INFLUENCE OF FRICTION STIR WELDING PARAMETERS ON PROPERTIES OF 2024 T3 ALUMINIUM ALLOY JOINTS

by

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Original scientific paper
DOI: 10.2298/TSCI130307170E

The aim of this work is to analyse the process of friction stir welding (FSW) of 3 mm thick aluminium plates made of high strength aluminium alloy - 2024 T3, as well as to assess the mechanical properties of the produced joints. Friction Stir Welding is a modern procedure which enables joining of similar and dissimilar materials in the solid state, by the combined action of heat and mechanical work. This paper presents an analysis of the experimental results obtained by testing the butt welded joints. Tensile strength of the produced joints is assessed, as well as the distribution of hardness, micro-and macrostructure through the joints (in the base material, nugget, heat affected zone and thermo-mechanically affected zone). Different combinations of the tool rotation speed and the welding speed are used, and the dependence of the properties of the joints on these parameters of welding technology is determined.

Key words: *friction stir welding, welding parameters, 2024 aluminium alloy, rotation speed, welding speed, welded joint properties.*

Introduction

The friction stir welding (FSW) process offers the possibility for joining the metallic materials which are difficult of impossible to join by conventional welding techniques. Most of these materials are lightweight metals and their alloys, such as aluminium, which has good corrosion resistance, stiffness to mass ratio (ratio of elasticity modulus and density) and strength to weight ratio. Bearing in mind the increase of usage in civil engineering and transport industry, including shipbuilding and airplane industry, aluminium alloys and their joining procedures are gaining more and more attention [1-7].

The FSW procedure is developed and patented by the Welding Institute (TWI, Cambridge, UK) in December 1991. Since then, it has constantly been improved, and the range of its possibilities has increased. Nowadays, this procedure can be used to weld aluminium parts with up to 50 mm thickness in one pass and up to 75 mm thickness in two

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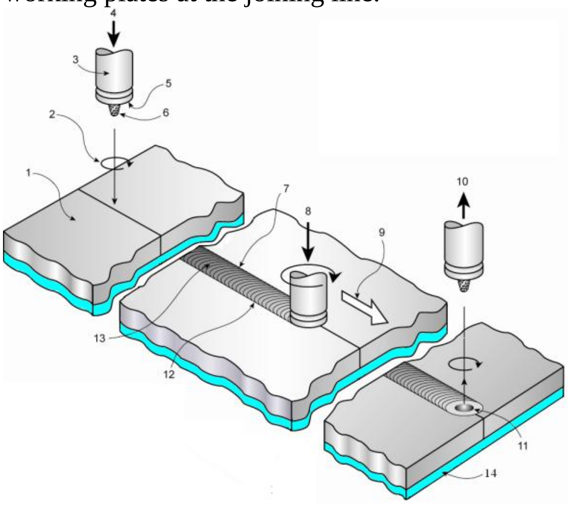
passes [2]. In addition to aluminium alloys, materials which can be joined include copper and alloys, lead, titanium and alloys, magnesium alloys, zinc, soft steels, stainless steels, nickel alloys, *etc*. Also, the same or different materials can be welded by FSW. Regarding the geometry, this process can be used for plates, sheets, cylindrical parts, assemblies, *etc*. [8-10].

The FSW process does not require the usage of additional material or protective gas, and highly qualified workforce is not necessary due to the automation. Small heat inflow in the welding region ensures minimum distortion and shrinkage. There is no danger of hot or cold cracks occurrence, corrosion resistance of the joint is good, the joint has the same properties along the length, there are no pauses during the welding process (changing the electrodes, etc.) and the joint has high quality and good mechanical properties [11].

The welding process - background

The FSW welding tool comprises two parts, cylinder and pin (fig. 1), and it rotates at high speed. At the beginning of the welding process, the pin located at the lower side of the tool (the pin has a conical shape, often threaded) has to form the initial hole, keyhole, in the working plates at the joining line.



(1) Base material
(2) Direction of tool rotation
(3) Welding tool
(4) Downward movement of the tool
(5) Tool shoulder
(6) Pin
(7) Advancing side of the weld
(8) Vertical (axial) force
(9) Welding direction
(10) Upward movement of the tool
(11) Exit hole
(12) Retreating side of the weld
(13) Weld face
(14) Backing plate

Figure 1. Illustrated scheme of the friction stir welding [12]

The pin penetrates into the plates until the tool shoulder has penetrated into the material at prescribed depth (a few tenths of a millimetre), enabling sufficient pressure to keep the material within the welding zone and produce enough heat by friction and plastic deformation for establishing the appropriate welding conditions. This is the end of the first welding stage - the plunging stage. For most of the aluminium alloys, the temperature in the welding zone is within the range 430-500°C. In the second welding stage, the rotating tool is moving along the joining line and continues to generate heat by friction and plastic deformation in the welding zone, along with stirring the material of both plates [13-17]. This enables the materials heated to a high temperature to be mechanically stirred. Additionally, the external loading transferred by the tool shoulder, the weld metal is being forged during welding. The root of the weld is formed in accordance with the shape of the backup plate, while the weld face is smooth and plane, due to the tool shoulder.

Prescribing the proper welding technology requires the determination of the optimum rotation and translation speeds of the tool, so that energy stemming from friction and plastic deformation enables adequate heating of the welding parts. All these factors depend on the base material (its physical and mechanical properties), plate thickness, forging force, *etc*.

Experiment

Experimental part includes the formation of the butt weld of high strength aluminium alloy Al 2024 T3 plates by friction stir welding. The plates were manufactured by the company „ALCOA“, USA. Chemical composition of the base material is given in tab. 1.

Table 1. Chemical composition of the base material, in accordance with [18]

Aluminium alloy	Contents, mass %							
	Cu	Mg	Mn	Fe	Si	Zn	Ti	Al
2024-T3	4.80	1.41	0.72	0.28	0.13	0.07	0.15	balance

Preparation of the working plates for welding was done by water jet cutting of the plate with size 680x580x5 mm, and subsequent machining to the size 180 x 65 x 3 mm, including the intensive cooling in order to avoid the thermal influence on the material structure.

The experiment is performed on a CNC milling machine, type AG400, power 12 kW. This enabled the welding process to be controlled by the prescribed parameters and ensured repeatability. Tool rotation is provided by the main spindle, while plunging and translation during welding is provided by the movement of the working table.

Table 2 contains the plan of the experiment. The rotation speed of the tool, as well as the welding speed, was varied, while the tool geometry, plunging speed and plunging depth were the same in all cases (for all specimens).

Table 2.Plan for carrying out the experiment

Specimen	Plunging speed	Rotation speed of the tool	Plunging depth of the shoulder	Welding speed
	v_{plunge} [mms^{-1}]	n [rpm]	h [mm]	v_{weld} [mmmin^{-1}]
1	0.05	500	0.2	50
2	0.05	400	0.2	50
3	0.05	500	0.2	40
4	0.05	400	0.2	40
5	0.05	447	0.2	44.7
6	0.05	447	0.2	44.7
7	0.05	447	0.2	44.7
8	0.05	447	0.2	44.7

Welding process was performed by using the tool manufactured from Cr-V-Mo tool steel (56NiCrMoV7), in accordance with the drawing shown in fig. 2. The hardness of the tool after thermal treatment by tempering and annealing was 54 HRC. The left thread enabled a better flow of the material around the pin and its movement downwards to the weld root, causing the vertical component of the material flow. Profiled tool shoulder (concentric circles) provides a more intensive friction between the contact surfaces of the tool and the working plates, as well as easier transport of material around the tool.

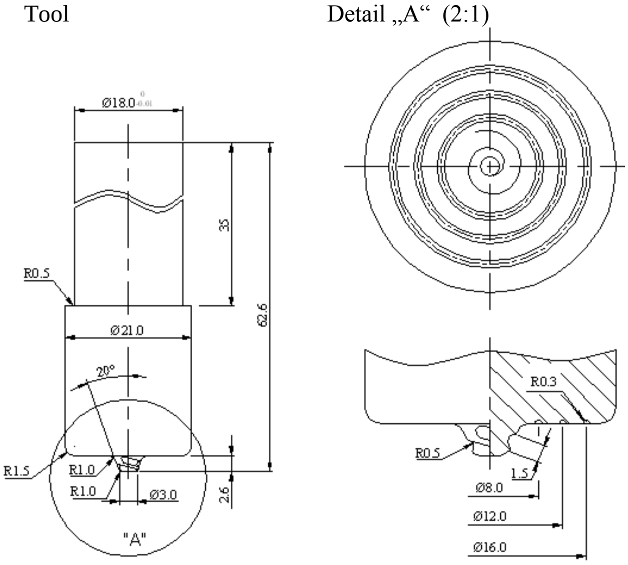


Figure 2. Technicaldrawing and photo of the tool used in the experiment

All specimens were subjected to non-destructive evaluation (NDE) by penetrants and radiographic testing; no flaws were detected. Subsequently, tensile testing of the specimens was performed; the specimens cut from the base metal and the welded joint were prepared in accordance with the standard AWS D17.3/D17.3M:200X - fig.3.

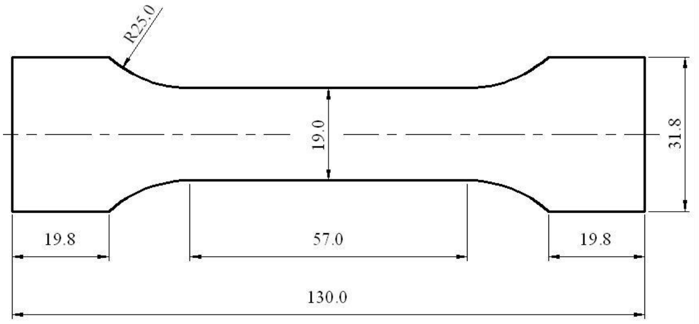


Figure 3. The tensile specimen according to AWS D17.3/D17.3M:200X

Preparation of the samples for testing the macro- and microstructure was done by grinding and polishing, and etching was performed in the solution with 45 ml HCl + 15 ml HNO_3 + 15 ml HF + 25 ml H_2O. The etching time was around 10 s for macrostructure and around 15 s for microstructure. The hardness distribution (HV10) across the joint, from the retreating to the advancing side of the weld, was determined.

Results and discussion

Figures 4 present the weld faces and radiographic images of the specimens 4. Radiographic images did not reveal the existence of flaws: tunnelling incompletely filled root. The weld face was in an excellent shape. The remaining specimens had a similar appearance; hence they are not shown here.

Figure 4. Specimen No. 4-welding parameters *n/v* = 400/40

For the high strength alloys, the fracture most frequently occurs at the locations with the coarsest precipitate- in the heat affected zone (HAZ) close to the thermo-mechanically affected zone (THAZ), fig.5. In this location, plastic deformations during welding are not pronounced (they are almost negligible), hence the thermal influence causes the formation of smaller number of larger precipitate particles, which results in decrease of hardness and tensile strength. The transition zone between the nugget and the weld is significantly narrower at the advancing side (when compared to the retreating side), *i. e.* TMAZ is narrower due to the asymmetrical shape of the nugget. Therefore, the influence of the temperature is more pronounced and the precipitates are coarser as expected; hence the hardness and tensile strength are lower [19].

Table 3. Tensile strength hand efficiency of the welded joints

Specimen no.	Specimen	L_0 [mm]	R_m [MPa]	Joint efficiency [%]	Tool and welding par. n / v_{weld}
1	1A	57	376.31	86.19	Tool A5 500/50=10
	1B	57	363.28	83.20	
	Mean val.	57.00	369.80	84.69	
2	2A	57	363.76	83.31	Tool A5 400/50=8
	2B	57	369.01	84.51	
	Mean val.	57.00	366.38	83.91	
3	3A	57	359.16	82.26	Tool A5 500/40=12.5
	3B	57	362.90	83.11	
	Mean val.	57.00	361.03	82.68	
4	4A	57	358.71	82.15	Tool A5 400/40=10
	4B	57	354.68	81.23	
	Mean val.	57.00	356.69	81.69	
5	5A	57	364.40	83.46	Tool A5 447/44.7=10
	5B	57	370.51	84.86	
	Mean val.	57.00	367.45	84.16	

The hardness profile of the welded joint cross section corresponds to a typical "W" shape for the thermally treated alloys, figs. 6 and 7. The highest hardness values are observed in the base material, while the smallest ones were measured in the HAZ, closer to the thermo-mechanically affected zone. Due to the thermo-mechanical treatment, fine-grain structure can be found in the nugget and the hardness is higher than in the HAZ, but lower than in the base material. If comparison is made between the areas with the lowest hardness, lower hardness is obtained at the advancing side, as expected. In the nugget of the specimen 5, no coarse precipitates were observed due to the higher tool rotation speed; hence the hardness of this area is higher in comparison with the specimen 4.

The results of the tensile testing of the welded joint and the joint efficiency, obtained by comparison with the tensile strength of the base metal (perpendicular to the rolling direction, R_m = 436.63 MPa), are given in tab. 3. The joint efficiency is within the range of 82 - 85%, which is significantly higher in comparison with the limit efficiency of welded joint, 70%. Based on these results, it can be concluded that the parameters of the FSW used in this work have optimal values.

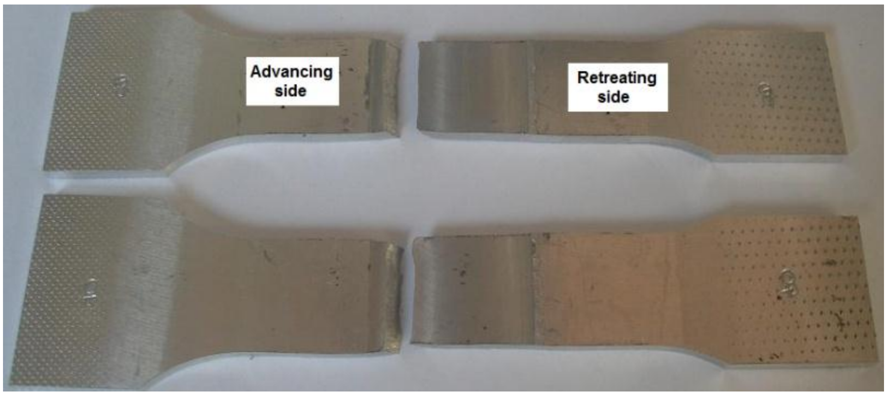


Figure 5. Fractured tensile specimens showing the failure location

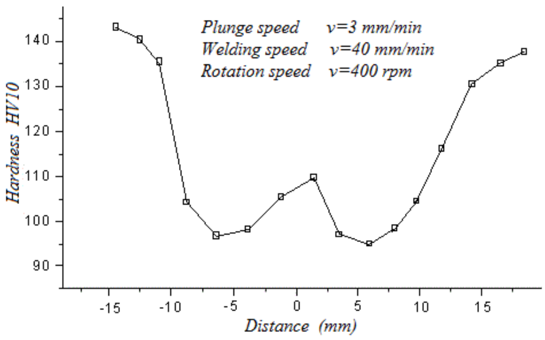


Figure 6. Change of hardness in the cross section of the welded joint specimen 4

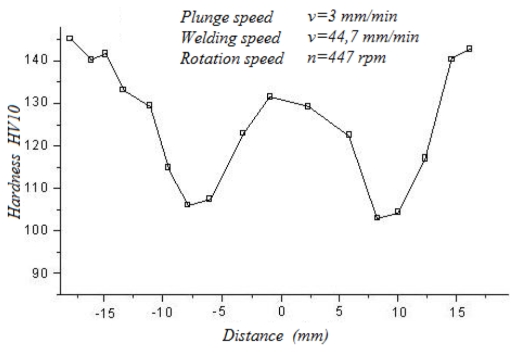


Figure 7. Change of hardness sin the cross section of the welded joint specimen 5

Conclusions

Based on the presented results of the testing of welded joint produced by friction stir welding, following conclusions can be drawn:

- The tool manufactured from the tool steel 56NiCrMoV7 has great durability in the friction stir welding process, i.e. it has great wear resistance. Even in the more severe welding regimes, fracture or excessive deformation of the pin did not occur.
- Tensile testing revealed that the critical spot of the welded joint, i.e. the location of the most frequent fracture occurrence, is the advancing side in the HAZ close to TMAZ.

- With optimal welding parameters, joint efficiency of up to 85% can be achieved.
- For smaller rotation speeds, traces of precipitate can be noticed in the nugget.
- The nugget is spreading towards the advancing side.
- Fine-grained structure is present at the nugget.
- Hardness profile has a typical "W" shape with the lowest hardness in the HAZ close to TMAZ.
- Comparison of the areas with the lowest hardness revealed that the hardness is lower at the advancing side.
- Hardness in the nugget is higher in comparison with HAZ and TMAZ and lower than the base metal hardness.
- For smaller tool rotation speeds, lower hardness in the nugget is observed.

Acknowledgments

The authors acknowledge the financial support of the Serbian Ministry of Science under the projects TR 34018andTR 35006

Nomenclature

h − Plunging depth of the tool shoulder [mm]
L_0 − Gauge length of the specimen [mm]
n − Rotation speed of the tool [rpm]
R_m − Tensile strength [MPa]
v_{plunge} − Plunging speed of the tool [mm/min]
v_{weld} − Welding speed [mm/min]

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Paper submitted: March 7, 2013
Paper revised: May 5, 2013
Paper accepted: September 16, 2013