Microstructure and mechanical properties of friction stir welded joints of AC4A cast aluminium alloy

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AC4A cast aluminium alloy was friction stir welded, and the microstructure and mechanical properties of the joint and its component parts were examined and analysed. In the weld nugget of the weld, a large number of small silicon particles were homogeneously distributed in a continuous aluminium matrix, and the original casting voids were completely eliminated from the weld nugget, which therefore exhibited much better mechanical properties than the base material. In the thermomechanically affected zone (TMAZ) of the weld, there were short silicon plates and no void flaws, accordingly the weld composed of weld nugget and TMAZ exhibited better mechanical properties than the base material. The global joint fractured in the base material, and thus possessed the same tensile strength as the base material. These results clearly show that friction stir welding is an optimum welding process for cast aluminium alloys. MST/5913

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Introduction

Cast aluminium alloys are widely used in the transportation industries and can be arc welded in a protective atmosphere or joined by brazing.[1] Unfortunately, the welding production cost is relatively high and some welding defects such as porosity and slag inclusion are easily formed in the weld. Friction stir welding (FSW) is a promising process that can produce high quality, low cost joints.[2] This welding process is being extensively and intensively studied in order to weld various types of wrought aluminium alloys, especially heat treatable aluminium alloys that are difficult to fusion weld.[2–4] It is also being developed to weld other materials such as magnesium, titanium, copper, steel, and aluminium matrix composites.[5–10] In the present study, a cast Al–Si alloy, AC4A, was selected as the experimental material to demonstrate the feasibility of FSW. Emphasis is placed on the microstructure and mechanical properties of the joint and its components.

Experimental procedure

The base material used in this study was a 5 mm thick AC4A cast aluminium alloy plate with chemical composition and mechanical properties as listed in Table 1. The plate was cut and machined into rectangular welding samples, 300 mm long by 80 mm wide, and they were longitudinally butt welded using an FSW machine (Hitachi, SHK207-899). The welding tool size and welding parameters used in the experiments are listed in Table 2.

After welding, 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). The cross-sections of the metallographic specimens were polished with an alumina suspension, etched with Keller's reagent and observed by optical microscopy (Olympus, HC-300Z).
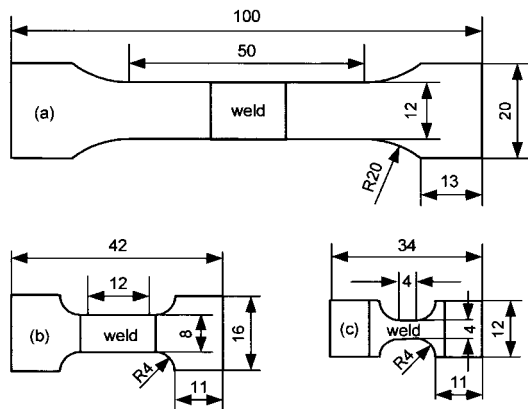
The mechanical properties of the joint and its component parts were measured by tensile tests. The configuration and size of the transverse tensile specimens were prepared according to Fig. 1, in which different size specimens were used to determine the mechanical properties of the joint and its component parts. Before the tensile tests, Vickers hardness profiles across the weld, heat affected zone and partial base material were measured along the centrelines of the cross-sections of the tensile specimens under a load of 0·98 N for 10 s using an automatic microhardness tester (Akashi, AAV-502). Tensile tests were carried out at room temperature at a crosshead speed of 1 mm min^{-1} using a computer controlled testing machine (Shimadzu, AG-10TB), and the mechanical properties of the joint or each

Table 1 Nominal compositions and mechanical properties of AC4A cast aluminium alloy

Chemical composition, wt-%												Mechanical properties		
Al	Si	Fe	Mn	Mg	Cu	Zn	Ti	Cr	Ni	Pb	Sn	Tensile strength	Proof stress	Elongation
Bal.	8–10	0·55	0·45	0·45	0·25	0·25	0·20	0·15	0·10	0·10	0·05	150 MPa	81 MPa	1·9%

Table 2 Tool size and welding parameters used in the experiments

Tool size, mm			Welding parameters			
Shoulder diameter	Pin diameter	Pin length	Tool tilt	Rotation speed	Welding speed	Revolutionary pitch
15	6	4·7	3°	1500 rev min^{-1}	200 mm min^{-1}	0·13 mm rev^{-1}

2 Cross-section and microstructural zones of typical AC4A joint

a joint; *b* weld; *c* weld nugget

1 Configuration and size of joint transverse tensile test specimens and component parts examined
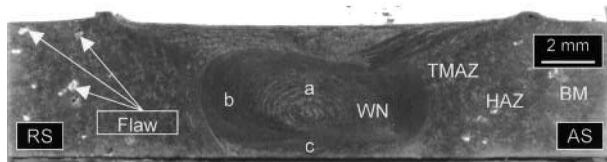
component part were evaluated using three tensile specimens.

Results and discussion

MICROSTRUCTURE

Figure 2 shows a low magnification cross-section of a typical AC4A joint. In this figure, RS and AS denote the retreating side and advancing side of the joint, respectively. The microstructural zones of the joint include the unaffected base material (base material), heat affected zone (HAZ) and weld. The weld is composed of the thermomechanically affected zone (TMAZ) and weld nugget. The core, side and bottom of the weld nugget are marked by a, b, and c, respectively. The morphology, size, and distribution of the silicon phase in the Al–Si alloy and its joint are examined and analysed because they are the decisive factors that influence the mechanical properties of the alloy and its joint.

The microstructures of the base material, HAZ, and TMAZ are shown in Fig. 3. The base material is a hypo-eutectic Al–Si alloy (Table 1), and has a coarse microstructure in which the eutectic comprises large silicon plates in a continuous aluminium matrix (Fig. 3*a*). In addition, there are some void flaws in the base material (Fig. 2). Compared with the base material, the HAZ does not change

in morphology, size, and distribution of silicon phase (Fig. 3*b*) because the friction heat produced during the FSW is not enough to result in the solution and growth of the original silicon plates. However, the microstructure of the TMAZ is, to some extent, different from that of the base material. Large silicon plates have changed into short plates that have a specific orientation (Fig. 3*c*), and no void flaws are present (Fig. 2).

Figure 4 shows the microstructure at different locations in the weld nugget. There are two kinds of alternating structural bands in the core of the weld nugget, one with large silicon particles and the other with small silicon particles (Fig. 4*a*). The orientations of these silicon particles are related to their location in the core of the weld nugget. In the side and bottom of the weld nugget the silicon phase assumes a particulate form. A large number of small silicon particles are homogeneously distributed in the aluminium matrix. Among them, the silicon particles in the side of the weld nugget have an orientation approximately perpendicular to the top surface of the base material (Fig. 4*b*), and the orientation of the silicon particles in the bottom of the weld nugget is approximately parallel to the top surface of the base material (Fig. 4*c*). Under the twofold effects of friction heating and mechanical stirring, the original large silicon plates in the base material have been broken into small silicon particles in the weld nugget, and such particles are dispersed in the continuous aluminium matrix. In addition, the original casting voids are completely eliminated from the weld nugget (Fig. 2).

In practice, the microstructure of an Al–Si alloy, especially the size and form of the silicon phase in the alloy, has a decisive effect on the mechanical properties.[1] When the eutectic comprises large silicon plates in a continuous aluminium matrix, the alloy exhibits low ductility because of the brittle nature of the large silicon plates. When the eutectic is refined and the silicon phase assumes a fibrous or particulate form, both ductility and tensile strength are much improved. In other words, the
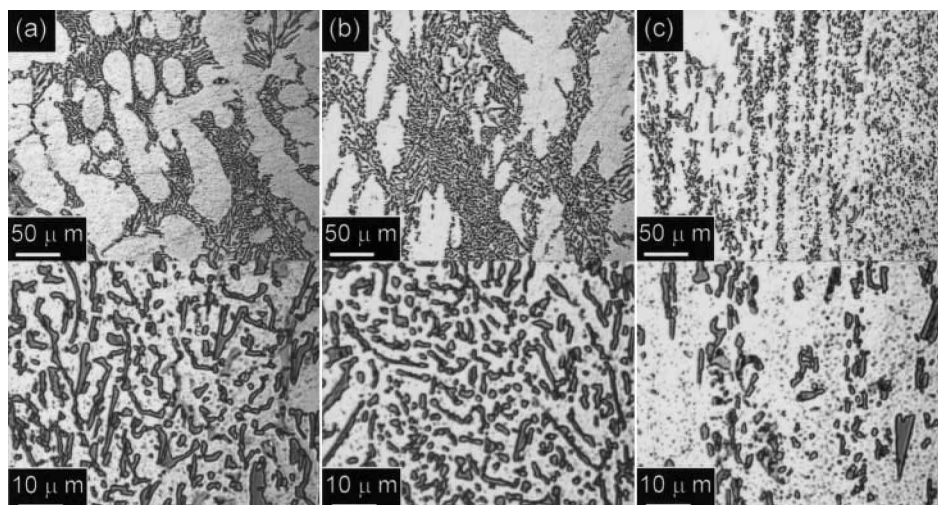
a base material; *b* HAZ; *c* TMAZ

3 Microstructure of typical zones of the joint
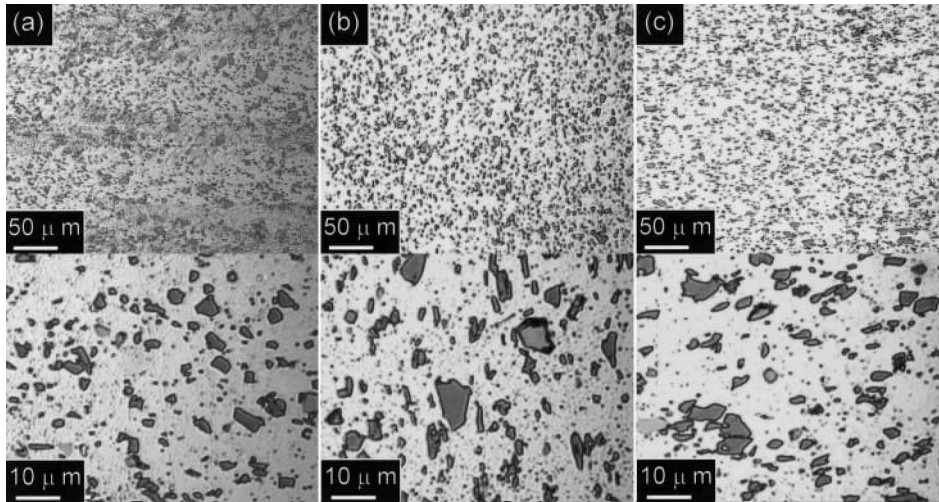
a, *b*, *c* correspond to positions a, b, and c marked in the weld nugget (WN) in Fig. 1

4 Weld nugget microstructures

smaller the size of the silicon phase particles, the better the mechanical properties of the alloy. Therefore, the mechanical properties of the Al – Si alloy must have been improved by the FSW because of the decrease in size of the silicon phase. Similarly, the breakup of constituent particles is also present in the friction stir weld of metal matrix composites (MMC), resulting in the increase in hardness of the MMC weld.[9]

MECHANICAL PROPERTIES

Table 3 shows the tensile test results of the joint and its component parts. With regard to the global joint, the tensile strength, proof stress and elongation are 150 MPa, 85 MPa, and 1·6%, respectively. The joint is fractured in base material far distant from the weld. From the viewpoint of the component parts of the joint, the fracture produced in the base material instead of the weld implies that the tensile strength of the weld is higher than that of the base material.

In order to evaluate the tensile properties of the weld, the gauge length of the tensile specimens was reduced to 12 mm (Fig. 1). The tensile test results for the weld are listed in Table 3. It can be seen from Tables 3 and 1 that the tensile properties of the weld are higher than those of the base material. In addition, the weld is fractured in the TMAZ instead of the weld nugget. This implies that the weld nugget has a higher tensile strength than the TMAZ.

In order to further evaluate the tensile properties of the weld nugget, the gauge length of the tensile specimens was reduced to 4 mm (Fig. 1). The tensile strength, proof stress, and elongation of the weld nugget were measured to be 251 MPa, 96 MPa and 14·4%, respectively. This indicates that the tensile properties of the weld nugget are much higher than those of the base material. The weld nugget is also shown to have higher tensile properties than the weld.

DISCUSSION

The mechanical properties of the joint and its component parts are dependent on their corresponding microstructures. As mentioned above, there are some void flaws and many large silicon plates with a brittle nature in the base material; therefore the base material exhibits poor mechanical properties (Table 1). Compared with the base material, the weld nugget possesses a large number of small silicon particles, and original casting voids are completely eliminated; consequently the mechanical properties of the weld nugget are much better than those of the base material (Table 3). In the weld, apart from the weld nugget having good mechanical properties, the TMAZ also has relatively good mechanical properties because of the transition of large silicon plates into short plates, and the elimination of void flaws. The weld, which comprises weld nugget and TMAZ, exhibits better mechanical properties than the base material (Table 3). With respect to the global joint, one of its component parts is the partial base material that has a coarse microstructure and low tensile strength, therefore the joint fractures in the base material where the tensile strength is the same as the overall base material. However, the elongation of the joint is slightly lower than that of the base material (Table 3). The reason for this is that the higher strength weld exhibits lower plastic deformation than the low strength base material under the same tensile load conditions.

Conclusions

The microstructure and mechanical properties of the friction stir welded joint of an AC4A cast aluminium alloy were examined and analysed. With regard to the component parts of the joint, the weld nugget comprises a large number of small silicon particles homogeneously distributed in a continuous aluminium matrix from which the original casting voids are completely eliminated; therefore the weld nugget exhibits much better mechanical properties than the base material. In the TMAZ, there are short silicon plates and no void flaws; accordingly the weld, composed of weld nugget and TMAZ, has better mechanical properties than the base material. The global joint is fractured in the base material, and thus possesses the same tensile strength as the

Table 3 Tensile properties and fracture locations of the joint and its component parts

Test object	Tensile strength, MPa	Proof stress, MPa	Elongation, %	Fracture location
Joint	150	85	1·6	Base material
Weld	179	87	5·3	TMAZ
Weld nugget	251	96	14·4	Weld nugget

base material. These results clearly show that FSW is an optimum welding process for cast aluminium alloys.

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