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Effect of cooling conditions on microstructure and mechanical properties of friction stir welded 7055 aluminium alloy joints

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ABSTRACT

The microstructure and mechanical properties of friction stir welded 7055 aluminium alloy under air cooling and water cooling were investigated by means of hardness and tensile testing, optical microscopy and transmission electron microscopy. Water cooling results in reduced softening in the weld zone and therefore higher tensile strength compared to air cooling. Fracture generally occurs within the thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) on the retreating side in joints welded under air cooling but shifts towards the TMAZ and nugget zone (NZ) in the joints welded under water cooling. The fracture surfaces are generally flat for the air-cooled joint, but exhibits a zig-zag feature for the water-cooled joint. The mechanical behaviour of the weld has been discussed in light of the change in grain structure and precipitation in the NZ, TMAZ and HAZ caused by cooling conditions.

1. Introduction

Friction stir welding (FSW) is a solid-state joining technique and has been successfully employed to join aluminium alloys, such as high strength 7XXX aluminium alloys [1]. During FSW, a rotating tool is plunged into the interface between fixed work pieces and moved along the interface. The strong frictional interaction between the rotating tool and the work pieces can introduce high temperature and high plastic deformation, resulting in material flow around the tool. However, the thermal and mechanical effect results in the dissolution or coarsening of strengthening precipitates in the weld zone; consequently, the mechanical strength of the joints are generally lower than that of the base alloy.

Numerous investigations have been carried out on the effects of welding parameters on the mechanical properties of FSW joints of precipitation hardening aluminium alloys. It has been shown that apart from intrinsic FSW parameters such as tool rotation rate and transverse speed, cooling conditions can also influence the weld quality and rapid cooling generally improves the mechanical properties of the resultant joints [2–11]. There are however, differing perspectives on cooling effects relating to FSW joints of 7XXX alloys. For instance, Fratini et al. [2,3] found that water cooling may enhance FSW joint strength of AA7075-T6 aluminium alloy. Wang et al. [4] showed that underwater FSW of spray-formed 7055 aluminium alloy leads to higher tensile properties than traditional welding in air. However, after comparing the tensile properties of FSW joints of 7039 aluminium alloy obtained under ambient natural cooling, compressed air cooling, liquid nitrogen cooling and water cooling, Sharma et al. [5] found that the highest ultimate tensile strength and elongation were obtained under ambient natural cooling rather than water cooling. Fu et al. [6] investigated submerged FSW of 7050 aluminium alloy and found that strength was the highest for the joint welded in hot water, intermediate in cold water and the lowest in air. Thus, it is evident that cooling conditions can change the thermal boundary conditions and, consequently, exert complex effects on the microstructure and mechanical properties of the resultant FSW joints. Therefore, it is of scientific interest and of technological importance to develop a better understanding of the effect of cooling conditions.

For high strength 7XXX aluminium alloys, previous investigations on the effect of cooling conditions were primarily focused on 7075, 7050, 7039 aluminium alloys [1–3,5,6], with fewer on 7055 aluminium alloy [4]. Compared with these alloys, 7055 aluminium alloy contains a higher quantity of alloying elements and possesses higher strength; moreover, it is quench sensitive, specifically, the mechanical properties tend to deteriorate rapidly with the decrease of quenching rate [12]. In this work, the effect of cooling conditions on the mechanical properties

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Table 1
Tensile properties of base alloy and FSW joints of 7055 aluminium alloy.

Materials conditions	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Ultimate tensile strength efficiency (%)	Elongation efficiency (%)
Base alloy	630 ± 8	584 ± 10	12.9 ± 1.5	–	–
Air-cooled joint	417 ± 11	368 ± 11	3.4 ± 1.1	0.66	0.26
Water-cooled joint	457 ± 9	440 ± 12	4.0 ± 1.3	0.73	0.31

of FSW joints of 7055 aluminium alloy has been investigated using optical microscopy (OM), conventional transmission electron microscopy (TEM) and high resolution transmission electron microscopy (HRTEM).

2. Experimental Procedure

Rolled sheets of 7055 aluminium alloy with a thickness of 1.8 mm, with the chemical composition (wt%): Zn, 7.68, Mg 1.98, Cu, 2.21, Zr, 0.12, Fe < 0.12, Si < 0.10, Al, Bal., were used. The sheets were solution heat treated at 470 °C for 30 min in an air furnace, quenched in water (≈20 °C) and then artificially aged at 120 °C for 24 h and then at 160 °C for 6 h. The Vickers hardness of the aged sheets is 205 ± 3 HV3. The ultimate tensile strength, yield strength and elongation at room temperature are given in Table 1.

The diameter of the tool shoulder for FSW was 8 mm, the pin diameter was tapered from 2.0 mm at the tool shoulder to 1.5 mm at the tip and the pin length was 1.7 mm. The aged sheets were welded with a tool rotation speed of 1200 rpm and tool traverse speed of 100 mm/min, a tilt angle of approximately 1° was maintained; the welding direction was perpendicular to the rolling direction (RD) of the sheet; after welding, the joints were cooled naturally in still air or by spraying cold water using a nozzle kept about 25 mm behind the tool. Fig. 1 shows photographs of air-cooled and water-cooled joints. After holding at room temperature for ten days, the joints were subjected to microstructure examination, hardness and tensile testing.

Vickers hardness testing was carried out on the polished joint sample with a spacing of 0.5 mm from base alloy on the advancing side (AS) to retreating side (RS) perpendicular to the weld centerline, as schematically shown in Fig. 2. The testing was performed on a Model HV-10B hardmeter with a load of 3 kg for a dwell time of 15 s. Tensile samples were cut perpendicular to the welding direction (Fig. 2) and thus parallel to the RD of the sheet; tensile testing was performed on a CSS-4410 machine according to GB/T228–2010 at room temperature, and three samples were tested for each state. The fracture surfaces were examined using a FEI Quanta 200 scanning electron microscopy (SEM).

Metallographic specimens were cut from the joint, ground and then polished with a diamond paste; after etching in a reagent composed of 1 ml HF, 16 ml HNO_3, 3 ml CrO_3 and 83 ml H_2O, then thorough rinsing in deionized water and being dried in a cold air stream, they were examined on an MX-3000 optical microscope to investigate grain structure. Thin foils were cut from the top surface of the joint for TEM and HRTEM examination; they were thinned to a thickness of about 0.08 mm, punched into a disk with 3 mm in diameter, then electropolished using 20% HNO_3 + 80% CH_3OH solution at −20 °C, and finally examined on a TECNAI G^2 20 TEM operated at 200 kV.

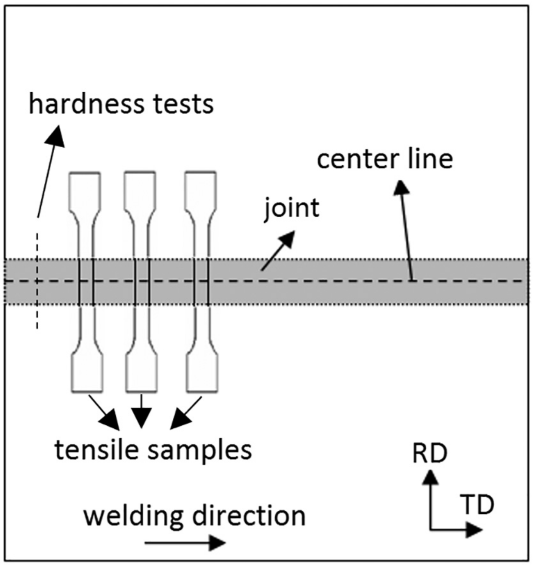

Fig. 2. Schematic of hardness tests and tensile samples cut from the joint (RD: rolling direction of the base alloy, TD: transverse direction of the base alloy).

3. Results and Discussion

3.1. Microstructure of the Base Alloy

Fig. 3 shows an optical image of a cross section of the base alloy after etching. The grain structure is typical of Zr-containing 7XXX aluminium alloys sheet [13–16]. The bright zones are recrystallized grains, while the dark zones are unrecrystallized grains which include subgrains, as shown in Fig. 4(a). Most subgrains have a size in the range from 1 μm to 3 μm. A number of Al_3Zr dispersoids with size of about 25 nm can be seen at subgrain boundaries and in the interior of subgrains. It is known that Al_3Zr dispersoids can effectively retard migration of grain boundaries [15,16], leading to partial recrystallization. Moreover, as shown in Fig. 3, recrystallized grains exhibit band distribution along RD and layered distribution along normal direction (ND) because of the long thin bands distribution of Al_3Zr dispersoids after rolling deformation as revealed in previous work for this alloy [16]. The size of recrystallized grains is not uniform. The largest ones have dimensions of about 170 μm along RD and about 12 μm along ND; while the smaller grains have dimensions of about 7 μm along both RD and ND.

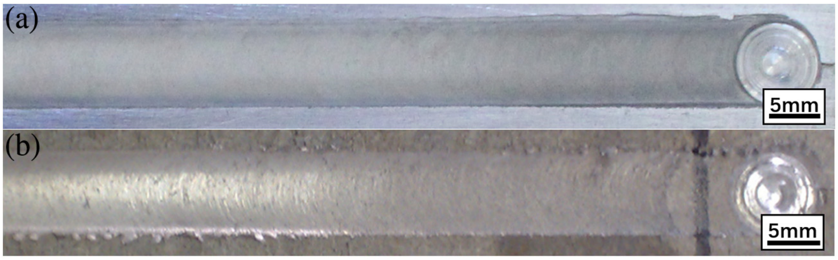

Fig. 1. Photographs of (a) air-cooled and (b) water-cooled FSW joints of 7055 aluminium alloy.