Effect of Rotational Speed on Wear Behavior and Mechanical Properties of Friction Stir Welded AA6061+15%Al_2O_3p Metal-Matrix Composite

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Abstract: The main objective of the present work was to investigate the effect of tool rotational speed on the mechanical and microstructural properties of aluminum based metal matrix composites (AA 6061 alloy reinforced with 15% of Al_2O_3 particles). The welds were produced by varying the rotational speed from 630 to 1250 r/min while the chosen welding speed was 80 mm/min for analysis. It was found from the analysis of the microstructure that the changing of the rotational speed leads to variation of the grain size and also the fragmentation and improvement of Al_2O_3 particles distribution in nugget zone. Moreover, the obtained results clearly depicted that increasing rotational speed from 630 to 1250 r/min resulted in improvement of the wear resistance and also decreases the fluctuations of friction coefficient which can be attributed to the presence of Al_2O_3 particles which acted as barriers and restricted the grain growth in nugget zone. The lowest wear rate was achieved at welds produced at rotational speed of 1250 r/min. It was seen from the hardness results that the highest tensile strength value was obtained for 1250 r/min rotational speed with an average value of about 320 MPa (equivalent to 82% that of the base metal).

Keywords: Friction stir welding, Metal matrix composite, Rotational speed, Tensile strength, Wear resistance

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1 INTRODUCTION

Metal matrix composites (MMCs) have attracted considerable attention due to their appealing mechanical such as: excellent strength to weight, good thermal conductivity, low specific density, high specific stiffness, good dimensional stability, and low coefficient of thermal expansion [1]. A major problem during fusion welding of MMCs is chemical reaction between the matrix and the reinforcement, enhancement of the fabrication costs, and also the clustering and deterioration of the reinforcement [2] in comparison with the Friction stir welding (FSW) processes, whilst unlike welds produced by conventional fusion welding techniques, the FSW process allows to obtain more efficient design and reduce the fabrication costs [3]. FSW technology invented at The Welding Institute (TWI), UK in December 1991 is a solid-state joining process for joining aluminum alloys [4]. Fig. 1 shows a schematic of FSW process. During FSW, the pin is inserted into the faying surface of the base metals and then moved horizontally in the direction of the joint line [1].

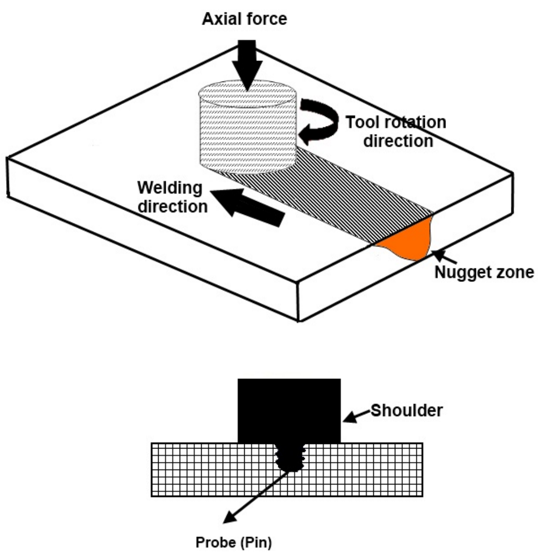

Fig. 1 Schematic drawing of friction stir welding process

Since, the FSW is solid-state joining processes, this results in higher mechanical properties of the joint in comparison of fusion welding and it can be said that FSW seems to be a good candidate in successfully joining MMCs [2]. The most significant benefit of the FSW process in comparison with the fusion welding processes is that the joint can be made without melting the base metal with low deformation and residual stress [5]. The most significant benefit of the FSW process in comparison with the fusion welding processes is that the joint can be made without melting the base metal with low deformation and residual stress [5].

A number of studies were conducted to evaluate the feasibility of FSW of MMCs in recent years. For instance, Marzoli et al [2] investigated FSW of an AA6061/Al2O3/20p reinforced alloy and found that the stirring of the tool has a considerable effect on the reinforcement particles distribution and shape. These results were confirmed by Feng et al., [6].

Feng et al., [6] explored the effect of the microstructural evolution on mechanical properties of FSW of AA2009/SiCp composite. They indicated that FSW resulted in the production of the fine grains and the breaking and uniform distribution of the SiC particles in the nugget zone. Gopalakrishnan et al., [7] studied on FSW of aluminium matrix TiCp particulate reinforced composite and remarked that the tool pin profile has maximum effect on tensile strength of joints and also reported that the tool rotational speed had negligible effect on mechanical properties.

In this study, the influence of the rotational speed (630, 1250 r/min) has been compared on the wear behaviour and mechanical properties of friction stir welded AA6061+15%Al_2O_3p metal-matrix composite. Furthermore, the effect of tool rotational speed on the distribution of Al_2O_3 particles in nugget zone has been discussed.

2 EXPERIMENTAL PROCEDURE

AA6061/15%Al_2O_3p composite with thickness of 5 mm, fabricated by Modified Stir Casting Process with bottom pouring arrangement in an argon atmosphere, was used as the FSW samples in this investigation. The dimensions of the aluminium alloy plates were 50 mm × 125 mm. The used rotational speed of the tool was 630 and 1250 r/min while the chosen welding speed was 80 mm/min. The tool was made of H13 steel with a hardness of 50±2 HRc. Pin and shoulder diameters were 6 and 18mm, respectively, with a concave profile angled at 8°. Pin had the length of 4.7 mm (see Fig. 2).

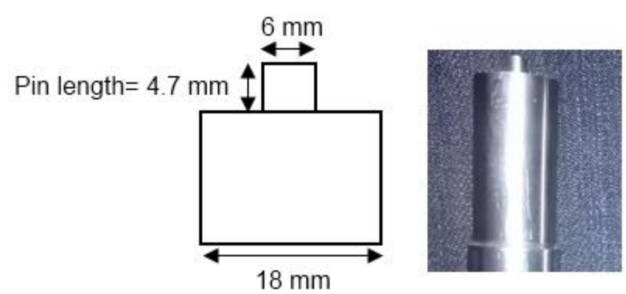

Fig. 2 Schematic representation of used FSW tool for this study

The threaded pin had 1 mm pitch. Afterwards for metallographic process, the specimens were polished and then etched by a Weck reagent (4 g $KMnO_4$, 1 g NaOH and 100 ml H_2O) for 10 s. At room temperature and under ASTM G99 standard in air, friction and wear behavior were investigated by a pin on disc test rig. Pin with 5mm in diameter with the axis normal to the FSP direction as specimens and the hardened steel disc (steel 52100) as counter disc were used.

In Table 1, the wear test (pin on disk) conditions are mentioned. By measuring the frictional force with a stress sensor, the coefficient of friction between the disk and the pin specimen was calculated. Before loading, the surface of samples on the test was rigged and the disc were ground and then were cleaned in acetone by 800 grit SiC paper and then worn surfaces were checked by SEM.

Table 1 Wear test conditions (pin on disk)

Pin shape	Pin diameter, cm	Applied force, N	Sliding velocities, $cm \cdot s^{-1}$	Pin rotating speed, $r \cdot min^{-1}$
Cylindrical	1	40	35	26.4

The tensile tests were performed at room temperature by an INSTRON 5500R testing machine with a cross-head speed of 5 $mm \cdot min^{-1}$. In addition, the scanning electron microscope (SEM, OXFORD) equipped with energy dispersive spectroscopy (EDS) and the optical microscope (OM, Olympus CK40) were used to evaluate the microstructure and worn surface of samples. To understand the effects of tool rotational speed on the microhardness of the nugget zone, Vickers hardness testing was done by applying indentation load of 100-g load, loading time of 15 s for hardness survey across the interface.

3 RESULTS AND DISCUSSION

3.1. Effect of the tool rotational speed on the appearance of the weld

The effect of tool rotational speed on surface appearance of the welded samples is shown in Figs. 3. As seen, surface appearance of the joints changed with increasing rotational speed. According to Fig. 3, it is well known that at low rotational speed, the surface of specimens is coarser than that at high rotational speed which can be attributed to the higher heat input which is generated at 1250 r/min rotational speed. However due to increase of heat input, flashes were formed. Aydin et al. [8] found that the increasing the rotational speed resulted in the increase of the heat input and consequently decrease of surface roughness. In other words, it can be said that increasing rotational speed leads to the increase of flash.

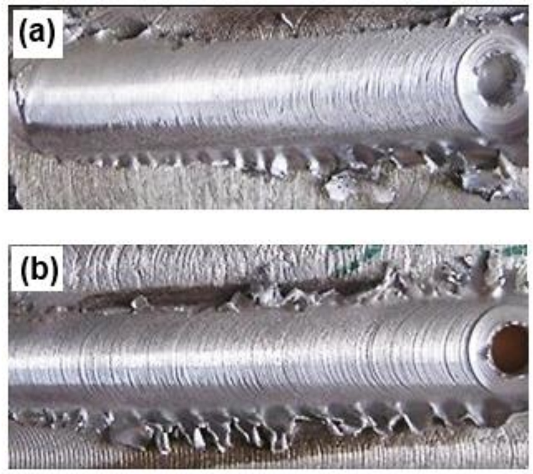

Fig. 3 Surface appearances of 6061+15% Al_2O_3p composite joined by FSW as a function of tool rotational speed, (a) 630 r/min and (b) 1250 r/min

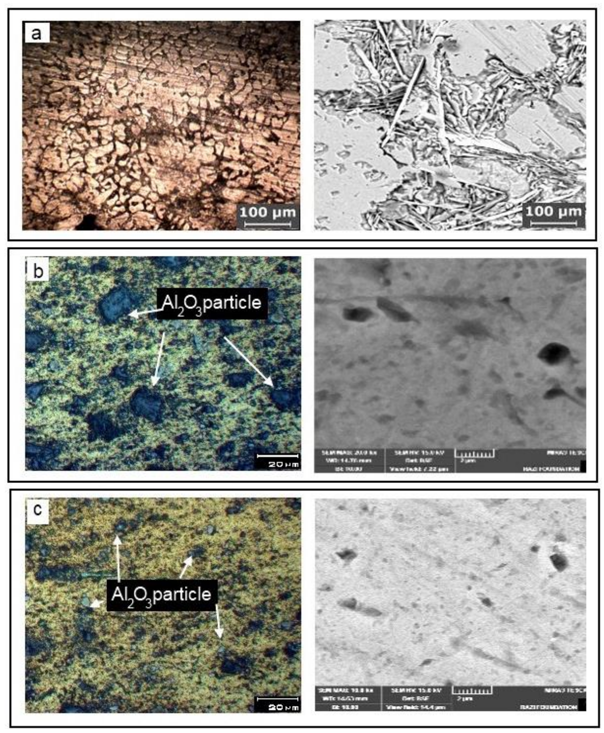

Fig. 4 Micro photography of MMC composite, (a) base metal, (b) microstructure of nugget zone at 630 r/min, and (c) microstructure of nugget zone at 1250 r/min

3.2. Effect of the tool rotational speed on microstructure of the nugget zone

The relationship between microstructure of nugget zone and the tool rotational speed is represented in Fig. 4. Microstructure of parent material is seen in Fig. 4a. It can be seen from the results, Figure 4, that increasing the rotational speed increases the occurrence of variation of the grain size and also the fragmentation and improvement of Al_2O_3 particles distribution in nugget zone, which it can be attributed to the higher stirring of materials by increasing rotational speed. Cavalier et al., [3] reported that the particle fracture in this kind of joints results in a positive effect. Because the smaller particles favor the recrystallization phenomena and act as new grain nucleation sites which leads to the production of a finer grain structure in nugget zone.

Based on the above mentioned results, the microstructure of nugget zone is dependent upon the tool rotational speed. At the end, it should be pointed out that, changing the rotational speed not only affects the microstructure of FSWed welds, but also follows the mechanical properties of welds. In other word, there is a direct correlation between rotational speed and tensile strength and also wear behavior; which means that variation of the tool rotational speed caused a variation in the generated friction coefficient during FSW (as later discussed in the wear studies results section).

3.3. Effect of the tool rotational speed on the mechanical testing

In this section, the effect of rotational speed on tensile strength and hardness of nugget zone was discussed. Fig. 5 presents the influence of rotational speed on ultimate tensile strength (UTS) of the welded joints. As it is illustrated, the tool rotational speed has vital effect on the UTS. In fact, based on the above mentioned results, it can be said that increasing the rotational speed led to change of UTS of the joints and increased up to a maximum value about 320 MPa (equivalent to 82% that of the base metal). As you know, increasing tool rotational speed leads to the variation of the heat input and subsequently temperature produced in nugget zone which leads to an increase in the grain size.

But, it must be mentioned that the presence of Al_2O_3 particles acted as barriers and restricted the grain growth [9], [10]. On the other hand, as mentioned before, increasing tool rotational speed led to the more breaking of Al_2O_3 particles in nugget zone. Therefore, it improves numerous sites for nucleation in the nugget zone [11]. Additionally, the results show that the tool rational speed had a major effect on the fracture location of the welded specimens. Indeed, it can be said that the fracture location of the joints is dependent on the tool rotational speed. It has been found that the fracture location at welding condition with rotational speed of 630 r/min occurred at nugget zone, whilst at 1250 r/min rotational speed, the fracture location is nearer to the interface between the nugget zone and the base metal.

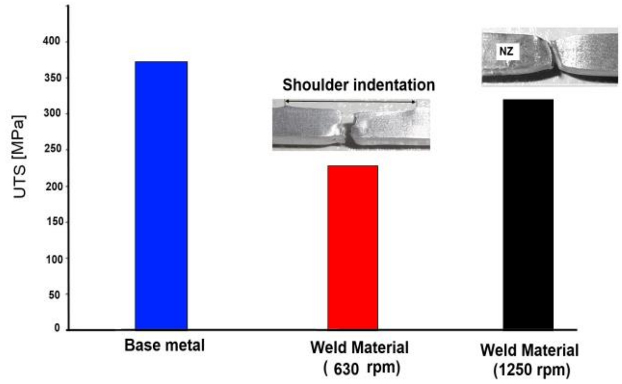

Fig. 5 UTS of welded joint differ due to different tool rotational speeds

Vickers microhardness was performed to evaluate the effect of the welding parameters on the hardness nugget zone of joints. Fig. 6 presents a comparison between Vickers microhardness variations as a function of tool rotational speed. As it can be seen in Fig. 5, when the tool rotational speed increases from 630 r/min to 1250 r/min, the joint hardness will increase. This is owing to vital effect of ceramic particles on grain size in nugget zone. As it was expected, the hardness value of the joints welded by 1250 r/min is more than those welded by 630 r/min rotational speed.

Since at higher rotational speed of tool, excess stirring action is applied to the nugget zone, it can lead to fragmentation of Al_2O_3 particles, which can affect the mechanical properties of welds. Because, according to Hall–Petch equation, the finer grain structure results in tensile strength improvement. It should be pointed that the hardness of received composite was 89 HV. Considering OM and SEM micrographs of Al_2O_3 particles distribution and the corresponding UTS values and hardness profile, it could be inferred that the ceramic particles play the major role in evaluation of mechanical properties.

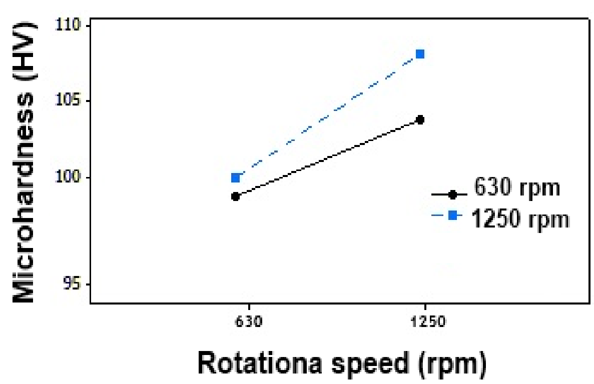

Fig. 6 Effect of tool rotational speed on microhardness of AA6082/15%Al2O3 composite

3.4. Effect of the tool rotational speed on the wear studies

Fig. 7 illustrates the influence of tool rotational speed on wear rate. From Fig. 7 it can be seen that the tool rotational speed of 630 r/min has the lowest resistance to wear. The measured wear rate can be related to the enhanced hardness obtained by higher rotational speed compared to the low rotational speed. Indeed, the attained data shows that, the change in tool rotational speed causes varying stirring action, which induces breaking and fragmentation of Al_2O_3 particles in nugget zone and also improvement of Al_2O_3 distribution in composite.

According to these results and since 1250 r/min rotation speed produces finer Al_2O_3 particles and finer grain size in nugget zone, higher wear resistance is obtained. In other words, the presence and distribution of Al_2O_3 particles in nugget zone are functions of tool rotational speed. To sum up, in accordance with results, it can be said that wear resistance is high and friction coefficient was low with finer Al_2O_3 particles size and these results may stem from the fine particle produced in nugget zone whereas Srinivasu et al., [12] reported that the reason behind this behavior could be originated from decrease in the plastically deformed contact areas. It is while that Eftekharinia et al., [13] attributed it to better dispersion of ceramic particles in the matrix in their study.

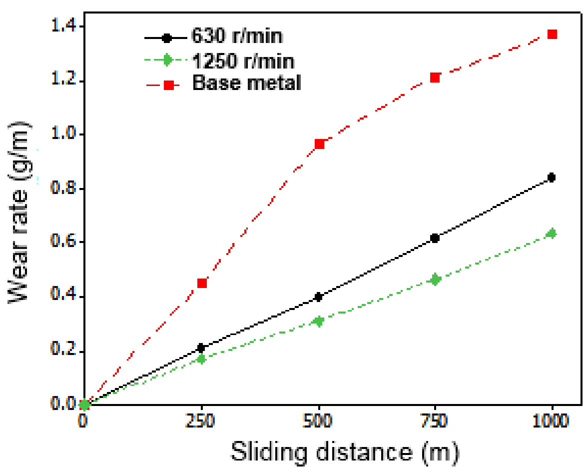

Fig. 7 Effect of rotational speed on wear rate

Fig. 8 compares the effect of the rotational speed on friction coefficient and worn surface of welded joints. As it is clear in Fig. 8, increasing rotational speed decreases the wear rate but in fact improves the wear resistance. Moreover, increasing the rotational speed decreases the fluctuations of friction coefficient. The average coefficient of friction of the specimen fabricated at 1250 r/min is somewhat lower than that fabricated at 630 r/min rotational speed as clear in Fig. 8.

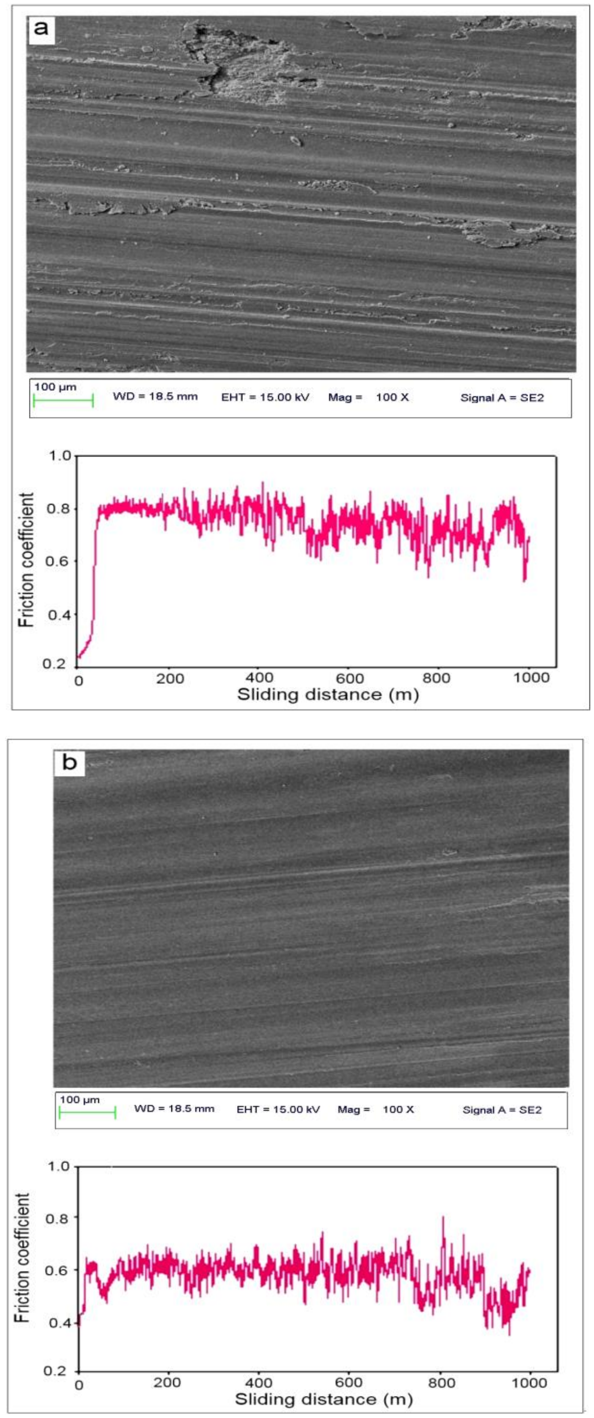

Fig. 8 SEM images of wear tracks and friction coefficient as a function of tool rotational speed: a 630 r/min and b 1250 r/min

7 CONCLUSION

Friction stir welding of the AA6061+15%Al_2O_3p metal-matrix composite was investigated using the rotational speed (630 and 1250 r/min). The important results obtained can be summarized as follows:

1- The size and distribution of Al_2O_3 particles in nugget zone are functions of tool rotational speed.

2- The best consistent tensile strength was produced at 1250 r/min rotational speed with an average value of about 320 MPa (equivalent to 82% that of the base metal).

3- Increasing the rotational speed led to improvement of reinforcement particles dispersion in the matrix and consequently reducing the wear rate.

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