Materials and Design 31 (2010) 4786–4791

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Immersed friction stir welding of ultrafine grained accumulative roll-bonded Al alloy

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A R T I C L E   I N F O

Article history:
Received 24 March 2010
Accepted 2 May 2010
Available online 10 May 2010

Keywords:
D. Welding
E. Mechanical properties
F. Microstructure

A B S T R A C T

In this research, ultrafine grained strips of commercial pure strain hardenable aluminum (AA1050) were produced by accumulative roll-bonding (ARB) technique. These strips were joined by friction stir welding (FSW) in immersed (underwater) and conventional (in-air) conditions to investigate the effect of the immersion method on the microstructure and mechanical properties of the joint, aiming to reduce the deterioration of the mechanical properties of the joint. Transmission electron microscopy and X-ray diffraction analyses were used to evaluate the microstructure, showing smaller grains and subgrains in the stir zone of the immersed FSW condition with respect to the conventional FSW method. The hardness and tensile properties of the immersed friction stir welded sample and ARBed base metal show more similarity compared to the conventional friction stir welded sample. Moreover, the aforementioned method can result in the enhancement of the superplasticity tendency of the material.

1. Introduction

Ultrafine grained (UFG) and nanostructured materials are very interesting for commercial applications due to their enhanced mechanical properties (such as strength, hardness etc.) in comparison with medium to coarse grain materials [1]. Processing of metals and alloys by severe plastic deformation (SPD) is a promising procedure to produce submicron and nanostructured materials [2,3]. ARB is a major SPD process for manufacturing sheet UFG materials [4–6]. However, owing to the size and shape limitation of ARBed sheets and other SPD processed materials, the application of these sheets for the production of large or complex parts like car bodies is limited. Therefore, to develop the application of these types of materials, their joining is essential. Hereon, maximizing the lowest local strength present in any part of the weld and/or minimizing the strength differential between the weld and base metal (BM) are the main strategies.

The microstructural sensitivity of UFG materials to temperature increment due to extremely high structural defects [7], is a main challenge in welding of these types of materials. Obviously, since the molten pool generated during commonly used fusion welding processes will inevitably destroy the UFG structure and leads to the formation of very coarse grains in the weld nugget, the UFG material is not desirable to be welded by these methods [7]. Previous researches imply that FSW is one of the best methods to join UFG and nanostructure materials [8–10]. However, even in this method, hardness values of the weld zone show a decrease in comparison with those reported for BM, due to recrystallization and grain coarsening via grain growth [7–9]. It seems that altering the process temperature could be an interesting point for investigations on FSW of UFG materials [9].

Hofman and Vecchioe [11] worked on immersed friction stir processing (IFSP) as a new technique to modify the microstructure of Al-6061 alloy and showed that, this leads to the creation of UFG in stir zone (SZ) because of the lower amount of heating load to the sample during the process. Also, the thermal history analysis of immersed and conventional friction stir processed aluminum alloy was focused [12]. In the mentioned researches, no study on mechanical properties of the processed materials was conducted. In addition, it has been shown that immersed FSW (IFSW) of AA7075 alloy results in just a little enhancement in the weld strength in comparison with in-air welding condition [13]. All previous investigations on IFSW or IFSP have focused on heat treatable Al alloys, in which precipitation reaction is responsible for strength and local strength variations as the dominant mechanism [9,14]. This means that the effect of grain boundary strengthening (Hall–Petch relationship) is swamped in these alloys.

To our knowledge, no evaluation has been conducted on the underwater FSW of strain hardenable Al alloys to show clearly the effect of the process on grain boundary strengthening. Moreover, no study has been reported on FSW of UFG materials in different thermal boundary conditions. In this work, six cycles ARBed commercial AA1050 sheets with an ultrafine grained structure were FSW processed in-air and underwater conditions, to evaluate the effectiveness of IFSW on the joining of UFG strain hardenable

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doi:10.1016/j.matdes.2010.05.007

Al alloy, in comparison with conventional FSW (CFSW). To do so, the resultant microstructure and mechanical properties of these two welding conditions were compared to those of BM. X-ray diffraction (XRD) peak profile analyses were used as a complementary to transmission electron microscopy (TEM), since the parameters provided by the two different methods are never identical, presenting a more detailed understanding of the microstructures [15].

2. Experimental procedure

The starting materials used in this study were 2 mm thick fully annealed commercial pure AA1050 aluminum alloy plates with an average initial grain size of $\sim$85 μm and Vickers hardness of 30. Prior to roll bonding, the Al sheets were cut in dimensions of 250 mm × 60 mm. In the ARB process, the sheets were wire-brushed to remove surface oxides and then rinsed with acetone (two steps) for degreasing. Fig. 1 illustrates the principle of the ARB process. Two sheets were stacked and bound tightly. Then, the stacked sheets were rolled to 50% reduction in thickness. Afterwards, the rolled sheet was cut into two pieces, stacked to be the initial dimension and then rolled again. The procedure was repeated up to six, so that the total equivalent strain applied was 4.8 [4]. The roll diameter and roll peripheral speed were 136 mm and 6 m min^{-1} respectively. The force applied on the rollers was 7.3 ton for the annealed samples in the first cycle and increases gradually to 14.1 ton in the last (6th) cycle. The roll bonding process was carried out at ambient temperature without any lubrication.

In order to prepare the samples for welding, the ARBed strips were cut with the dimensions of 70 mm × 25 mm and the edges of the strips were properly prepared by milling to avoid any uncertain contact. Also, the samples were again degreased by acetone to eliminate the effect of oil in heat transferring between the samples and water in the immersed condition.

These samples were butt welded along the rolling direction (RD) by the IFSW and CFSW methods by a traditional vertical milling machine using a Z-axis displacement control system. In the immersed condition, 2 L of water with the initial temperature of 25 °C was employed, where the samples were located approximately 25 mm below the water surface. The chosen tool rotation and traveling speed were 630 rpm and 50 mm/min, respectively. The tool was a simple cylindrical pin and flat shoulder with the diameters of 3 and 9 mm, respectively. Previous researches distinctly showed that this tool shape and proportion of pin and shoulder diameters (1:3) lead to the maximum joint strength in AA1050 alloy [16,17]. The welding tool was made of high speed steel with the hardness of 62 HRC due to its proper mechanical properties in the process. The tool to the workpiece angle was 3° from the vertical axis in the weld. The length of the pin and the tool penetration depth were approximately 1.7 and 1.9 mm, respectively.

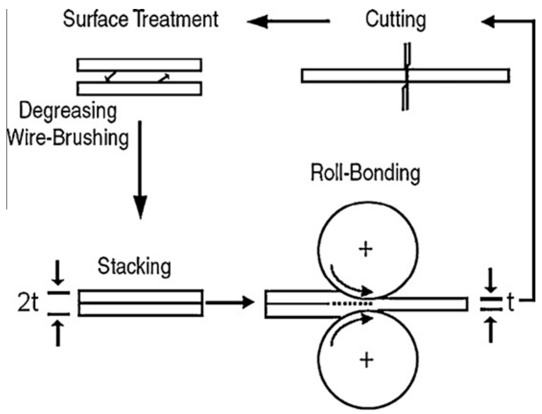

Fig. 1. Schematic illustration of the principle of the ARB process.

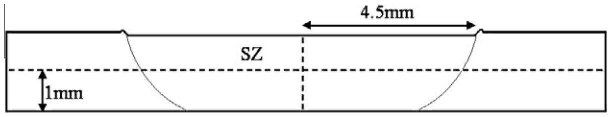

Fig. 2. Schematic illustration of the microhardness measurement paths in the joint of the FS welded samples (dashed lines).

Microhardness and tensile tests were conducted to identify the mechanical properties of the weld zone and BM. Vickers microhardness values of the samples welded in the conventional and immersed conditions were measured on the centerline of a plane normal to the welding direction along two horizontal and vertical lines, as shown in the Fig. 2. The microhardness measurement was performed using a Koopa MH1 hardness measuring machine with a load of 25 g and a dwell time of 15 s. Two general types of tensile test specimens were used to determine the transverse tensile properties of the welded samples and the longitudinal tensile properties of SZ. The width and gauge length of the tensile test specimens were 5 and 10 mm, respectively (according to 1/5 scale of the JIS-No. 5 standard). The surface of the tensile specimens in both sides was approximately 0.25 mm polished to eliminate the cross section non-uniformity created in the weld zone. In addition, the tensile tests were accomplished on the non-polished samples for comparison. The tensile test at ambient temperature was carried out at a nominal strain rate of 10^{-3} s^{-1} by using an Instron universal testing machine. The tensile tests were performed three times at each condition to make the reliability.

TEM and XRD methods were used for the microstructure characterization. Thin foils perpendicular to the normal direction (ND) were cut from the ARBed strip and the center of SZ in the welded samples for TEM observations. The samples were prepared by mechanical polishing followed by dimpling and Ar ion-milling. The TEM analysis was conducted using a 300 kV JEM-2100F microscope. The high resolution XRD experiment was performed by a D8 Bruker diffractometer with negligible instrumental broadening using Cu $K\alpha_1$ radiation in the range $2\theta = 20$–105° with a step size of 0.01° and a counting time of 1 s per step. The modified Warren–Averbach and Williamson–Hall methods were used for the microstructure characterization. These methods are based on the fact that diffraction peaks broaden when crystallites are small or the material contains lattice defects. Details of these methods have been explained in Refs. [15,18–20].

For the metallographic analyses of the joints cross-section, perpendicular to the welding direction, the specimens were polished and then etched by Keller reagent (150 ml H_2O, 3 ml HNO_3, 6 ml HCl, 6 ml HF). Observation performed through an optical microscope.

3. Results and discussion

The upper surfaces and cross-sections of the FS welded samples in both the welding conditions are shown in Figs. 3 and 4, respectively. Due to the more cooling rate and lower temperature in the immersed condition [11], the roughness of the upper surface increased. Furthermore, the continuous joints (without any defect) are formed in both the welding conditions (Fig. 4).

Fig. 5 shows the TEM images of ARBed BM and also SZ of both the CFS and IFS welded ARBed samples. Submicron grains can be obviously observed in BM with a mean grain size of $\sim$0.6 μm, as determined based on the line intercept method (Fig. 5a). Some pre-