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Friction stir spot welding of single-crystal austenitic stainless steel

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Abstract

The high-resolution electron backscatter diffraction technique was employed to study the structural response of single-crystal austenitic stainless steel to friction stir spot welding. The strain-induced crystal rotations were found to be governed by simple-shear deformation. In contrast to aluminum alloys, the developed texture showed pronounced $A/\overline{A}$ $\{111\}\langle110\rangle$ simple-shear texture components, this effect being attributed to the suppression of cross-slip. Grain boundary development was demonstrated to be closely linked with texture evolution. During pin plunging, at relatively low temperatures, microstructural evolution was shown to be dictated by continuous recrystallization. Due to this process, the single-crystal structure was broken up into an ultrafine-grained polycrystalline aggregate with a mean grain size of ~0.2 μm. During shoulder contacting, however, the temperature rose and discontinuous recrystallization became predominant.

Keywords: Friction stir welding; Austenitic stainless steel; Single crystal; Electron backscatter diffraction; Recrystallization

1. Introduction

Friction stir welding (FSW) is a revolutionary joining technique invented in 1991 [1]. Being a solid-state process, FSW avoids solidification problems associated with conventional fusion welding and thereby yields sound joints, even in materials usually considered to be unweldable. The triumph of this technology resulted in its widespread usage for joining of various structural materials [2] and gave rise to the development of derivative techniques – friction stir processing [3] and friction stir spot welding (FSSW) (e.g. [4]). The practical success of the friction stirring techniques necessitates a more fundamental understanding of the underlying physical processes. Thus, microstructural and textural studies are presently becoming key issues in the friction stirring field.

In this context, an approach involving experiments with single crystals deserves particular attention. This method may significantly simplify the microstructural and textural observations because any grain-boundary development as well as crystallographic rotations can easily be traced and interrelated with each other. For example, Fonda et al. [5,6] have provided an excellent illustration of how initial single-crystal orientations transform into simple-shear texture during FSW. On the other hand, Shibayanagi et al. [7] have found the formation of compression texture components during FSSW and attributed this effect to the vertical component of material flow. The observed crystal rotations have been clearly demonstrated to be closely linked with grain-boundary development, which ultimately breaks up the initial single-crystal structure into a polycrystalline aggregate [5–7]. Generally, these single-crystal observations have elucidated the structural response of materials to FSW, thus providing conclusive confirmation of the results obtained in polycrystalline materials.

So far, however, single-crystal experiments in FSW are still rare and, more importantly, are performed mainly on aluminum alloys [5–7], i.e. on the materials with high stacking fault energy (SFE). It would be useful to expand this approach to other structural materials for which FSW is used. For instance, there is considerable interest in the

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application of FSW to low SFE metals (typically austenitic steels and nickel-based alloys). Superior corrosion properties of these materials are usually degraded during fusion welding, and thus FSW is considered to be an alternative welding technique.

The present work is a part of a wide-ranging research project employing the single-crystal approach to study the grain structure and texture evolution during friction stirring of a typical low SFE material. Taking into account the complicated character of material flow during FSW, only the first stage of the process – the tool plunging step – is considered in detail in this paper. This step is also known as the FSSW technique.

2. Experimental

The material used in the present investigation was 304 austenitic stainless steel supplied as a single crystal, $120 \times 80 \times 15\ mm^3$ in size. From the provided material, a slab with dimensions of $80 \times 25 \times 5\ mm^3$ was cut using an electro-discharge machine (Fig. 1a). The longitudinal, transverse and normal directions of the slab (LD, TD and ND, respectively) were employed as a reference frame in this study. In the machined single-crystal slab, the $\langle 100 \rangle$ crystallographic direction was close to the TD and the $\{110\}$ crystallographic plane was nearly parallel to the slab plane (LD–TD). The crystallographic orientation of the single-crystal slab was checked with electron backscattered diffraction (EBSD) and found to be within an accuracy of $\sim$10° (Fig. 1b).

The top surface of the slab was ground using 80-grit emery paper to remove oxides and contaminants, then subjected to FSSW. The welding tool was fabricated from a cobalt-based superalloy [8] and consisted of a shoulder having a diameter of 15 mm and a pin length of 1.8 mm. The pin was tapered from 6.0 mm at the shoulder to 3.5 mm at the pin tip and had no threads or other features.

To enable a better understanding of microstructural evolution and material flow during tool plunging, three bead-on-plate welding trials were conducted at a constant tool rotational speed of 300 rpm and variable plunge depths of 1, 1.5 and 1.9 mm. In Fig. 1a (and throughout the paper), the trials are denoted as Welds 1–3, respectively. The material flow in Weld 1 is expected to be mainly governed by the tool pin, whereas that in Weld 3 should be greatly influenced by the tool shoulder. Weld 2 was selected as an intermediate case. However, microstructural and textural observations showed that the material response in this case was broadly similar to that in Weld 1 and thus these data were omitted in this paper.

In all welding trials, the tool was rapidly extracted after plunging to the predetermined depth (i.e. dwell time was zero). No tool tilting was applied in any of the cases. To minimize surface oxidation, argon shielding was employed around the tool during FSSW.

The obtained welds were longitudinally sectioned in the ND–LD plane (Fig. 1a) and then studied by optical microscopy (OM) and the EBSD technique. For OM observations, the microstructural samples were ground with water abrasive paper, mechanically polished with 1 μm diamond paste and then electro-etched in nitric acid at 30 V for 5 s. A suitable surface for EBSD was obtained by mechanical polishing in a similar fashion, with a final polishing step comprising vibratory polishing with a colloidal silica suspension for 12 h.

The OM studies were carried out using a Nikon Optiphot-100 optical microscope. High-resolution EBSD analysis was conducted with a Hitachi S-4300SE field-emission gun scanning electron microscope equipped with the TSL OIM™ EBSD system. Orientation mapping was performed using a triangular scanning grid. On each pattern, seven Kikuchi bands were used for indexing, thus minimizing the possibility of misindexing error. EBSD maps of $\sim$400,000–1,300,000 pixels with step (pixel) sizes of 0.05–0.6 μm were obtained. The average confidential index (CI) for each EBSD map ranged from 0.21 to 0.78. By comparison, experiments on face-centered cubic (fcc) materials have shown that the fraction of correctly indexed patterns with CIs greater than 0.1 is 95% [9]. In order to ensure the reliability of the EBSD data, all small grains comprising three or fewer pixels were automatically removed from the maps using the grain-dilation option in the TSL

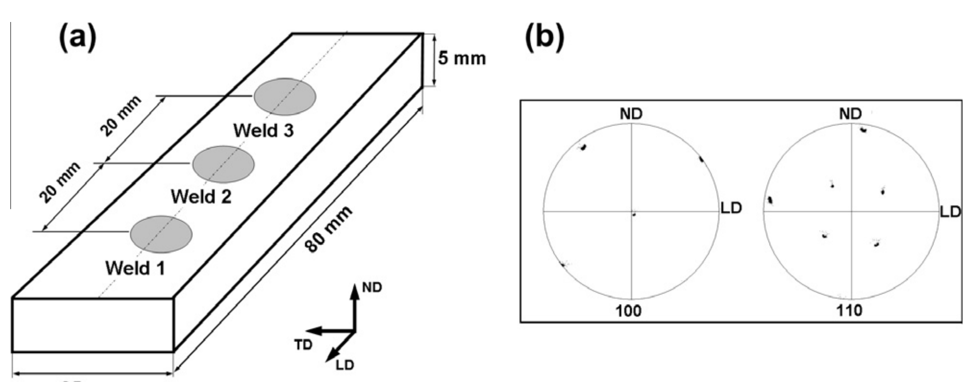

Fig. 1. Schematic of single-crystal sample with employed reference frame (a) and 100 and 110 pole figures showing crystallographic orientation of the single crystal (b). Note: LD, TD and ND are longitudinal, transverse and normal directions, respectively. See text for details.