Effect of tool pin geometry and weld pass number on microstructural, natural aging and mechanical behaviour of SiC-incorporated dissimilar friction-stir-welded aluminium alloys

MOHAMMAD MAHDI MORADI, HAMED JAMSHIDI AVAL*
and ROOHOLLAH JAMAATI

Department of Materials Engineering, Babol Noshirvani University of Technology, Shariati Avenue,
Babol 47148-71167, Iran
e-mail: h.jamshidi@nit.ac.ir

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Abstract. The aim of this investigation was to study the effect of tool pin geometry and pass number on mechanical and microstructural behaviour of SiC-incorporated dissimilar friction stir welding of 6-mm-thick plates of AA6061-T6 and AA2024-T351. Two tool pin geometries, square and triangle frustum, were used. It was found that the weld made by square frustum pin and two passes with rotation in the same direction produces more homogenized and finer distribution of SiC particles. Also, the grain size of stir zone in the weld made by two passes is finer than that made by one pass. The weld made by triangle frustum pin shows higher thermo-mechanically affected zone hardness, natural aging kinetics and tensile strength than the others.

Keywords. Dissimilar friction stir welding; aluminium alloys; SiC particles; tool geometrical parameters.

1. Introduction

Friction stir welding (FSW) as a solid-state severe plastic deformation joining process is one of the simplest and well-developed techniques for welding aluminium alloys. A rotating non-consumable tool is inserted in the workpiece interface and the heat generated by the tool softens the material in the joint line. The softened material stirs around the tool and gets extruded from leading side of the tool to the trailing side. Besides, as a novel approach in the FSW of materials firstly proposed by Sun and Fujii [1], addition of ceramic reinforcement particles in the joint line by making metal matrix composite (MMC) in the stir zone (SZ) improved the joint properties. Accordingly, successful works have been performed to investigate various aspects of FSW process on dissimilar joining of aluminium alloys [2–9]. However, according to the literature, there are limited works on the effect of geometric tool parameters on FSW of AA6xxx and AA2xxx series.

Li *et al* [10] studied the complex flow patterns developed in the dissimilar FSW of 6.5-mm-thick AA2024 and AA6061 alloys using differential etching behaviour of alloys. They used a cylindrical pin; rotation speeds were varied between 400 and 1200 rpm, and the travel speed was constant at 1 mm/s. They reported complex vortex, whorl and swirl features in the SZ that are characteristic of

anarchic mixing produced by accommodating alloys lamellae. Ouyang and Kovacevic [11] investigated the effect of welding rotational and transverse speeds on micro- and macrostructural aspects of dissimilar friction-stir-welded 12.7-mm-thick AA2024-T3 and AA6061-T6 alloys. They found that mechanical mixing of material and material flow patterns changed with welding speed. With increasing rotational/traverse speed ratio, more uniform and rounder lamellae of different alloys are produced in the weld nugget. Also, the microstructural changes in the nugget zone result in hardness fluctuations in cross sections of joints. Amancio *et al* [12] studied dissimilar FSW of 4-mm-thick AA2024-T351 and AA6056-T4 alloys by varying rotational speed (500–1200 rpm) and the welding speed (150–400 mm/min) and using a threaded cylindrical pin. They reported that defect-free and the strongest joints (90% of AA6065-T4 strength) can be achieved at 800 rpm and welding speed of 150 mm/min. Also, they show that the joint component with the greatest strength reduction controls the performance of the joint. Cavaliere *et al* [13] studied the mechanical and microstructural properties of dissimilar 4-mm-thick AA6082-T6 and AA2024-T3 friction-stir-welded joints using two traverse speeds of 80 and 115 mm/min and the constant rotational speed 1600 rpm with a conical pin tool. They reported that the vertical force increases on positioning AA2024 in the advancing side and increasing traverse speed. Also, the joint made using traverse speed of 115 mm/min and AA6082 on the advancing

*For correspondence

Table 1. Chemical composition of alloys (wt%).

Alloy	Al	Mg	Si	Fe	Cu	Cr	Mn
AA2024-T351	Base	0.68	0.47	0.40	0.19	0.19	0.06
AA6061-T6	Base	1.2	0.50	0.50	3.80	0.10	0.30

Table 2. Mechanical properties of alloys.

Alloy	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness (VHN)
AA2024-T351	469	324	19	137
AA6061-T6	310	278	12	107

side shows the best tensile and fatigue properties. Izadi *et al* [14] studied the material flow in the weld nugget of a dissimilar joint of 6.35-mm-thick AA2024-T351 and AA6061-T6 made by three FSW tool pin profiles (grooved pin, three-flat pin and threaded pin). They show that a three-flat pin imposes vertical material flow, which results in better material mixing in the SZ. Also, on using a grooved pin and AA2024 positioned in the advancing side, the intermixed lamella of material in the weld nugget cannot be seen.

Although a few works have been conducted to investigate the effects of tool pin geometry in dissimilar FSW of aluminium alloys, the effect of tool pin geometry and FSW pass number in dissimilar FSW of two age-hardenable aluminium alloys AA6061 and AA2024 with incorporated ceramic reinforcement particles has never been investigated. In this work, dissimilar FSW of AA6061-T6 and AA2024-T351 was carried out using SiC particles in the joint line, and the effects of tool pin geometry, number and direction of FSW passes and natural aging behaviour of joints have been investigated.

2. Experimental

The AA2024-T351 and AA6061-T6 aluminium plates used for the butt FSW had dimensions of 100 mm × 50 mm × 6 mm. The chemical composition and mechanical properties of aluminium plates are presented in tables 1 and 2. A groove with dimensions of 90 mm length, 0.15 mm width and 5.8 mm depth was created on the side of plates that were welded together. After the plates were clamped on the back plate, SiC microparticles ranging 11–18 µm in size were applied into the groove and pressed tightly. Figure 1 displays the square and triangle frustum tools used in this

Figure 1. The tools geometry used in this study.**Table 3.** Welding parameters used in the experiments.

Sample	Pin geometry	Pass number	Second rotational direction
A	Square frustum	1	–
B	Triangle frustum	1	–
C	Square frustum	2	Same direction
D	Square frustum	2	Inverse direction

study. Both of them have an 18-mm diameter shoulder with a 2° conical cavity and a frustum pin 5.8 mm in length. The inscribed circle diameter up and down of the pin is 7 and 3.5 mm, respectively. The AA6061 aluminium alloy was located in the retreating side. To study the effect of number of FSW passes on the joint, welding was done in one pass and two passes. Besides, the second pass was performed in two rotational directions, same and inverse directions, in comparison with the first pass. The welding conditions investigated in this study are listed in table 3. The constant welding speeds and groove dimensions used in this investigation are selected by several tests to determine the set of welding parameters that give sound welds.

The microstructural issues of joints are investigated using a Dewinter optical microscope and a VEGA3 TESCAN electron microscope on a cross section of the welds perpendicular to the welding direction. Keller's reagent and modified Polton solution were employed to etch the AA2024 and AA6061 alloys, respectively. EDS analyses were performed to determine element distribution in the weld nugget. The Vickers micro-hardness was also measured using a Koopa-MH3 Vickers indenter on cross sections of welded samples with a test load of 100 gf for 15 s according to ASTM E92 [15]. To evaluate tensile strengths of the welded samples, the tensile test sub-size specimens were prepared according to ASTM E8M [16]. By flat surface finishing of tensile test specimens, the effect of shoulder irregularities on the joint strength was removed.

Figure 2. Optical micrograph of friction-stir-welded samples: (a) sample A, (b) sample B, (c) sample C and (d) sample D.

3. Results and discussion

Optical micrographs of friction-stir-welded samples are shown in figure 2. AA2024 is located in the left hand side of figures and etched darker than AA6061 alloy. It can be seen that sample A welded by a square pin, compared with sample B, welded by a triangle pin, has a more interleaved layer of materials in the weld nugget. Besides, the SiC particles agglomeration near tool shoulder of sample B is more visible than in sample A. The tool pin geometry and welding speed (rotational and traverse speeds) have a strong effect on material flow in the weld nugget [17, 18]. According to past research [19] on the effect of number of flat surfaces of pin on material flow in the weld nugget, the pulsating stirring action and eccentricity of tool due to flat faces of pin control flow of plasticized material in the weld nugget. As reported in [20], a triangular pin can stir a greater material volume compared with a circular pin as well as polygonal pins with higher number of sides. One of the objectives of our research was increasing weld nugget homogeneity. Since the triangular and square-shaped tool probes can stir a greater material volume, we choose these types of pin in our study. The higher eccentricity, i.e., the higher ratio of the dynamic volume swept by the tool to the static volume of the tool, results in easier flow of material

around the pin. The square and triangle frustum pin has eccentricity of 3.14 and 1.22, respectively. The higher pulsation per second, i.e., rotational speed in seconds $\times$ number of flat faces, led to more effective stirring. The square and triangle frustum pin at rotational speed of 800 rpm has pulsation of 53 and 40 pulse per second, respectively. Therefore, the higher eccentricity and pulsating action of square frustum pin produce more homogenized weld nuggets (figures 3a and b).

With increasing weld pass number the interleaved layer structure disappeared and in sample C, an agglomeration band of particles appeared (figure 3c). This agglomeration band becomes wavy in sample D with changing direction of tool rotation in the second pass (figures 2d and 3e). SEM investigation at the centre of weld nugget (figures 3d and f) shows that the SiC particles are uniformly distributed. In sample D, inverting tool rotation results in a thicker agglomerated band and smaller area with uniform distribution of SiC particles in the weld nugget. Also, comparing weld cross sections of samples A, C and D shows that the volume of AA6061 alloy (light colour part near the top of weld nugget) extruded to the AA2024 side in sample D is higher than that in the others. Although the SiC particles homogeneity increases at the weld centre on increasing weld pass number, the agglomerated band formed in these

Figure 3. SEM image of various zones of weld nugget marked in figure 2: (a) zone A, (b) zone B, (c) zone C, (d) zone D, (e) zone E, (f) zone F and EDS analysis of white particles in the SEM micrograph rich in (g) iron and (h) copper.

Figure 4. Microstructure of weld nugget of (a) sample A, (b) sample B, (c) sample C and (d) sample D.

joints can show adverse effect on weld strength. According to figure 3g and h the white particles in the SEM micrograph of AA6061 and AA2024 side are rich in iron and copper particles as verified in EDS analysis, respectively.

The effect of tool pin profile, weld pass number and rotational direction on the microstructure of the welds nugget centre is shown in figure 4. The microstructure of the weld nugget consists of fine equi-axed grains. The formation of the equi-axed grain structure in FSWed welds is commonly referred to as dynamic recrystallization and is a prominent effect of grain refinement in weld nugget [21]. Addition of second-phase particles influences the grain growth by increasing the number of recrystallized grains nuclei sites and Zener pinning effect. In the MMCs, the second-phase particles, by applying pinning pressure, counteract pushing driving force of moving boundary during grain growth. This pinning pressure increases with decreasing particle size and/

or increasing particles volume fraction. It can be seen that in the weld made with square frustum pin, the SZ grain size is smaller than that with triangle frustum pin. The SZ grain size of sample A and B is 8.1 ± 1.2 and 10.2 ± 1.3 μm , respectively. It may be due to the effect of higher number of flat surfaces of square frustum pin that produce higher plastic deformation and more homogenized distribution of SiC particles that control recrystallization and grain growth in the weld nugget. Increasing weld pass number in both rotational same and inverse directions leads to smaller SZ grain size. The smaller initial grain size in the weld nugget zone and more homogenized and finer distribution of SiC particles result in smaller SZ grain size in the welds made by two passes. Considering figure 4c and d it appears that the weld made with two passes of rotation in the same direction, due to the production of more homogenized distribution of SiC particles in the weld nugget than the weld made in inverse

Figure 5. Microhardness profile for different aging periods after FSW of weld cross section of (a) sample A, (b) sample B, (c) sample C and (d) sample D.

direction, yields finer grain in the nugget. The SZ grain size of sample C and D is 5.8 ± 0.9 and 6.5 ± 0.7 μm , respectively.

Figure 5 shows the horizontal hardness profiles across the joints measured at mid-thickness of weld cross section for different aging periods after FSW, where AA6061-T6 and AA2024-T351 base metals show average Vickers hardness of about 107HV0.1 and 137HV0.1, respectively. In the precipitate-hardened 6061 and 2024 aluminium alloys, the imposed weld thermal cycles as well as severe hot deformation lead to elimination of the precipitation hardening effect and finally an abrupt decrease in hardness profile can be observed, as mentioned previously in other publications [22, 23]. The minimum hardness of all samples is in the thermo-mechanically affected zone (TMAZ) of AA6061 side. It can be seen that sample B exhibits higher

nugget hardness and TMAZ minimum hardness than those in the others. It is worth noting that samples C and D, because of more heat applied during two passes, show lower hardness in the weld nugget and TMAZ of AA6061 side. Considering that welding rotational and travel speeds are the same in both samples A and B, the only difference that can control heat input in samples A and B is tool pin profile. The lower contact surface due to three flat surfaces of triangle frustum pin compared with four flat surfaces in square frustum pin results in lower heat production by friction and plastic deformation heat generation. Therefore, lower heat input in sample B results in higher cooling rate; thus, one expects that the amount of precipitates just after welding is lower in the weld zones of this sample than in sample A. However, as shown in figure 6, due to re-

Figure 6. Hardness versus aging time of welded samples: (a) stir zone and (b) TMAZ.

Figure 7. Tensile strength and toughness of welded joints.

precipitation after natural aging, hardness in the weld nugget and TMAZ of samples increases. It can be seen in the image that the aging effect is more pronounced in the first few days. As shown in sample B, increasing of hardness after natural aging is more than those in the others. This may be because of higher cooling rate due to lower heat input in sample B.

The results of the tensile strength and toughness of welded joints after 70 days natural aging are shown in figure 7. It is worth noting that fracture in tensile samples occurs in TMAZ of AA6061 side where a minimum of hardness is observed; see figure 5. It can be seen that sample B shows higher yield strength (YS) and tensile strength (UTS) than those of the others. As shown in figure 5, higher hardness in TMAZ of sample B may be the agent of higher strength in this sample. Besides, lower strength in samples C and D can be related to lower hardness in the TMAZ of AA6061 side and SiC agglomerated band formed in the SZ, which results in inhomogeneous

mechanical properties across the weld joint. Considering the hardness profile and minimum hardness of samples C and D, the lower tensile strength of sample D may be due to thicker SiC agglomerated band and smaller area with uniform distribution of SiC particles. As seen, the welds made by two passes show higher tensile toughness than those of the others. The higher elongation and not too low tensile strength result in higher amount of tensile toughness in the welds made by two passes. The SEM image of fracture surfaces of welded samples is shown in figure 8. Both dimples and tear ridges are evident in the fracture surface of samples A and B. This fracture feature represents quasi-cleavage fracture mode. The fracture surface of samples C and D is covered by only large and deep dimples, which indicates ductile fracture. Considering the agglomerated SiC particles band in the weld nugget of samples C and D, it is expected that tear ridges exist in the fracture surface of these joints but the lower hardness in the TMAZ of AA6061 side and more homogenous distribution of SiC particles in the SZ can overcome the effect of agglomerated SiC particles band in the weld nugget. Therefore, dimple fracture surface appears in samples C and D.

4. Conclusions

The effect of tool pin geometry and pass number on microstructure and mechanical behaviour of dissimilar friction stir welds of AA6061-T6 and AA2024-T351 reinforced with SiC microparticles was studied in this research. The results can be summarized as follows:

1. The higher eccentricity and pulsating action of square frustum pin produce more homogenized and effective distribution of SiC particles in the weld nugget.
2. With increasing weld pass number the interleaved layer structure disappeared and the SiC particles homogeneity increased at the weld centre. Besides, an agglomeration

Figure 8. SEM image of fracture surface of (a) sample A, (b) sample B, (c) sample C and (d) sample D.

- band of particles appeared in the weld nugget; this agglomeration band became wavy and thicker with changing direction of tool rotation in the second pass.
3. The plastic deformation and homogenized distribution of SiC particles control recrystallization and grain growth in the weld nugget. Thus, the weld made by square frustum pin and two passes with rotation in the same direction, due to more homogenized and finer distribution of SiC particles, results in smaller SZ grain size.
 4. Increasing weld pass number, due to more heat applied during welding, results in lower hardness in the weld nugget and TMAZ of AA6061 side. Also, the driving force for natural aging after welding in the weld by two passes decreased. The weld made by triangle frustum pin shows higher TMAZ hardness, YS and tensile strength (UTS) than those of the others.

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