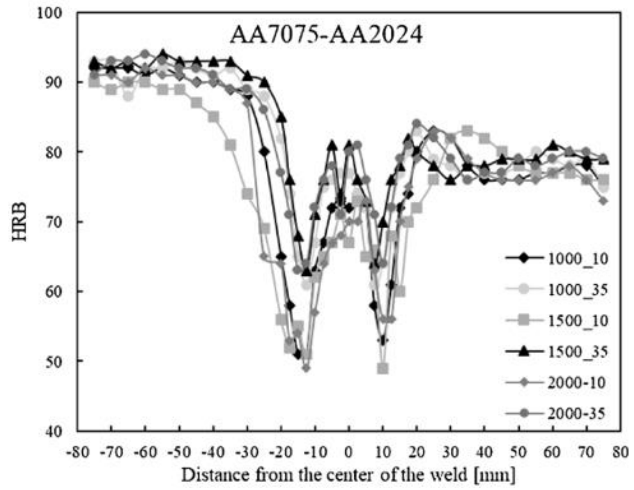

Fig. 13. Example of the influence of tool rotation speed and welding speed on the hardness profile of an FSW joint made of aluminum alloys AA7075-AA2024 [45]

Studies carried out on end-to-end structures on AA2024 and AA7075 materials, confirm that the mechanical properties are considerably influenced by the values of the input parameters. Bocchi S. et al. [45] analyzed the influence of the two most important parameters, rotation and welding speeds, and showed the Rockwell hardness values superimposed graphically, which are predominantly between 60 and 95 units (figure 13). Most experiments provide the best values of mechanical properties in the middle range, with a strong increase or decrease of a parameter having a negative impact on the structure. The most dangerous zone of the structure, in terms of hardness, with the lowest hardness values, is located in most cases in the TMAZ zone, while the highest values of 80 HRC are located right in the Nugget zone, and are obtained at 1500 rpm and speeds of 35 mm/min [45].
Many studies regarding the FSW lap structures referred to the mechanical properties obtained. Thus, it was concluded that the most influential factors are the geometry of tools, the tilt angle, the positions of the materials, and the process parameters (especially the rotational speed).
The geometry of the tool is a great influencing factor in the quality of lap joints [49]. Kersharwani et. al concluded that it can obtain a defect-free lap joint, with good microstructure, higher tensile strength, and hardness using a tapered cylindrical threaded pin in comparison with a square one. In FSLW the length of the pin is important as well. He et. al. [35] observed that a short length of the pin can lead to an insufficient penetration in the lower sheet.
Another direction of research in studying the FSW joining of overlapping structures is the impact of plate positioning on its mechanical properties. For example, Attah et. al. [49] demonstrated that positioning in the upper portion (in contact with the tool's shoulder) of the AA1200 alloy results in superior mechanical properties of the welded structure compared to positioning in the upper portion of the AA7075 alloy (figure 14). They conclude that, if the soft material is placed on the advancing side of the structure better weld characteristics can be obtained.

The hardness joint increases when the rotational speed increases to 1500 rpm and then decreases (figure 15). They also concluded that using a 2-degree tilt angle improves material flow through the increase in heat generation, thereby extending the interaction of the tool with the workpiece and minimizing the formation of weld defects.

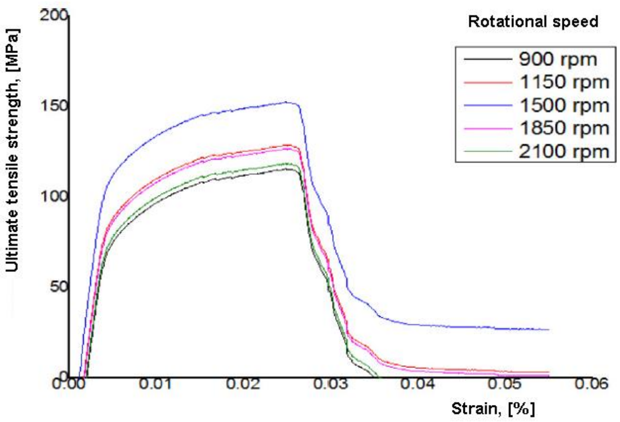

Fig. 14. Variation of Ultimate Tensile strength of 1xxx and 7xxx FSW lap joint at different rotational speeds [49]

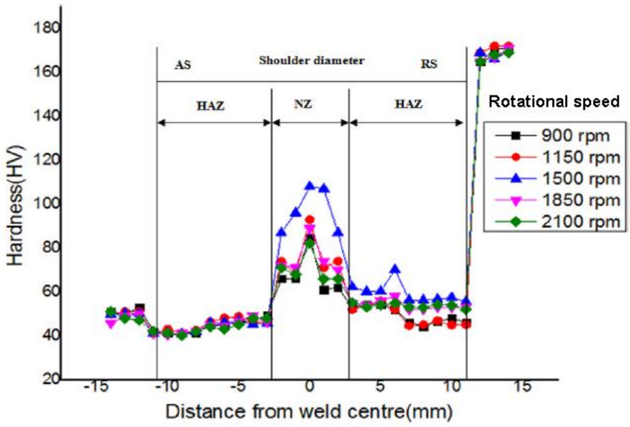

Fig. 15. Hardness profile of the FSW AA1120-AA7075 joint at different rotational speeds [49]

4. CONCLUSIONS

The comparative study of joining heterogeneous structures made from some aluminum alloys using the FSW process, presented in this paper, highlights important conclusions, which can be summarized as follows.

(1) The use of the FSW welding process for joining heterogeneous aluminum alloys, especially the "non-weldable" ones, is increasingly common because this is a solid-state welding process, but also because the process is economic and ecological.

(2) The most common configurations of FSW structures are end-to-end (butt) and lap joints.

(3) The main differences between the FSW welding of these two types of structures relate to the location of the plates (implicit in the clamping fixtures) and the geometry of the tool (especially the length of the pin):

- for end-to-end welded structures, it is important how the plates are positioned concerning the direction of rotation of the tool (AR or RR) and/or the line of the welding seam, while for overlapping structures it is important which of the plates is in contact with the tool shoulder;
- the pin of the tools used for FSW welding of overlapping plate structures has a longer length than for butt welding and, as a rule, is threaded, while the shoulder is cylindrical.

(4) The microstructure of the FSW joint presents the same four zones (NZ - the nugget zone, TMAZ - the thermo-mechanically affected zone, TAZ - the thermally affected zone, and BM - the base material), both for the welded structure of plates positioned end-to-end or for one of the overlapping plates.

(5) The rotation speed of the tool and the welding speed have important influences on the characteristics of the welded structure: the microstructure of the joint and the mechanical properties of the structure. Also, the inappropriate choice of their values can lead to the appearance of defects in the joint, with a negative effect on the behavior of the structure in operation. These influences are determined by the amounts of heat and the deformations induced by the two parameters. Most research leads to the conclusion that the best values of the mechanical properties are obtained by using a set of parameters (tool rotation speed - welding speed) in an average range, a strong increase or decrease of a parameter harming the properties of the structure. Some general recommendations for choosing the values of these parameters, for the two types of analyzed structures, are the following:

- the speed of the tool should be in the range of 1000-1300 rpm;
- the welding speed should be in the range of 50-150 mm/min.

Conflicts of Interest: There is no conflict of interest.

REFERENCES

1. Kaufman, J., (2000). *Applications for Aluminum Alloys and Tempers*, Introduction to Aluminum Alloys and Tempers, Editor Kathy Dragolich, pp. 87-107, AST International, United States of America.

2. Bachmann, A., Roehler, M., Pieczona, S. J., Kessler, M., and Zaeh, M. F., (2018). *Torque-based adaptive temperature control in friction stir welding: a feasibility study*, Production Engineering, 12(3–4), 391–403.
3. Schaff, F., Bachmann, A., Zens, A., Zaeh, M. F., Pfeiffer, F., and Herzen, J., (2017). *Grating-based X-ray dark-field computed tomography for the characterization of friction stir welds: A feasibility study*, Mater Charact, 129, 143–148, https://doi.org/10.1016/j.matchar.2017.04.023.
4. Stephen Leon, J., Bharathiraja, G., and Jayakumar, V., (2020). *A review on Friction Stir Welding in Aluminium Alloys*, IOP Conference Ser.: Mater. Sci. Eng. Vol. 954, No. 1, IOP Publishing Ltd, doi:10.1088/1757-899X/954/1/012007.
5. Mishra, R. S., and Ma, Z. Y., (2005). *Friction stir welding and processing*, Materials Science and Engineering R: Reports, 50(1–2), https://doi.org/10.1016/j.mser.2005.07.001.
6. Çam, G., and Mistikoglu, S., (2014). *Recent developments in friction stir welding of al-Alloys*, J. Mater. Eng. Perform., 23(6), 1936–1953.
7. Elatharasan, G., and Kumar, V. S. S., (2013). *An experimental analysis and optimization of process parameter on friction stir welding of AA 6061-T6 aluminum alloy using RSM*, in Procedia Engineering, Elsevier Ltd, pp. 1227–1234, https://doi.org/10.1016/j.proeng.2013.09.202.
8. He, C., et al., (2020). *Interface characteristics and mechanical properties of ultrasonic-assisted friction stir lap welded 7075-t6 aluminium allo*y, Materials, 13(23), 1–17, https://doi.org/10.3390/ma13235335.
9. Buffa, G., Campanile, G., Fratini, L., and Prisco, A., (2009). *Friction stir welding of lap joints: Influence of process parameters on the metallurgical and mechanical properties*, Materials Science and Engineering A, 519(1–2), 19–26, https://doi.org/10.1016/j.msea.2009.04.046.
10. Kesharwani, R., Jha, K. K., Anshari, M. A. A., Imam, M., and Sarkar, C., (2022). *Comparison of microstructure, texture, and mechanical properties of the SQ and thread pin profile FSW joint of AA6061-T6 with Al2O3 particle reinforcement*, Mater. Today Commun., 33, pp.1, https://doi.org/10.1016/j.mtcomm.2022.104785.
11. Buffa, G., Campanile, G., Fratini, L., and Prisco, A., (2009). *Friction stir welding of lap joints: Influence of process parameters on the metallurgical and mechanical properties*, Materials Science and Engineering A, 519(1–2), 19–26, doi: 10.1016/j.msea.2009.04.046.
12. Mahto, R. P., Kumar, R., and Pal, S. K., (2020*). Characterizations of weld defects, intermetallic compounds and mechanical properties of friction stir lap welded dissimilar alloys*, Mater. Charact., 160, pp. 2, https://doi.org/10.1016/j.matchar.2019.110115.
13. Banik, A., Deb Barma, J., and Saha, S. C., (2020). *Effect of Threaded Pin Tool for Friction Stir Welding of AA6061-T6 at Varying Traverse Speeds: Torque and Force Analysis*, Iranian Journal of Science and Technology - Transactions of Mechanical Engineering, 44(3), pp. 3.
14. Maji, P., Karmakar, R., Kanti Nath, R., and Paul, P., (2022). *An overview on friction stir welding/processing tools*, Mater. Today. Proc., 58(57–64), https://doi.org/10.1016/j.matpr.2022.01.009.
15. Niu, P. L., Li, W. Y., Li, N., Xu, Y. X., and Chen, D. L., (2019*). Exfoliation corrosion of friction stir welded dissimilar 2024-to-7075 aluminum alloys*, Mater. Charact., 147, 93–100, https://doi.org/10.1016/j.matchar.2018.11.002.
16. Guo, Y., Ma, Y., Zhang, X., Qian, X., and Li, J., (2020). *Study on residual stress distribution of 2024-T3 and 7075-T6 aluminum dissimilar friction stir welded joints*, Eng. Fail. Anal., 118, pp. 2, https://doi.org/10.1016/j.engfailanal.2020.104911.
17. Safarbali, B., Shamanian, M., and Eslami, A., (2018). *Effect of post-weld heat treatment on joint properties of dissimilar friction stir welded 2024-T4 and 7075-T6 aluminum alloys*, Transactions of Nonferrous Metals Society of China (English Edition), 28(7), 1287–1297, https://doi.org/10.1016/S1003-6326(18)64766-1.
18. Cavaliere, P., Nobile, R., Panella, F. W., and Squillace, A., (2006). *Mechanical and microstructural behaviour of 2024-7075 aluminium alloy sheets joined by friction stir welding*, Int. J. Mach. Tools. Manuf., 46(6), 588–594, https://doi.org/10.1016/j.ijmachtools.2005.07.010.
19. Cavaliere, P., and Panella, F., (2008). *Effect of tool position on the fatigue properties of dissimilar 2024-7075 sheets joined by friction stir welding*, J. Mater. Process. Technol., 206(1–3), 249–255, https://doi.org/10.1016/j.jmatprotec.2007.12.036.
20. Zhang, C., Huang, G., and Liu, Q., (2021). *Quantitative analysis of grain structure and texture evolution of dissimilar AA2024/7075 joints manufactured by friction stir welding*, Mater. Today Commun., 26, 101920, https://doi.org/10.1016/j.mtcomm.2020.101920.
21. Avinash, P., Manikandan, M., Arivazhagan, N., Devendranath, R. K., and Narayanan, S., (2014). *Friction stir welded butt joints of AA2024 T3 and AA7075 T6 aluminum alloys*, Procedia Engineering, Elsevier Ltd, pp. 98–102, https://doi.org/10.1016/j.proeng.2013.11.020.
22. Zhang, C., Huang, G., Cao, Y., Li, Q., Niu, L., and Liu, Q., (2020). *Characterizations of microstructure, crystallographic texture and mechanical properties of dissimilar friction stir welding joints for AA2024 and*

AA7075 under different tool shoulder end profiles, Mater. Today Commun., 25, pp. 1-3, https://doi.org/10.1016/j.mtcomm.2020.101435.
23. Wang, X., and Lados, D. A., (2022). *Friction Stir Welding of Similar Aluminum Alloys Thick Plates: Understanding the Material Flow, Microstructure Evolution, Defect Formation, and Mechanical Properties*, Materialia (Oxf), 24, https://doi.org/10.1016/j.mtla.2022.101508.
24. Sivaraj, P., Kanagarajan, D., and Balasubramanian, V., (2014). *Effect of post weld heat treatment on tensile properties and microstructure characteristics of friction stir welded armour grade AA7075-T651 aluminium alloy*, Defence Technology, 10(1), 1–8, https://doi.org/10.1016/j.dt.2014.01.004.
25. Kumar, R., Singh Bhadauria, S., Sharma, V., and Kumar, M., (2022). *Effect on microstructure and mechanical properties of single pass friction stir welded aluminium alloy AA-7075-T651 joint*, Mater. Today Proc., 80(I), 40-47, https://doi.org/10.1016/j.matpr.2022.10.111.
26. Kumar, K. S. A., and Yogesha, K. B., (2021). *Experimental investigations to find the effect of post weld heat treatment (PWHT) on the microstructure and mechanical properties of FSW dissimilar joints of AA2024-T351 and AA7075-T651*, Materials Today: Proceedings, Elsevier Ltd, pp. 243–249, https://doi.org/10.1016/j.matpr.2021.01.867.
27. Barcellona, A., Buffa, G., Fratini, L., and Palmeri, D., (2006). *On microstructural phenomena occurring in friction stir welding of aluminium alloys*, J. Mater. Process Technol., 177(1–3), 340–343, https://doi.org/10.1016/j.jmatprotec.2006.03.192.
28. Cavaliere, P., Nobile, R., Panella, F. W., and Squillace, A., (2006). *Mechanical and microstructural behaviour of 2024-7075 aluminium alloy sheets joined by friction stir welding*, Int. J. Mach. Tools Manuf., 46(6), 588–594, https://doi.org/10.1016/j.ijmachtools.2005.07.010.
29. Khodir, S. A., and Shibayanagi, T., (2008). *Friction stir welding of dissimilar AA2024 and AA7075 aluminum alloys*, Mater. Sci. Eng. B Solid State Mater. Adv. Technol., 148(1–3), 82–87, https://doi.org/10.1016/j.mseb.2007.09.024.
30. Balasubramanian, V., (2008). *Relationship between base metal properties and friction stir welding process parameters*, Materials Science and Engineering A, 480(1–2), 397–403, https://doi.org/10.1016/j.msea.2007.07.048.
31. da Silva, A. A. M., Arruti, E., Janeiro, G., Aldanondo, E., Alvarez, P., and Echeverria, A., (2011). *Material flow and mechanical behaviour of dissimilar AA2024-T3 and AA7075-T6 aluminium alloys friction stir welds*, Mater. Des., 32(4), 2021–2027, https://doi.org/10.1016/j.matdes.2010.11.059.
32. Avinash, P., Manikandan, M., Arivazhagan, N., Devendranath, R. K., and Narayanan, S., (2014). *Friction stir welded butt joints of AA2024 T3 and AA7075 T6 aluminum alloys*, Procedia Engineering, Elsevier Ltd, pp. 98–102, https://doi.org/10.1016/j.proeng.2013.11.020.
33. Padmanaban, R., Balusamy, V., Saikrishna, V., and Gopath Niranthar, K., (2014). *Simulated annealing based parameter optimization for Friction Stir Welding of dissimilar aluminum alloys*, Procedia Engineering, Elsevier Ltd, pp. 864–870, https://doi.org/10.1016/j.proeng.2014.12.361.
34. Maji, P., Karmakar, R., Kanti Nath, R., and Paul, P., (2022). *An overview on friction stir welding/processing tools*, Mater. Today Proc., 58, 57–64, https://doi.org/10.1016/j.matpr.2022.01.009.
35. Banik, A., Deb Barma, J., and Saha, S. C., (2020). *Effect of Threaded Pin Tool for Friction Stir Welding of AA6061-T6 at Varying Traverse Speeds: Torque and Force Analysis*, Iranian Journal of Science and Technology - Transactions of Mechanical Engineering, 44(3), 749–764.
36. Suresh, S., Natarajan, E., Shanmugam, R., Venkatesan, K., Saravanakumar, N., and AntoDilip, A., (2022). *Strategized friction stir welded AA6061-T6/SiC composite lap joint suitable for sheet metal applications*, Journal of Materials Research and Technology, 21, 30–39, https://doi.org/10.1016/j.jmrt.2022.09.022.
37. Fadaeifard, F., et al. (2014), *Influence of rotational speed on mechanical properties of friction stir lap welded 6061-T6 Al alloy*, Transactions of Nonferrous Metals Society of China (English Edition), 24(4), 1004–1011, https://doi.org/10.1016/S1003-6326(14)63155-1.
38. He, C., et. al. (2020). *Interface characteristics and mechanical properties of ultrasonic-assisted friction stir lap welded 7075-t6 aluminium alloy*, Materials, 13(23), 1–17, https://doi.org/10.3390/ma13235335.
39. Song, Y., Yang, X., Cui, L., Hou, X., Shen, Z., and Xu, Y., (2014). *Defect features and mechanical properties of friction stir lap welded dissimilar AA2024-AA7075 aluminum alloy sheets*, Mater. Des., 55, 9–18, https://doi.org/10.1016/j.matdes.2013.09.062.
40. Dubourg, L., Merati, A., and Jahazi, M., (2010). *Process optimisation and mechanical properties of friction stir lap welds of 7075-T6 stringers on 2024-T3 skin*, Mater. Des., 31(7), 3324–3330, https://doi.org/10.1016/j.matdes.2010.02.002.

41. Cavaliere, P., and Panella, F., (2008). *Effect of tool position on the fatigue properties of dissimilar 2024-7075 sheets joined by friction stir welding*, J. Mater. Process. Technol., 206(1–3), 249–255, https://doi.org/10.1016/j.jmatprotec.2007.12.036.
42. D'Urso, G., Giardini, C., Lorenzi, S., Cabrini, M., and Pastore, T., (2017). *The Effects of Process Parameters on Mechanical Properties and Corrosion Behavior in Friction Stir Welding of Aluminum Alloys*, Procedia Engineering, Elsevier Ltd, pp. 270–276, https://doi.org/10.1016/j.proeng.2017.04.038.
43. Gowthaman, P. S., and Saravanan, B. A., (2021). *Determination of weldability study on mechanical properties of dissimilar Al-alloys using Friction stir welding process*, Materials Today: Proceedings, Elsevier Ltd, pp. 206-212, https://doi.org/10.1016/j.matpr.2020.08.599.
44. Jayapriya, J., Muruganandam, D., and Subha, J., (2020). *Cracks detection in age hardenable aluminum alloys*, Materials Today: Proceedings, Elsevier Ltd, pp. 897–901, https://doi.org/10.1016/j.matpr.2020.11.873
45. Bocchi, S., Cabrini, M., D'Urso, G., Giardini, C., Lorenzi, S., and Pastore, T., (2018). *The influence of process parameters on mechanical properties and corrosion behavior of friction stir welded aluminum joints*, J. Manuf. Process, 35, 1–15, https://doi.org/10.1016/j.jmapro.2018.07.012.
46. Zhang, G., Xiao, C., and Ojo, O. O., (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, https://doi.org/10.1016/j.dt.2020.03.008.
47. Gharavi, F., Fadaeifard, F., Matori, K. A., Yunus, R., and Othman, N. K., (2016). *Mechanical and structural evaluation of friction stir welded 6061 aluminium alloy lap joints at different welding speeds*, 54, 351–361, doi: 10.4149/km.
48. Rezaei, H., Mirbeik, M. H., and Bisadi, H., *Effect of rotational speeds on microstructure and mechanical properties of friction stir-welded 7075-T6 aluminium alloy*, Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 225(8), 1761–1773, doi: 10.1177/0954406211404633.
49. Attah, B. I., et al. (2022). *Effects of material placement and speed of tool rotation on the tensile strength of dissimilar friction stir welded AA7075-T651 and AA1200-H19 aluminium alloys*, Mater. Today Proc., 62, 4275–4282, https://doi.org/10.1016/j.matpr.2022.04.780.

Received: April 30th, 2024 / Accepted: June 15th, 2024 / Paper available online: June 20, 2024 © International Journal of Modern Manufacturing Technologies.