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Microstructure and mechanical properties of friction stir welded AC4A + 30 vol.%SiCp composite

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ABSTRACT

AC4A + 30 vol.%SiC particulates reinforced aluminum matrix composite was friction stir welded successfully. The influences of welding parameters on microstructure and mechanical properties of joints and welds were investigated. The results show that defect-free joints could be obtained in the welding speed range of 25–150 mm/min at a constant rotation speed of 2000 rpm. The optimum ultimate strength (UTS) of the joint is up to 140 MPa, while the optimum UTS of the weld is 279 MPa which is 1.72 times that of base material. The microstructure analyses indicate the reason for higher weld strength. On one hand, SiC particles are fractured and thus fined due to the intensive stirring action of tool pin during Friction Stir Welding (FSW). On the other hand, the plastic flowing of material in the weld is benefit to eliminate microporosities existed in original base material. In addition, higher welding speed causes the conglomeration of SiC particles in the upper section of the weld, which leads to inconsistent deformation between the upper section and the lower section in the weld zone (WZ) during tensile test, and thus resulting in the decrease of weld strength.

1. Introduction

Particulates reinforced aluminum matrix composites (PRAMCs) exhibit high specific stiffness and strength to weight ratio at room and elevated temperatures, high formability and improved wear resistance, having potential structural applications in the aerospace and automotive industries [1–6]. It is inevitable to develop a more suitable welding technique in order to accelerating PRAMCs application in practical projects. However, it is hard to achieve high-performance joints by using conventional fusion welding, brazing and transient liquid phase diffusion welding (TLP-DW). Conventional fusion welding leads to the occurrence of segregation and deleterious reactions between the reinforcement particles and liquid aluminum in the fusion zone, thus decreasing the mechanical properties of joints [7]. Even if laser welding is used, the heating zone becomes small, but there is still the same problem as conventional fusion welding [8,9]. As for brazing, it is difficult for the reinforcing particles to enter the brazing seam because the filler materials cannot wet and spread on the reinforcing particles, and thus resulting in the weak joining [10]. TLP-DW is considered to be an effective method for joining PRAMCs, but the welding process is carried out in vacuum furnace, welding time is long and weldment dimensions are limited, therefore it is difficult for TLP-DW to use widely [11].

Friction Stir Welding (FSW) is a novel solid-state joining technique, dominating by the severe plastic deformation and adiabatic shear instabilities that cause dynamic recrystallization to facilitate the solid-state flow creating the weld [12]. In recent decade, FSW has been used to join PRAMCs. Feng et al. [13] reported that brittle intermetallic compounds did not generate in the FSW weld of AA2024 + 10%SiCp, but there was an obvious interface between SiC particles and aluminum matrix, and most of SiC particles aggregated in the thermo-mechanically affected zone (TMAZ), while the nugget region had low density of SiC particles. Uzun [14] studied the microstructural evolution of friction stir welded AA2124 + 25 vol.%SiC, and noticed the abrading action of tool pin on SiC particles and uniform distribution of SiC particles in the weld. Amirizad et al. [15] reported that the ultimate strength and elongation of the FSW weld of AA356 + 15%SiCp was 1.34 and 2.54 times, respectively, as compared with base material.

All in all, compared with previous welding techniques, FSW process can overcome their defects and improve mechanical properties of weld and joint by altering the size and distribution of SiC particles, and will become an optimum welding process for PRAMCs. However, with regards to PRAMCs of more than 25 vol.%SiC particles, which has a wide application prospect in electronic

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Table 1
Nominal compositions of SiC particles reinforced Al matrix composite (Weight%).

Al	Si	Fe	Mn	Mg	Cu	Zn	Ti	Cr	Ni	Pb	Sn	SiC (vol.%)
Balance	8–10	0.55	0.3–0.6	0.3–0.6	0.25	0.25	0.20	0.15	0.10	0.10	0.05	30

Table 2
Mechanical properties of SiC particles reinforced Al matrix composite.

Ultimate strength (MPa)	Elongation (%)	Vickers hardness (Hv)
162	0.32	125

Table 3
Material and size of FSW tool.

Type of material	Shoulder inclination (°)	Shoulder diameter (mm)	Pin diameter (mm)	Pin length (mm)
WC–Co hard alloy	3	13.6	6.0	4.85

packaging and aerospace, there is little report on the FSW and it is imperative to study their FSW characteristics. Therefore, PRAMCs of 30 vol.%SiC particles are attempted to joint by FSW, and the focus is placed on the microstructure and mechanical properties of welds and joints.

2. Experimental procedure

The base material was particulates reinforced aluminum matrix composites with 300 mm length, 100 mm width and 5 mm thickness, which is composed of AC4A aluminum alloy matrix, equivalent to ENAC-AlSi10 Mg in the European Grade, and 30 vol.%SiC particles, and the nominal compositions and tested mechanical properties of base material are listed in Tables 1 and 2, respectively.

The FSW tool was made of WC–Co hard alloy, and the columnar tool pin possessed right-handed threads. The tool size is listed in Table 3. The PRAMCs samples were rigidly fixed on stainless steel backing plate and were longitudinally butt welded using an FSW machine (Hitachi, SHK207-899) with the counter-clockwise rotating tool under the welding parameters listed in Table 4.

The joint was cross-sectioned perpendicular to the welding direction for metallographic analyses and tensile testing using an electrical discharge cutting machine (Brother, HSC-300). Optical microscopy (Olympus, HC-300Z) and scanning electron microscopy (SEM) were used for the typical microstructural observation. Before analysis, the metallographic specimens were prepared by sand papers grinding, diamond paste polishing and Keller's reagent etching.

Two kinds of tensile specimens were sectioned by electrical discharge cutting machine. The bigger size tensile specimens (Fig. 1a), perpendicular to welding direction, were used to evaluate tensile properties of joints. The small size tensile specimens, extracted from the weld zone (Fig. 1b) and parallel to welding direction, were used to evaluate tensile properties of welds. The bigger size tensile specimens were prepared with reference to China National Standard GB/T 2651-2008 (equivalent to ISO 4136: 2001) [16] and the small size tensile specimens were prepared with reference to China National Standard GB/T 2652-2008 (equivalent to ISO 5178: 2001) [17]. In each case, three specimens were prepared from the same joint, and their average was used to describe the tensile results.

Table 4
Welding samples and process parameters.

Welding samples	No. 1	No. 2	No. 3	No. 4
Rotation speed (rpm)	2000	2000	2000	2000
Welding speed (mm/min)	25	50	100	150

The mechanical properties of the joints and welds obtained in various parameters were measured by a computer controlled tensile testing machine (Shimadzu, AG-10TB) whose precision is up to 0.5%. Before the tensile tests, Vickers hardness profiles across the weld, heat affected zone and partial base material were measured by an automatic micro-hardness tester (Akashi, AAV-502).

3. Results and discussion

3.1. Mechanical properties and its relation to microhardness distribution

Fig. 2 shows the tensile fracture positions of the joints obtained at different welding speeds of 25, 50, 150 and 200 mm/min with a constant rotation speed of 2000 rpm. From the fracture locations, all of the joints were fractured in the heat affected zone (HAZ). It can be inferred that HAZ is the weakest region in the joint. Additionally, the fracture positions become close to weld center gradually with welding speed decreasing. This demonstrates that lower welding speed leads to higher heat input due to the long time of the process, which results in serious softening in the HAZ and the most serious softening region approaching to the weld center.

All the fracture positions are located in the HZA instead of the WZ. This indicates that the WZ demonstrates superior tensile properties to HAZ. In order to evaluate the tensile properties of the welds, it is necessary to extract tensile specimens in the WZ directly, as shown in Fig. 1b.

The tensile strengths of the joints and welds are shown in Fig. 3. It is clearly observed that whatever welding parameter is, the ultimate strength (UTS) of the welds are higher than the joints invariably. For the joints, with the welding speed increasing, the UTS demonstrates a slight increase. When the welding speed is 150 mm/min, the joint UTS reaches its maximum value, 140 MPa. However, the weld UTS suffers a sharp decline with welding speed increasing. The maximum UTS of the welds is 279 MPa, obtained at the welding speed of 25 mm/min, equivalent to 1.72 times of UTS of base material, 162 MPa. The UTS of the welds decreases to 159 MPa rapidly at the welding speed of 150 mm/min, only equivalent to 98.1% of the UTS of base material, which is still higher than the maximum UTS of the joints. In general, welding speed has a significant effect on tensile strength of joints and welds.

Fig. 4 shows the elongation of joints and welds obtained at various welding speeds. It can be seen that, when the welding speed increases from 25 mm/min to 150 mm/min, the joint elongation suffers a minor fluctuation, about 0.31%, which is almost the same as the base material. However, it is important to note that, the value of the weld elongation is fluctuating nearby 0.89%, which is 2.7 times that of the joints.

Tensile properties of the joints and the welds are closely related to microhardness distribution. In order to compare tensile properties