Journal of Materials Science & Technology 31 (2015) 953–961

Contents lists available at ScienceDirect

Journal of Materials Science & Technology

journal homepage: www.jmst.org

Influence of Test Temperature on the Tensile Properties along the Thickness in a Friction Stir Welded Aluminum Alloy

Weifeng Xu [1],*, Jinhe Liu [1], Daolun Chen [2]

[1] State Key Laboratory of Solidification Processing, Shaanxi Key Laboratory of Friction Welding Technologies, Northwestern Polytechnical University, Xi'an 710072, China

[2] Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, Canada M5B 2K3

ARTICLE INFO

Article history:
Received 13 January 2015
Received in revised form
17 April 2015
Accepted 11 May 2015
Available online 10 July 2015

Key words:
Friction stir welding
Aluminum alloy
Microstructure
Tensile properties
Strain hardening
Test temperature

The aim of this study was to evaluate microstructures and the influence of test temperature on the tensile properties, strain hardening behavior and fracture characteristics of friction stir welded (FSWed) 2219-T62 aluminum alloy thick plate joints. A fine and equiaxed recrystallized grain structure had no significant change in grains at the top of weld nugget zone (WNZ) at a rotational rate of 500 r/min compared with 300 r/min, but the grains and second-phase particles at the middle of WNZ exhibited obvious coarsening. The yield strength, ultimate tensile strength and joint efficiency were observed to decrease with increasing test temperatures. However, the elongation presented a contrast trend. Compared with the middle and bottom slices, the top slice (216 and 342 MPa) had a higher strength and a lower elongation (8.5%) at different test temperatures. Hardening capacity and strain hardening exponent of bottom slices were higher than those of the top and middle slices. Both of them at room temperature (RT) were bigger than those at higher temperature (HT) and lower temperature (LT). The FSWed joints basically failed in the border area between the thermo-mechanical affected zone (TMAZ) and heat-affected zone (HAZ) of the top slice, and in the HAZ of the middle or bottom slices, while the fracture surfaces exhibited dimple fracture characteristics at different test temperatures.

1. Introduction

To reduce anthropogenic climate-changing, environment-damaging, costly and human death-causing emissions, a significant increase in fuel efficiency of vehicles is required[1,2]. Therefore, aerospace and automotive manufacturers are continuously looking for effective methods to achieve this goal. One of the popular methods to increase fuel efficiency is to use auto-body parts made of stronger materials, which will help in down-gauging, leading to a decrease in vehicle weight[2,3]. Advanced high-strength aluminum alloy is a family of such materials and is also lightweight, which can be used to replace the conventional heavy materials used in aerospace and auto-body structures. 2219Al-T62 alloy, being one of the high-strength aluminum alloys, is being increasingly used in the aerospace industry. The structural applications of aluminum alloys unavoidably involve welding and joining[4,5]. The welding of aluminum alloys is fairly challenging using the conventional fusion welding techniques, e.g., gas metal arc welding (GMAW)[6], gas tungsten arc welding (GTAW)[6], plasma arc welding (PAW)[7] and electron beam welding (EBW)[8], with a joint efficiency of about 50%-70% due to the formation of flaws such as voids and hot cracks.

Friction stir welding (FSW) is a relatively new solid-state joining technique, which was developed by The Welding Institute, UK, in 1991[5]. This technique has been termed "green" technology due to its energy efficiency and environmental friendliness. FSW has been successfully used to join aluminum alloys, especially the precipitation-hardened (2xxx, 6xxx and 7xxx) ones[4–6,9,10]. Based on the microstructure features, several zones were identified on the cross-section of FSW joint, such as weld nugget zone (WNZ), thermo-mechanically affected zone (TMAZ), heat-affected zone (HAZ) and base material (BM). Severe plastic deformation and high temperatures in the WNZ and partial TMAZ resulted in grain refinement, texture development, and dissolution or re-precipitation of precipitates. The partial TMAZ appeared due to the shear stress along the plastic flow of material, resulting in elongated grains along the direction of maximum shear stress. In the HAZ only a slight growth of the grains, and dissolution or coarsening of the precipitates occurred. The problem related to these changes in the microstructure was the softening of the FSWed joints, including that along the thickness direction of plate in the FSWed thick plate joint.

A lot of work has been done to optimize the welding process parameters, such as the effects of welding speed, rotational rate,

---

* Corresponding author. Ph.D.; Tel.: +86 29 88492624; Fax: +86 29 88492624.
E-mail address: xwf1982@nwpu.edu.cn (W. Xu).

http://dx.doi.org/10.1016/j.jmst.2015.07.005

welding tool geometry, etc., which have been well documented in Xu et al. [5–7,9–13]. For example, Ji et al.[11] studied how to avoid the root flaws by changing the design of friction stir welding tool. Recently, Zhang et al.[12] used a composite backplate in FSW of AA2024 alloy and observed significantly the refinement of grain sizes and the improvement of tensile strength and elongation. Strain hardening (or work hardening) is one of the most important considerations in the evaluation of plastic deformation of metallic materials[13–15]. The strength, ductility, toughness and deformability of materials are intimately related to strain hardening characteristics[16]. For this reason, many investigations have studied the strain hardening behavior and physical mechanisms of conventional metallic materials[14,17–19].

To the authors' knowledge, however, a lot of studies about the evaluation of microstructure and mechanical properties of FSWed joints made with different welding parameters were done in the precipitation-hardened aluminum alloys. FSW resulted in a severely softened region in the HAZ[5,20], which was basically characterized by the dissolution/coarsening of precipitates during the thermal cycle. The tensile strength could be improved via additional rapid cooling with flowing water[19] or in underwater friction stir weld[21]. But little information on the tensile properties of FSWed aluminum alloys at different temperatures is available in the open literature, in particular for the slices of FSWed joints along the thickness direction of thick plate. It is unknown if and to what extent the mechanical properties tested at different temperatures of an FSWed aluminum alloy joint using water cooling would change. This study was, therefore, aimed at evaluating the effect of rotational rate on the tensile properties and identifying the strain hardening behavior in a slice of FSWed 2219Al-T62 alloy joint along the thickness direction at varying test temperatures.

2. Experimental

The 20-mm thick AA2219-T62 aluminum alloy plates, with a nominal composition (wt%) of 6.48Cu–0.32Mn–0.23Fe–0.06Ti–0.08V–0.04Zn–0.49Si–0.2Zr, were selected in the present study. Prior to FSW the surface oxides were removed and the surface was cleaned using ethanol. The FSW tool had a shoulder of 34 mm in diameter and a threaded (left-handed screw) cone-shaped pin of 13.5 mm in root diameter and 9.3 mm in tip diameter, and rotated clockwise. FSW was conducted at a rotational rate of 300, 400, 500 r/min and a constant welding speed of 80 mm/min, with a tilt angle of 2.8° with respect to *Z*-axis of FSW system, then water sprayed onto the welding tool and on the top surface of the weld.

Metallographic samples were cut from the FSWed workpieces perpendicularly to the welding direction, then ground, polished and etched using Keller's reagent. Microstructures were examined via an optical microscope and a JSM-6380LV scanning electron microscope (SEM) equipped with Oxford energy dispersive X-ray spectroscopy (EDS) system.

The 20-mm thick tensile samples were cut perpendicularly to the welding directions and sliced into three pieces with the same thickness using electro-discharge wire cutting. Sub-sized tensile specimens with a gauge length of 25 mm and width of 6 mm in accordance with ASTM E8M standards were machined perpendicularly to the welding direction, as shown in Reference 22. The gauge area was hand-ground progressively along the loading direction with #120, #240, #320 and #600 SiC papers to remove the cutting marks and to achieve a smooth surface.

Tensile tests were conducted at a strain rate of 1×10^{-4} s^{-1} at three different test temperatures until rupture. A fully computerized united tensile testing machine was used at room temperature (RT, 25 °C), whereas for lower temperature (LT, –40 °C) and higher temperature (HT, 165 °C) tests an environmental chamber controller with a tolerance of ±5.5 °C was used. For low and high temperature tests, the samples were cooled or heated within the chamber without any load to allow possible change in dimensions before the tests. An extensometer with a gauge length of 25 mm and a strain limit of 20% was used to measure the strain during the tensile tests and at least two specimens were tested at each temperature. Fracture surfaces after tensile testing were examined by using SEM to identify the fracture mechanisms.

3. Results and Discussion

3.1. Microstructure

Fig. 1 shows the macrostructure of the transverse cross-section of the FSW 2219Al-T62 joint. No welding defects were detected in the FSW joint. Three microstructural zones, WNZ, TMAZ, and HAZ, were discernible in the FSW joint. The 2219-T62 aluminum alloy was characterized by the large, elongated, pancake-shaped grains of several hundred micrometers long in the transverse direction and tens of micrometers wide in the normal (or short transverse) direction resulting in the rolling process, as shown in References 19 and 23. Fig. 2 shows typical cross-sectional microstructures and second-phase particles of FSWed AA2219-T62 aluminum alloy joints obtained at different rotational rates of 300 or 500 r/min and welding speed of 80 mm/min. Three zones, i.e., a top of WNZ, a middle of WNZ, and a bottom of WNZ, appeared. The microstructure of WNZ was characterized by fine and equiaxed dynamically recrystallized grains (Fig. 2). Compared with the middle and bottom of WNZ, the grain size at the top of WNZ was larger. There was no significant change in grain at the top of WNZ at a rotational rate 500 r/min compared with 300 r/min, but the grain at the middle and bottom of WNZ was observed to grow. Second-phase particles at the middle also exhibited an obvious growth with finer ones at the top and bottom of WNZ. This was caused by the water cooling at the top surface of the weld. The growth of recrystallized grains at the top of WNZ was suppressed by water cooling. Therefore, the effect of rotational rate on the grain size at the top of WNZ was weak. At a high rotational rate of 500 r/min, the middle of the weld experienced a higher peak temperature and longer thermal cycles. Plastic softening may occur due to the abnormal plastic flow and the growth of second-phase particles as shown in Fig. 2(d). The top and bottom of the weld had finely dispersed second-phase particles caused by a large sufficient mechanical stirring and low thermal cycle during friction stir welding (Fig. 2(b) and 2(f)).

3.2. Effect of test temperature on UTS, YS and elongation

Fig. 3 shows typical stress–strain curves at a strain rate of 1×10^{-4} s^{-1} at different test temperatures obtained for BMs of 2219-T62 aluminum alloy, and their FSWed joints at a rotational rate of

Fig. 1. Cross-sectional macrostructures of FSW 2219Al-T62 joints. AS—advancing side, RS—retreating side.