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EFFECTS OF ROTATIONAL VELOCITY ON MICROSTRUCTURES AND MECHANICAL PROPERTIES OF SURFACE COMPENSATION FRICTION STIR WELDED 6005A-T6 ALUMINUM ALLOY

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Abstract:

Surface compensation friction stir welding (SCFSW) is successfully applied to weld 6005A-T6 aluminum alloy in order to eliminate disadvantages caused by flash and arc corrugation. The effects of rotational velocity on the microstructures and mechanical properties of SCFSW joints are investigated. The joints with equal thickness with respect to the workpiece to be welded are obtained using 4 mm thick plates with a convex platform in this study. The results show that welding process parameters exert a significant influence on the microstructures of nugget zone (NZ). Tensile strength and elongation of joints are both firstly increased and then decreased with an increase in the rotational velocity from 800 rpm to 1500 rpm under a constant welding speed of 200 mm/min. When the rotational velocity is 1300 rpm, the tensile strength and elongation reach the maximum values of 226 MPa and 6.5%, which are 75% and 67% of base metal (BM), respectively. The fracture surface morphology represents the typical ductile fracture. The hardness of NZ is lower than that of BM and the lowest hardness of joint is located at thermo-mechanically affected zone (TMAZ) on the advancing side (AS).

1 Introduction

Friction stir welding (FSW) is a maturing solid state joining process during which some defects occurring in conventional fusion welding techniques could be avoided. It has been widely used in automotive, aerospace, electronics and shipbuilding [1-3]. FSW has potential advantages to join low melting point alloys, especially aluminum alloys [4]. 6005A-T6 aluminum alloy is one of medium-strength aluminum alloys, which is extensively applied to high speed railway at home and abroad because of excellent extrusion forming, good corrosion resistance and weldability [5-8]. Lee et al. studied mechanical property of friction stir welded 6005A aluminum alloy and showed that 85% of BM tensile strength of joint could be reached and the weakest location of joint lied in heat affected zone (HAZ) [7]. Simar et

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al. also discussed relationship between mechanical properties and process parameters of FSW of 6005A aluminum alloy and found that the faster the welding speed was, the smaller second- phase particle strengthening, which resulted in a stronger and narrower HAZ joint [8].

It is well-known that flashes and arc corrugation are the typical defects of FSW joint. Some researchers have also investigated into such defects of FSW joint and showed that those defects influence the quality of the welding joint [9-12]. Crawford et al. drew the same conclusion, namely, that formation of flash are to be attributed to the high temperature distribution beyond the shoulder region [11]. Wang et al. illustrated that the occurrence of flashes together with arc corrugation caused local stress concentration easily [12]. Therefore, in this study, in order to eliminate the disadvantages generated by flash and arc corrugation, SCFSW is used to weld 6005A-T6 aluminum alloy. Moreover, the effect of rotational velocity on mechanical properties of SCFSW is further discussed.

2 Experimental

The method of surface compensation is that the same additional material as BM is added into the butt weld location of joint before welding. A schematic diagram of SCFSW is shown in Fig 1. After welding, the excess material beyond top surface of the workpiece is removed by grinding or milling methods. Then a joint with equal thickness relative to the workpiece without flash and arc corrugation is obtained.

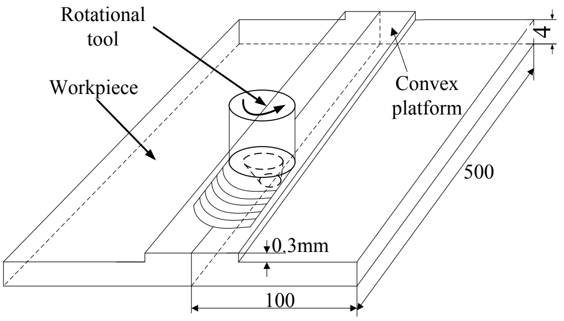

Figure 1. Schematic diagram of SCFSW.

The material used in the SCFSW experiment was 6005A-T6 aluminum alloy plate with the thickness of 4 mm. The tensile strength and elongation of BM at room temperature are 298 MPa and 9.7%, respectively. In this study, the plunge depth is 0.1 mm. To avoid the influence of plunge depth on the welding joint, the thickness of convex platform is chosen to be 0.3 mm and the width of the convex platform is slightly larger than shoulder diameter of the tool, so the dimensions of the convex platform are 500 mm× 8 mm×0.3 mm. The rotational tool is made of H13 tool steel. The tool consists of the concentric circles-flutes shoulder of 14 mm diameter and the right-screw pin of 4.1 mm in length whose diameters of pin bottom and pin tip are 5 mm and 3 mm, respectively. The SCFSW experiment was carried out with a FSW machine (FSW-3LM-4012) at a constant welding speed of 200 mm/min and various rotational velocities varying from 800 rpm to 1500 rpm, while the tilting angle was 2.5°. Prior to welding, surfaces of plates were polished with 240-grit emery paper and cleaned with acetone in order to wipe off the oxide layer.

After welding, three tensile specimens were prepared for each joint perpendicular to the welding direction according to GB/T 2651-2008(equivalent to ISO 9016: 2001) [13]. Besides, an average value was presented for discussion. The tensile tests were carried out at a constant crosshead speed of 5 mm/min using a universal tensile machine. Micro-hardness experiment of the joint was carried out with a micro-hardness tester at test load of 100 N for 10 s. The fracture surface of tensile specimen was observed with a scanning electron microscope (SEM).

3 Results and discussion

3.1 Macrostructure

Fig. 2 shows macrostructures of SCFSW joints under various rotational velocities. In comparison with conventional FSW joint, it is seen that the flash and arc corrugation emerge on the surface of the joint causing thickness reduction. However, the thickness of NZ due to convex platform is higher than that of the workpiece. After welding, the convex platform would be removed by milling. Then the equal thickness joint without flash and corrugation is attained, while shoulder affected zone (SAZ) is reduced. Moreover, the disappearance of arc corrugation also slows down the corrosion and increases the beauty of the joint. When rotational velocity is 800 rpm, the cavity defect is observed in AS, which results from insufficient heat input and material flow (Fig. 2a). When rotational velocity is increased to 1000 rpm, the cavity defect is obviously decreased. By further increasing the rotational velocity to 1300 rpm and 1500pm, no defect is observed because of better heat generation and plastic flow.

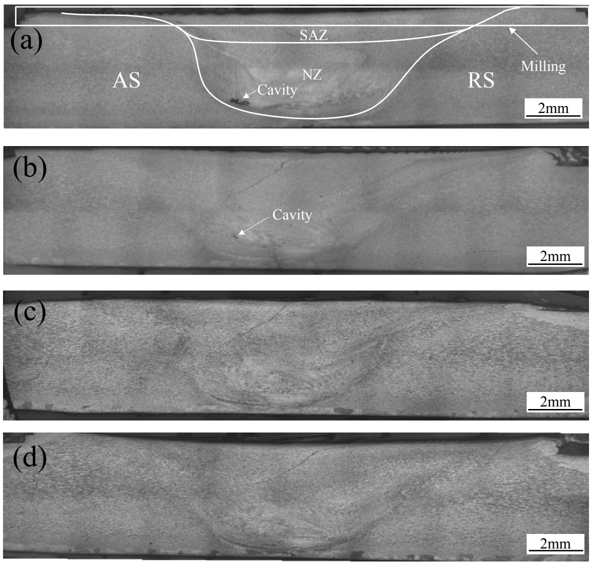

Figure 2. Macrostructure of SCFSW joints under various rotational velocities: (a) 800, (b)1000, (c)1300 and (d)1500 rpm.

Fig. 3 shows the microstructures in the NZ of joints under various rotational velocities. During FSW, the material of NZ is acted on with pin tools, and consequently it experiences higher temperature and strain rate. Therefore, the microstructure is characterized by fine and equaxied grains due to dynamic recrystallisation [14]. It is observed that the size of grains varies with an increase in rotational velocity, which is attributed to synergetic effects of strain rate of materials and heat input. The increase of rotational velocity is beneficial to increase strain rate by decreasing the grain size while the increase in heat input easily results in coarse grains. It can be seen that the grains are refined under the rotational velocities varying from 800 rpm to 1300 rpm, in which the function of strain rate is dominant (Fig. 3a~c). When the rotational velocity increases to 1500 rpm, the dynamic recrystallised grains of the NZ have enough time to become coarse grained due to the larger heat input (Fig. 3d).

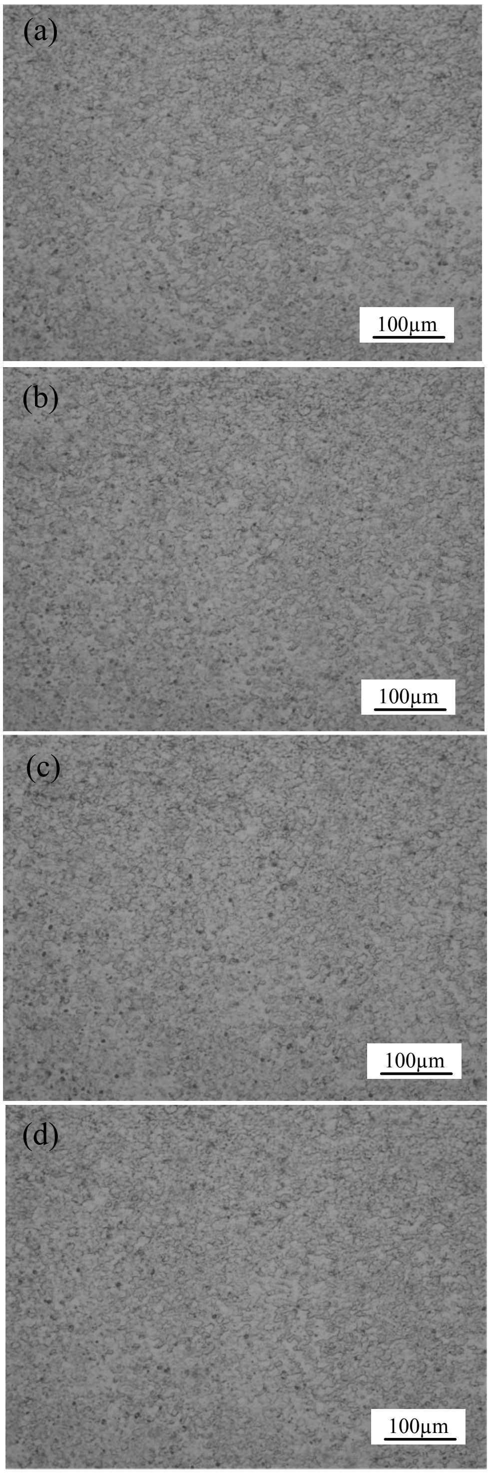

Figure 3. Microstructures in the NZ of joints under various rotational velocities: (a) 800, (b)1000, (c)1300 and (d)1500 rpm.

3.2 Mechanical properties

The effect of rotational velocity on the tensile strength and elongation of SCFSW joints is shown in

Fig. 4. Meanwhile, Fig. 5 shows stress and strain of the joints at different rotational velocities. It is distinctly observed that rotational velocity exerts a profound influence on mechanical properties of SCFSW joints. By increasing the rotational velocity, tensile strength and elongation of the joint is firstly increased and then decreased. When the rotational velocity is 1300 rpm, the maximum values of tensile strength and elongation are up to 226 MPa and 6.5%, equivalent to 75% and 67% of BM, respectively.
According to the formula of heat input under quasi stable state [15]:

$$Q_s = \frac{5}{6}\omega\tau_s(T)(R_0{}^3 - r_0{}^3) \qquad (1)$$

Where Q_s is heat input; ω is rotational velocity, r_0 is the diameter of rotational pin; R_0 is the diameter of shoulder; T is an arbitrary temperature during FSW process; τ_s is shear yield strength of material, which is decreased with an increase in temperature. Therefore, heat input per unit length of weld influences rotational velocity(ω) and shear yield strength(τ_s) thus affecting plastic flow behavior.

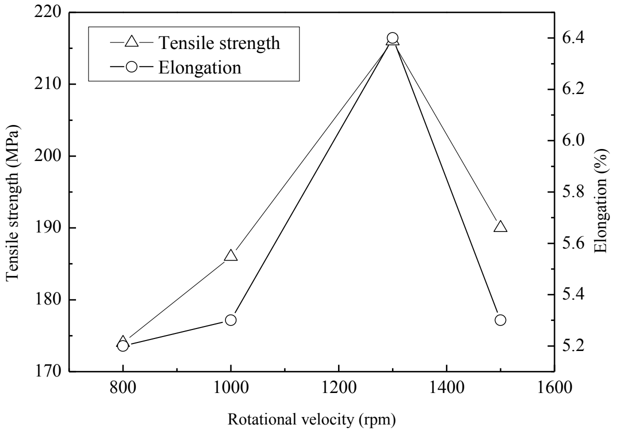

Figure 4. Tensile strength and elongation of joints under various rotational velocities.

When the rotational velocity is 800 rpm, inadequate frictional heat produced by rotational tool pin is lower whereas the shear yield strength is higher. It follows that higher flow stress cannot make material plastic enough, and this results in insufficient plastic flow behavior and the formation of cavity.

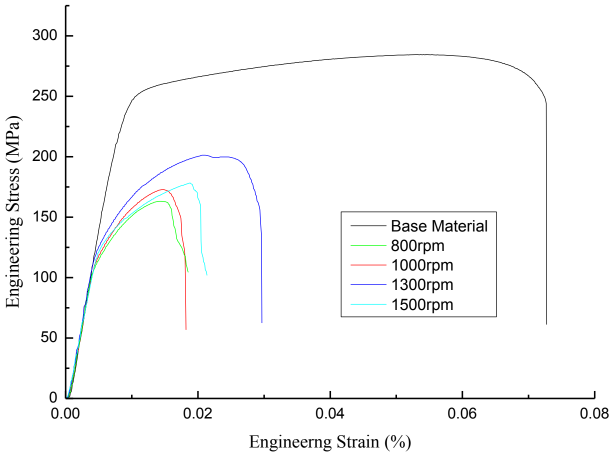

Figure 5. Engineering stress and strain of BM and joints under various rotational velocities.

When the rotational velocity reaches 1000 rpm, an increase in heat input and decrease in shear yield strength produce mechanical properties characterized by increasingly good plastic flow. By increasing the rotational velocity to 1300 rpm, the tensile strength and elongation are dramatically increased. This is brought about by increasing the rotational velocity, which in turn increases the heat input and decreases the shear yield strength. Moreover, the increasing rotational velocity relative to welding seed is beneficial to improve the plastic flow, which consequently results in sufficient mixture of materials and disappearance of cavity defects thus enhancing mechanical properties. However, by increasing the rotational velocity further to 1500 rpm, higher peak temperature and longer cooling time are attained in NZ, which subsequently causes higher residual stress and enlarges the softening degree of the joint, thus deteriorating mechanical properties of the joint.

3.3 Fractography

The effect of rotational velocity on fracture surface morphologies of joints is shown in Fig. 6. It can be observed that all the fracture surface morphologies of joints consist of an amount of dimples of varying size and shapes, indicating the typical ductile fracture. A larger number of dimples are shallower and smaller in Fig.6a; the observed cavity defect formed in NZ (Fig.2a), shows less ductility. When the rotational velocity is 1000 rpm, the ductility slightly improved because of the bigger size of dimples and small cavity defect (Fig.2b and Fig.6b).

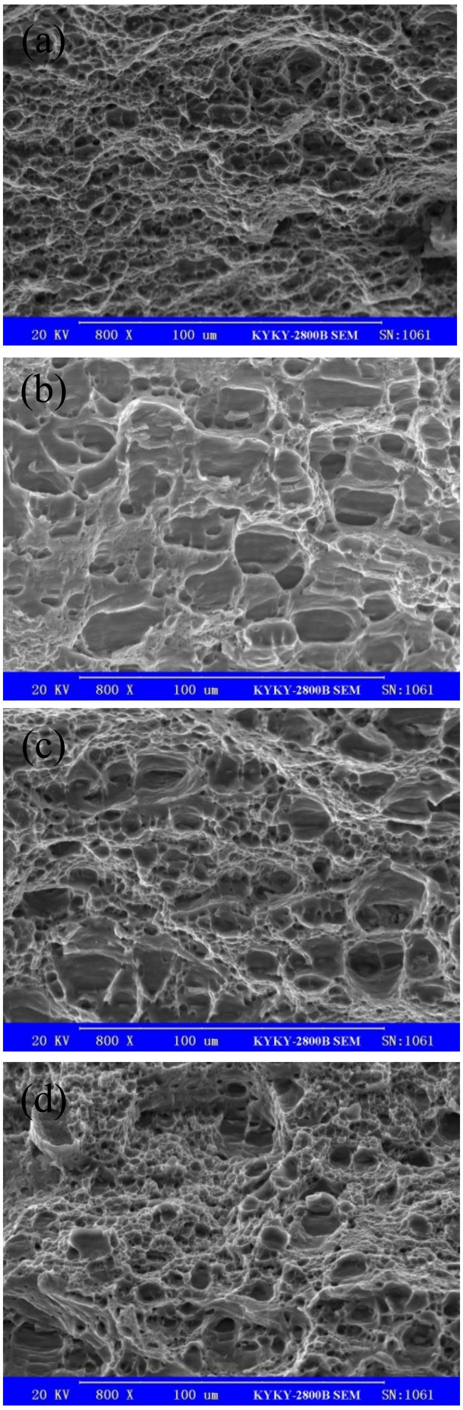

Figure 6. Fracture surface morphologies of joints under different rotational velocities: (a) 800, (b)1000, (c)1300 and (d)1500 rpm.

By further increasing the rotational velocity to 1300 rpm, the fracture surface contains large amounts of bigger and deeper dimples which exhibits the best ductility which does not exceed the ones in BM. In Fig.6d, smaller and shallower dimples with varying sizes when compared to Fig.6c are observed. Generally speaking, the deeper, the bigger and the larger the dimples, the more ductile they are. Therefore, the ductility at the rotational velocity of 1500 rpm is lower than that at the velocity of 1300 rpm. Under various rotational velocities, integrated cavity defects, the shape of dimples, and fracture surface morphologies are consistent with the change of elongation.

3.4 Microhardness

Microhardness of the cross-section of the joint under various rotational velocities is measured to evaluate the effect of rotational velocity on hardness, as shown in Fig.7.

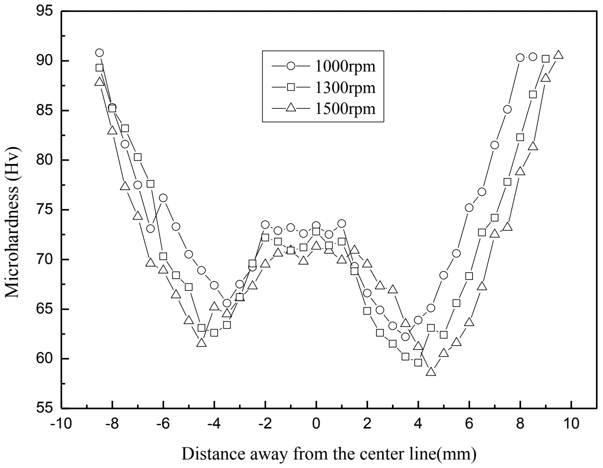

Figure 7. Hardness of SCFSW joints under different rotational velocities.

It is found that distribution of hardness presents an asymmetrical ‘W’ curve. The curve of hardness is made up of NZ, TMAZ, HAZ and BM. It can be observed that the hardness decreases from BM to HAZ, which is due to the fact that the material of HAZ undergoes only a thermal cycle but not plastic deformation, which eventually results in coarse-grained materials. The TMAZ of AS region is not as hard as that of RS. This is because that material in the AS experiences higher plastic strains than RS, which results in plastic deformation causing higher temperature. Moreover, the formation of flash on RS also takes away a portion of heat, and consequently material in the TMAZ of AS is severely softened. However, the hardness values of NZ are higher than those of HAZ and TMAZ, which are due to the existence of fine and equiaxed grains formed in NZ.

It can be also found that an increase in the rotational velocity is beneficial to improve the hardness of NZ, but the change is negligible. However, it can be clearly seen that by increasing the rotational velocity, the zone is enlarged, which results from higher welding temperature and longer cooling time.

4 Conclusions

In order to avoid disadvantages of arc corrugation and flashes on conventional FSW joint, SCFSW was developed to weld a 4 mm thick 6005-T6 aluminum alloy workpiece. The following conclusions can be summarized:

(1) For SCFSW technology, the removal of excess material beyond the top surface of workpiece causes the decrease of SAZ width, which is beneficial for the quality of the welding joint.

(2) At the rotational velocity of 800 rpm or 1000 rpm, the appearance of cavity in AS of NZ largely reduces the tensile strength of the welding joint. By increasing the rotational velocity, the cavity defect can disappear and the sound joint can be attained, but on the other hand, higher heat input enlarges the region and degree of softening.

(3) The tensile strength and elongation reaches 224 MPa and 6.5%, which are 75% and 67% of BM, respectively.

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