

Wear characteristics of a WC–Co tool in friction stir welding of AC4A + 30 vol%SiCp composite

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Abstract

Tool wear is a key issue for the friction stir welding (FSW) of aluminum matrix composites (AMCs), especially when the volume fraction of reinforcing particulates is relatively high. In this study, a threaded tool of WC–Co hard alloy is used to weld a cast AMC composed of Al–Si matrix and 30 vol%SiC particulates so as to examine the wear characteristics of the tool. Experimental results indicate that the tool wear is appreciable although the shoulder size and pin length are changed slightly. The radial wear of the pin is very different at different locations of the pin, and the maximum wear is finally produced at a location of about one-third pin length from the pin root. The welding speed has a decisive effect on radial wear rate of the pin, and the maximum wear rate is produced in the initial welding.

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1. Introduction

Particulates reinforced aluminum matrix composites (AMCs) are considered as one of the most promising structural materials for advanced applications in aerospace, military and transportation industries [1]. However, in order to produce larger or more complex structural components, it is inevitable to join AMCs to themselves or other materials. Therefore, some joining processes such as fusion welding [2–4], brazing [5] and diffusion bonding [6–8] were developed, but they resulted, to different extent, in the degradation of mechanical properties.

Friction stir welding (FSW) [9] is being considered as a prospective joining process to solve this problem. As a solid-state joining process, FSW can eliminate the welding defects associated with fusion welding processes. In the friction stir welded joints, there is no transition zone or bonding zone related to diffusion bonding or brazing. Therefore, the original properties of AMCs can be held. A few researchers carried out preliminary studies on this topic,

and the feasibility of the FSW process was demonstrated [10–12]. However, the hard ceramic particulates in the AMCs resulted in appreciable tool wear when the FSW tool was made of tool steel [13–16]. In the present study, a WC–Co hard alloy tool was used to friction stir weld an AC4A + 30 vol%SiCp AMC, and the emphasis was placed on the wear characteristics of the tool.

2. Experimental procedure

The base material, composed of AC4A Al–Si alloy matrix and 30 vol%SiC ceramic particulates, was a 5-mm-thick cast AMC with the nominal compositions listed in Table 1. The FSW tool was made of a WC–Co hard alloy, and the tool pin possessed right-handed threads. The tool shoulder was designated as a frustum contour, as shown in Fig. 1, and the tool size is listed in Table 2. The AMC samples were butt welded by the counter-clockwise rotating tool under the welding sequences and process parameters listed in Table 3. After any one couple of samples were welded, the tool was placed in a 5% NaOH solution until the aluminum on the tool surface was completely removed,

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Table 1
Nominal compositions of AC4A + 30 vol%SiCp AMC

AC4A (wt%)												SiC (vol%)
Al	Si	Fe	Mn	Mg	Cu	Zn	Ti	Cr	Ni	Pb	Sn	
Bal.	9	0.55	0.45	0.45	0.25	0.25	0.20	0.15	0.10	0.10	0.05	30

and then the tool was photographed using a digital camera mounted in the optical microscopic system. In this way, a series of tool photographs was obtained, and the variation in tool geometry was accurately calculated in a computer system.

3. Results and analysis

Fig. 2 shows the appearance of the threaded tool after each FSW experiment. It can be seen from the figure that the threads near the pin root almost disappear after the first welding (see Fig. 2b). The maximum diameter, i.e. minimum wear, occurs in the upper half-part of the pin, while the minimum pin diameter, i.e. maximum wear, exists in the lower half-part near the shoulder (see Fig. 2b–h). After the sixth welding is performed, all the original threads of the pin have been completely worn away (see Fig. 2g and h). These results indicate that the tool is clearly consumed or its shape and size are significantly changed.

In order to quantitatively assess the tool wear, the percent variation in tool size is used as evaluation index, i.e. $\text{variation} = (\text{original size} - \text{measured size}) / (\text{original size}) \times 100\%$.

3.1. Shoulder wear and pin longitudinal wear

As shown in Fig. 3, the variations in shoulder size and pin length increase with increasing travel distance, but they are all very small. For example, when the seventh welding is completed, the shoulder diameter, shoulder height and pin length are merely changed by 2.2, 2.5 and 1.2%, respectively. This implies that the shoulder wear and the pin longitudinal wear are slight.

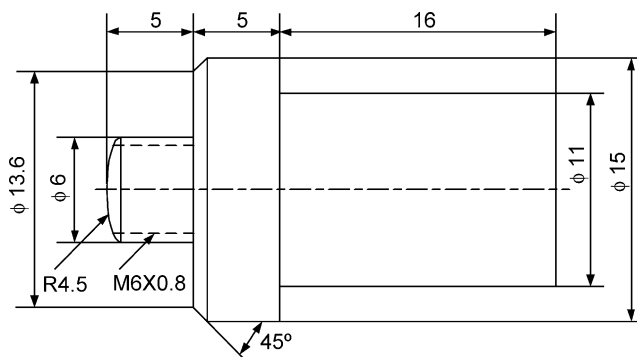


Fig. 1. The configuration and dimensions of the tool used in FSW experiments.

3.2. Radial wear of the pin

Different from the variation in pin length, the variations in pin diameter are very remarkable, as shown in Fig. 4. The pin diameter significantly decreases with increasing travel distance, especially when the welding speed is relatively low. For example, after an initial welding is performed at a welding speed of 25 mm/min, the pin diameter has at most decreased by 11%. After the seventh welding is performed, 27% of the pin diameter at the maximum-wear location has disappeared (see Fig. 4a). This indicates that the radial wear of the pin is appreciable and is related to the welding process parameters.

It should be pointed out that the variations in pin diameter are not the same for different locations of the pin although they all increase with increasing travel distance. With respect to the three typical locations of 0.6, 1.5 and 3.2 mm distant from the pin root, the moderate, high and low variations in pin diameter take place, respectively (see Fig. 4b). This indicates that the radial wear of the pin is uneven at different locations of the pin.

3.3. Radial wear location of the pin

The maximum and minimum wear of the pin are produced at apparently different locations of the pin and such locations change with the travel distance, as shown in Fig. 5a. With increasing travel distance, the maximum-wear location gradually reaches a distance of about 1.5 mm from the pin root, while the minimum-wear location steeply approaches a definite distance of about 3.2 mm. This indicates that the maximum wear is finally produced at a location of about one-third pin length from the pin root.

3.4. Radial wear rate of the pin

Radial wear rate of the pin is defined as the varying quantity of the pin diameter per unit travel distance of the pin, i.e. $\text{wear rate} = \text{varying quantity} / \text{travel distance}$.

As shown in Fig. 5b, the radial wear rate of the pin is changed with the travel distance. When the travel distance is

Table 2
Original size of the welding tool (mm)

Tool material	Shoulder diameter	Shoulder height	Pin diameter	Pin length
WC-Co	13.6	5.0	6.0	5.0

Shoulder height is considered to be the same as the pin length.

Table 3
Welding sequences and process parameters

Welding sequence	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Rotation speed (rpm)	2000	2000	2000	2000	1500	2000	2000
Welding speed (mm/min)	25	50	100	150	25	50	25
Travel distance (mm)	240	260	270	260	240	270	260

smaller than 1.27 m, the wear rate decreases with increasing travel distance. On the other hand, when the travel distance is greater than 1.27 m, the wear rate tends to change in the opposite direction.

The wear rates are different at different locations of the pin. With regard to the three typical locations of 0.6, 1.5 and 3.2 mm distant from the pin root, the low, high and moderate wear rates are produced, respectively, but this trend is not included in the initial welding.

The wear rate is related to the welding sequence. The maximum wear rate is always produced in the initial welding regardless of any locations of the pin.

In fact, the welding speed has a decisive effect on the wear rate. The lower the welding speed, the higher the wear rate. For example, when the welding speed increases to 150 from 25 mm/min, the wear rate at the location of 1.5 mm distant from the pin root decreases to 0.45 from 2.30 mm/m.

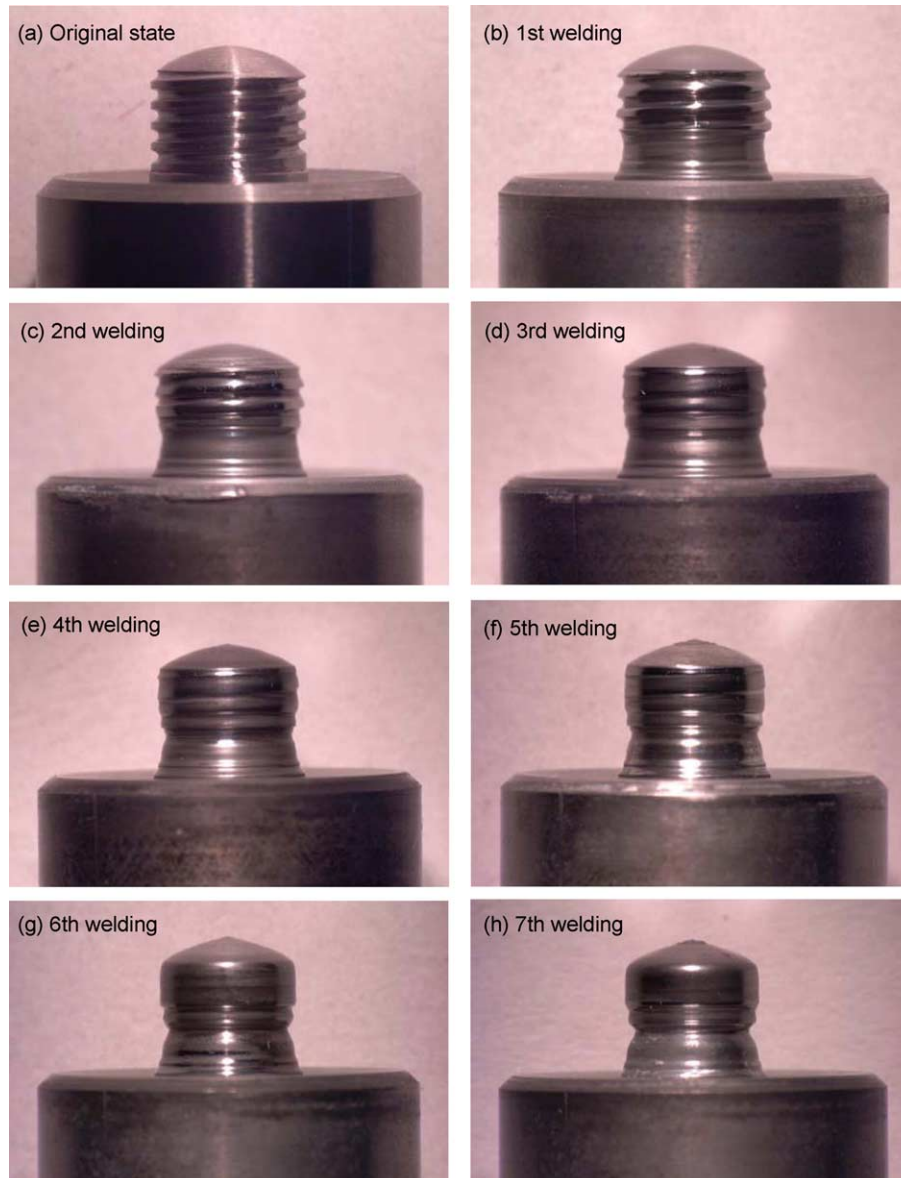


Fig. 2. Appearance of the threaded tool after each FSW experiment.

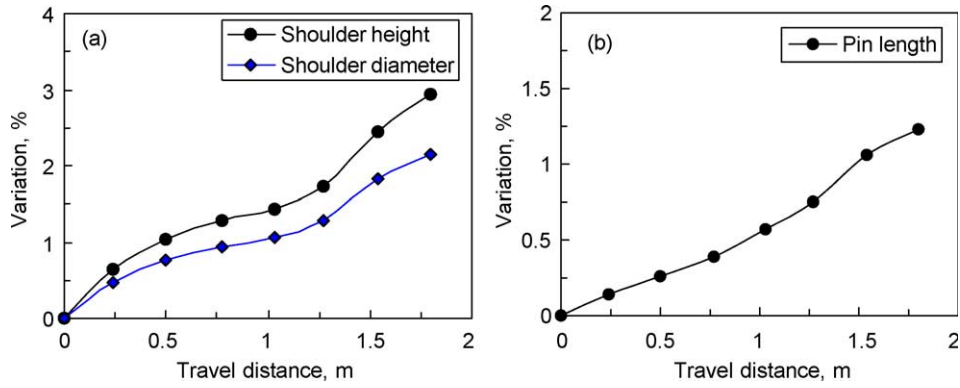


Fig. 3. Variations in: (a) shoulder size, and (b) pin length.

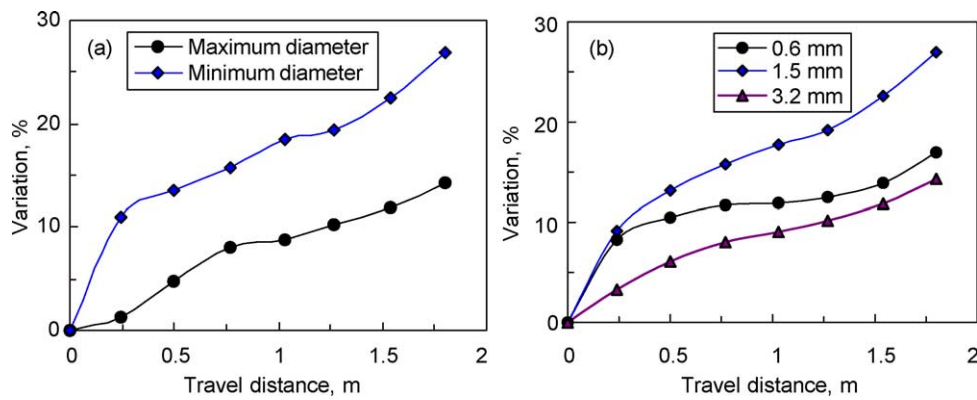


Fig. 4. Variations in pin diameter at: (a) the extreme-wear locations, and (b) typical locations.

In a word, the radial wear rate of the pin is related to many factors, and the decisive factor is the welding speed because the change of the welding speed means the change of the wear time for a definite travel distance of the pin.

4. Conclusions

(1) An appreciable tool wear is observed in the FSW of AC4A + 30 vol%SiCp AMC although the threaded tool is made of WC–Co hard alloy.

- (2) The shoulder size and pin length are changed slightly, and the radial wear of the pin is most severe for the whole tool.
- (3) The radial wear of the pin is very different at different locations of the pin, and the maximum wear is finally produced at a location of about one-third pin length from the pin root.
- (4) The welding speed has a decisive effect on radial wear rate of the pin. The lower the welding speed, the higher the wear rate, and the maximum wear rate is produced in the initial welding.

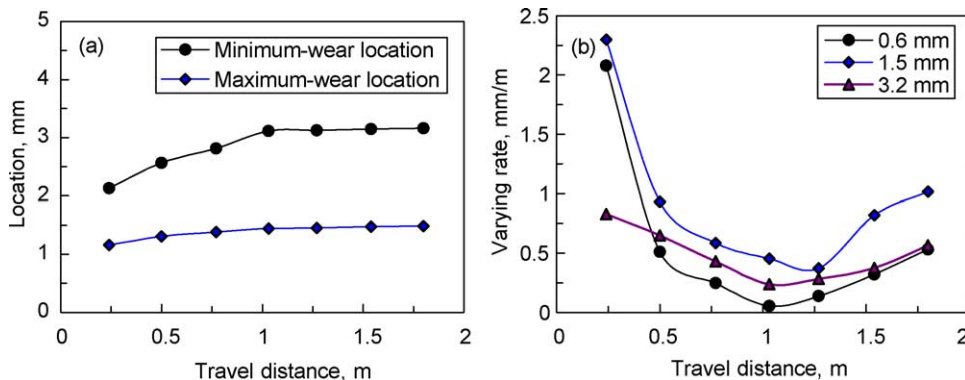


Fig. 5. (a) Extreme-wear location of the pin, and (b) varying rate of the pin diameter.

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