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Microstructure evolution and mechanical properties of dissimilar friction stir welded joints between AA1100-B_4C MMC and AA6063 alloy

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ABSTRACT

The feasibility of dissimilar friction stir welding (FSW) between the AA1100-16 vol.% B_4C metal matrix composite and the AA6063 alloy has been evaluated. The effect of the welding parameters on the interface bonding, joint microstructure and mechanical properties was investigated. The results revealed that all dissimilar joints produced under welding conditions investigated were stronger than the base materials of the Al-B_4C composite. Analysis of the Mg concentration and the B_4C particle distribution indicates that good material mixing and seamless bonding was achieved around the interface between the Al-B_4C composite and the Al 6063 alloy during FSW. The electron backscatter diffraction analysis (EBSD) shows that during dissimilar FSW, there was a gradual microstructural evolution on both material sides, resulting in a variety of grain structures in the different weld zones. In the weld zones of FSW joints, the materials underwent dynamic recovery and recrystallization to different extents depending on their thermal mechanical history. The grain refinement of both materials in the nugget zone was observed. It is recommended that the 6063 aluminum alloy should be fixed on the advancing side and the use of an appropriate offset to the 6063 aluminum side is preferred.

1. Introduction

Assemblies of metal matrix composites (MMCs) with monolithic metals are attractive for many applications and can be cost-effective if the costly MMCs are only used where necessary. However, one of the limitations for widespread MMC applications is the difficulty in using conventional fusion welding since problems such as porosity and chemical reaction between the matrix and the reinforcement can occur to deteriorate the mechanical properties of the joints [1–3]. In contrast, friction stir welding (FSW) may be a promising technique as it permits welding dissimilar materials in solid-state while avoiding the drawbacks of fusion welding [4].

As a new solid-state process, FSW has attracted great interest from industries as it avoids various problems that may otherwise be encountered during fusion welding. It is most suitable for welding light metal alloys, MMCs, and dissimilar metals [4,5]. The FSW of light metals has been extensively studied [4] and the FSW of MMCs or dissimilar monolithic metals has also become an important research topic in recent years [6,7]. High quality FSW joints of Al-based MMCs can be achieved under appropriate process conditions [6,7]. However, FSW between MMCs and monolithic metals has rarely been reported [8–10]. Wert [8] and Sharifitabar and Nami [9] studied the microstructural aspects of the dissimilar joints by varying the material on the advancing side and the number of welding passes respectively. However, no mechanical properties of dissimilar joints were reported in their studies. Xiao et al. [10] investigated both the microstructure and mechanical properties of the dissimilar joints of Al2009-SiC MMCs and 2024 alloy. They found that the microstructural evolution and the material flow during welding were complex and mainly dependent on the tool geometry and the process parameters. A tensile strength up to 85% of the weak material (2024 Al alloy) could be obtained in the FSW joints of Al2009-SiC MMCs and 2024 alloy [10]. Obviously, more systematic work should be performed in FSW of MMCs and monolithic metals, especially for different materials and joint configurations.

The present study aims at investigating the weldability of AA1100-B_4C MMC and monolithic 6063 aluminum alloy using the FSW technique. The Al-B_4C MMCs have been mainly used in nuclear spent fuel storage and transportation applications owing to their good mechanical properties, thermal conductivity and specific capability of capturing neutrons [11–13]. The AA1100 matrix is interesting as it can provide the highest B_4C loading while keeping a good formability [13]. The AA6063 aluminum alloy was used because of its good formability and mechanical property. During the experiments, different joint configurations and welding parameters were used. The effect of FSW on the interface bounding,

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Table 1
Chemical composition of extruded AA6063 plate (wt.%).

Alloy	Si	Fe	Cu	Mg	Mn	Ti	Al
Al 6063	0.44	0.19	0.01	0.50	0.03	0.01	Bal.

microstructural evolution and mechanical properties of the dissimilar joints was examined.

2. Experimental procedure

Rolled plates of AA1100-16 vol.% B_4C MMCs (4.4 mm thick) and extruded plates of Al 6063 alloy (4.5 mm thick) in a T5 temper condition were used in this study. The nominal median particle size of boron carbide in the MMCs is 17 μm and the matrix is a standard AA1100 aluminum alloy. The chemical composition of the AA6063 extruded plate analyzed by an optical emission spectroscopy is given in Table 1. The AA1100-16 vol.% B_4C composite was fabricated by Rio Tinto Alcan via an ingot metallurgy route [11]. The cast ingots were preheated and hot-rolled with multi-passes of cross-rolling to the final shape. All the Al-B_4C MMC plates were annealed (400 °C for 1 h) before welding as it was previously demonstrated that the FSW joints made under annealed condition had a good combination between strength and ductility [14].

All plates were cut into pieces measuring 150 mm long (rolling/extrusion direction) and 50 mm wide. They were carefully degreased with liquid acetone and air dried. A steel brush was used on the plate edges to remove residual smudges and oxide films before the actual welding. These plates were butt welded along the rolling/extrusion direction using a MTS I-Stir PDS FSW machine in force control mode. The welding parameters listed in Table 2 were selected to avoid macro-defects in the weld and excessive flash on the surface. Preliminary tests in position control mode were carried out in order to determine the appropriate vertical force for each condition. The offset used was the distance of the FSW tool axis when shifted from the original interface of the two welding plates to the 6063 plate. The material side of welds was varied by changing their relative positions while keeping the rotation direction of the FSW tool unchanged. A conical unthreaded WC–Co alloy tool was used for the FSW tests [14].

Based on ultrasonic inspections, the micrographic samples were transversely sectioned in the welded plates at positions where the FSW process was considered stable after the first 20 mm of each test. Microstructural characterization was performed using an optical microscope (OM) with an image analyzer and a scanning electron microscope (SEM) equipped with an energy dispersive spectrometry (EDS) and electron backscatter diffraction (EBSD). Step sizes between 0.4 and 0.5 μm were used for the EBSD analysis. The Vickers hardness of the matrix was also measured at the top and bottom of each joint at intervals of about 0.5 mm. A 10 g load indent was used in the Al-B_4C composite zones to avoid indentations on the B_4C particle-affected areas, while a 100 g load was used in the 6063 alloy zones. The tensile tests were carried out according to the ASTM E8-04 standard at a test speed of 1 mm min^{-1}. Rectangular flat samples with a 50 mm gauge length and a 12.5 mm width in the reduced section were used. Tensile samples of the joints were prepared according to the standard without any change of surface condition after welding (as-welded) and a minimum of three samples were used for each condition.

3. Results and discussion

3.1. Macroscopic structure

Fig. 1 shows the macroscopic images of dissimilar FSW joints produced under conditions listed in Table 2. It was observed that sound welds could be obtained for all the welding conditions investigated. A macro interface between the Al-B_4C MMC and the 6063 alloy can be readily identified. It is evident that the two materials were not completely blended and their identities were retained in the nugget zone for all four welding conditions. This can be attributed to the unthreaded feature of the FSW tool designed to reduce the tool wear in our prior study [14] and which was used in the present study. It was reported [8] that the macro-interface can also be easily identified in dissimilar FSW of AA2024 alloy and AA2014-20%Al_2O_3 MMC when using a tool with a square pin which is similar to the results in the present study. On the other hand, a banded structure in the nugget zone, which possessed alternated MMC and Al layers, was observed in dissimilar FSW of AA2024 alloy and AA2009-15%SiC MMC using threads on the pin [9,10]. It was also observed that FSW tools without threads could not fully mix the materials macroscopically as the materials experienced a weak vertical flow movement.

When the 6063 alloy was fixed on the advancing side (Fig. 1a), the weld nugget featured a convex aluminum alloy surrounded by a wedge-shaped layer of MMC on the top. When the welding speed increased to 200 mm min^{-1} (Fig. 1b), this wedge-shaped layer of MMC became thicker and more MMC material transferred into the aluminum alloy side. The use of an 0.8 mm offset to the 6063 aluminum side (Fig. 1c) did not change the materials flow pattern though the position of the interface somewhat shifted to the MMC side when compared to Fig. 1a. An appropriate offset to the 6063 aluminum side can significantly reduce the amount of the MMC in contact with the FSW tool. Thus, the use of an offset may reduce tool wear during the FSW of MMCs. However, in our preliminary tests, the use of a 1.5 mm offset failed to produce sound welds with full penetration. Therefore, the maximum offset must be carefully examined as sound welds can only be obtained in a very narrow welding window especially with the use of an unthreaded FSW tool. On the other hand, when the 6063 plate was fixed on the retreating side (Fig. 1d), the materials flow pattern was significantly changed. The interfaces of two materials are close to the original interface and some aluminum penetrated deeper into the MMC side to form bands. However, the deep concave top surface illustrated in Fig. 1d was observed on the aluminum side where the surface finish of the weld was negatively affected.

3.2. Microstructure

Fig. 2 shows the typical micrographs of the base material and the weld nugget zone on the MMCs side under an optical microscope. Some breakage and rotation of B_4C particles can be observed in the weld nugget of the dissimilar joints produced under all the welding conditions investigated. However, the particle breakage was

Table 2
Main welding parameters of dissimilar FSW.

Code	Advancing side material	Rotation speed (rpm)	Welding speed (mm min^{-1})	Offset (mm)	Tilt angle (°)
DF1	6063 alloy	2000	100	0	3
DF2	6063 alloy	2000	200	0	3
DF3	6063 alloy	2000	100	0.8	3
DF4	Al-B_4C MMCs	2000	100	0	3