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Twining and dynamic recrystallization in austenitic Alloy 718 during friction welding

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ABSTRACT

Quantitative boundary misorientation analysis verified that discontinuous dynamic recrystallization (DDRX) was the primary grain refinement mechanism in friction welding of Alloy 718. Two models were developed to explain the formation mechanism of intragranular twins and intergranular twins, respectively. Intragranular twins were caused by grain boundary growth incidents. After twin initiation, the twin boundary migrated toward the plastic-deformed grain interior to reduce the stored energy. Additionally, intergranular twin boundaries were ascribed to boundary growth stagnation. When boundary growth stagnation occurred, twin boundaries could form and altered the orientation of the boundary migration front, so that boundary migration could progress, leaving a single twin boundary behind.

1. Introduction

Thermal mechanical deformation, during which dynamic recrystallization (DRX) often occurs, has been widely applied in many metallic parts for microstructural control. In addition, thermal mechanical deformation can also be exploited to join metallic parts through solid state welding techniques, during which the processed material experiences severe plastic deformation at elevated temperatures and finally forms a weld zone (WZ) consisting of densely recrystallized grains [1–3]. The final microstructure and properties of the polycrystalline solids are largely determined by the recrystallization phenomena which are affected by many factors, such as deformation conditions, initial grain size, the chemistry of the material, and crystal structure.

Alloy 718 is an austenitic nickel-iron-based alloy. This alloy features good corrosion, oxidation, and creep resistance as well as high strength at moderately elevated temperatures. Fusion welding of Alloy 718 is prone to induce solidification cracking, and segregation of alloying elements [4,5]. The solidification problems can be avoid using solid state welding techniques, such as friction welding (FW) or friction stir welding (FSW) [6–9].

Previous works have shown that FW was a promising weld method to join Alloy 718 [8,10–14]. The WZ of FW Alloy 718 consisted of fine equiaxed recrystallized grains [14,15]. Deformation twins as well as new recrystallized grains around the deformed original grains were observed in thermo-mechanically affected zone (TMAZ) which experienced relatively lower strain and temperature compared to WZ [14]. The as-welded sample exhibited lower hardness at the WZ compared to the base metal (BM) due to the dissolution of strengthening precipitates. Because of the grain refinement and the formation of strengthening precipitates, the FW Alloy 718 joints which were subjected to post-weld aging treatment fail in the BM during tensile testing [14]. In addition, the feasibility of applying FW to repair service damaged Alloy 718 has been validated in a recent study [11]. It is extremely important to understand the microstructure evolution during FW to promote wider application of the versatile Alloy 718 and the promising friction welding.

The microstructure distribution at various locations of the friction welded Alloy 718 have been analyzed in a previous study [14]. Both DRX and deformation twins were observed in the TMAZ zone. Previous investigations have attempted to understand the twin formation during DRX [16–20], but the debate continues as in-situ observation is infeasible. In this study, the misorientation among the parent grains and the recrystallized grains in the TMAZ of friction welded 718 alloys were measured to determine the mechanism of recrystallization and twinning during dynamic recrystallization. The objective was to provide new insights into the process of DRX and twinning during FW or thermal plastic deformation.

2. Experimental Details

The friction welded Alloy 718 tube was produced by a multi-functional TTI-RM2 friction stir welding machine. The outer diameter and the wall thickness of the Alloy 718 tube were 25.4 and 2.54 mm,

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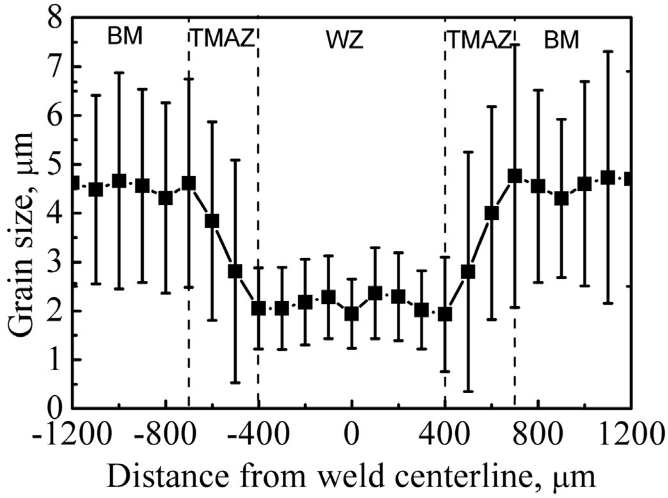

Fig. 1. Distribution of average grain size across WZ along tube wall edge.

respectively. The rotation rate, feeding speed and feeding distance was 500 rpm, 125 mm/min and 5 mm, respectively. The weld region was removed using electrical discharge machining for EBSD examination. EBSD samples were mechanical polished to 1 μm diamond followed by a vibratory polish using 0.05 μm colloidal silica. High-resolution EBSD data were obtained at 20 kV using FEI Helios Nanolab 600 with a Hikari EBSD camera. An OIM™ 6.0 Data Collection software was used. The average confidence index (CI) for each EBSD map was higher than 0.5. When CI is higher than 0.2, the indexing, which determines a crystal's orientation from information in the EBSD pattern, is virtually 100% accurate for face centered cubic. In order to eliminate spurious boundaries caused by orientation noise, boundaries with misorientation less than 2° were not considered. For twin boundary definition, a tolerance of 5° was allowed in both the rotation of twin plane normal and the angle between the twin planes on either side of the boundary.

3. Results and Analysis

Fig. 1 shows the distribution of average grain size across the weld zone along the edge of the tube wall. The average grain size was symmetric about the weld centerline. The average grain size of the as-received Alloy 718 was about 4.6 μm. As shown in Fig. 2a, the as-received Alloy 718 mainly consisted of equiaxed grains. Annealing twins were extensive within the equiaxed grains. The average grain size in the TMAZ decreased with approaching the WZ (Fig. 1). This is because the materials close to the WZ experience more plastic deformation and new recrystallized grains developed along the boundaries of prior coarse grains, as indicated in Fig. 2b. The average grain size in the WZ is about 1.9 μm, which is much smaller than that in the BM (Fig. 1). Fig. 2c shows that the WZ mainly consisted of fine recrystallized grains.

The microstructural investigation above indicated that plastic deformation induced recrystallization occurred in both TMAZ and WZ. Such microstructure changes have the potential to significantly affect mechanical properties and corrosion behavior of the joints. Detailed microstructure analysis in the TMAZ was conducted in this study to understand the microstructure evolution during welding and achieve precise local microstructure control.

In the TMAZ, grain boundary serrations or bulges were observed as a prelude to DRX (Fig. 2b). New recrystallized grains developed at the boundaries of prior coarse grains, producing a "necklace" structure of grains around the original grains. The development of "necklace" structure of grains was usually associate with discontinuous DRX (DDRX) [21]. However, it may be inaccurate to identify DDRX simply based on the observation of chains of recrystallized grains formed around original grains. This is because new grains may develop through another way. That is, bulges are divided from old grains by newly developed sub-boundaries, producing a "necklace" structure of recrystallized grains in a continuous manner. Ponge and Gottstein [22] have observed that the chains of new recrystallized grains in Ni_3Al were formed through bulging of prior grain boundaries, producing new recrystallized grains have orientations close to that of the parent grains. The misorientation among the parent grains and the recrystallized grains need to be measured to accurately determine the recrystallization mechanism.

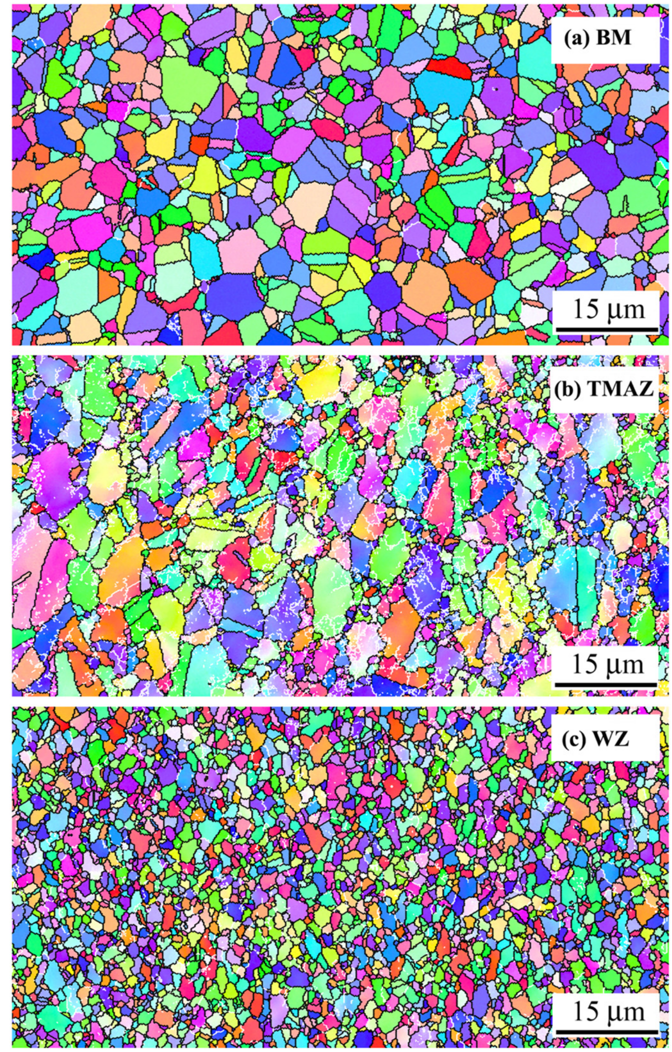

Fig. 2. Typical grain structure of (a) BM, (b) TMAZ and (c) WZ.

Fig. 3 shows the grain structure maps at Region I (200 μm away from the WZ) and Region II (80 μm away from the WZ) in the TMAZ. The low-angle grain boundaries (LAGBs ≤ 15°), high-angle grain boundaries (HAGBs > 15°), and Σ3 twin boundaries were displayed as white, black and red lines, respectively. The numbers in Fig. 3 indicated the misorientation of the closest boundaries. Within each grain, the points were shaded according to the misorientation it made relative to the average orientation of the grain. The deformed coarse grains had high orientation spread (≥ 2°) while the recrystallized grains were characterized by low intragranular orientation spread (< 2°). Thus, the orientation spread map can be roughly used as a reference to distinguish the deformed grains and new recrystallized grains.

A "necklace" structure of recrystallized grains (fine blue grains) began to form around the deformed coarse grains (large grains were dyed green, yellow or red) in Region I (Fig. 3a). This was more pronounced in Region II (Fig. 3b). If the fine grains developed through