Microstructural aspects of friction stir welding

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Abstract. Microstructural aspects of friction-stir welding were briefly reviewed. Particular emphasis was given to material flow, crystallographic texture, grain structure development, precipitation phenomena, phase transformations, and thermal stability

1. Introduction

Friction-stir welding (FSW) is an innovative joining technique [1, 2]. Technically, it involves a plunging of a specially designed welding tool, which rotates with a high spindle rate, between two butted sheets and its subsequent traversing along the joint line (Figure 1). The frictional heat and plastic deformation, induced by the rotating tool, rises the local temperature of the welded material so it can be plastically deformed at relatively low stress. The hot material is forced to flow around the rotating tool to fill the cavity at its rear and thus forming a joint in a solid state.

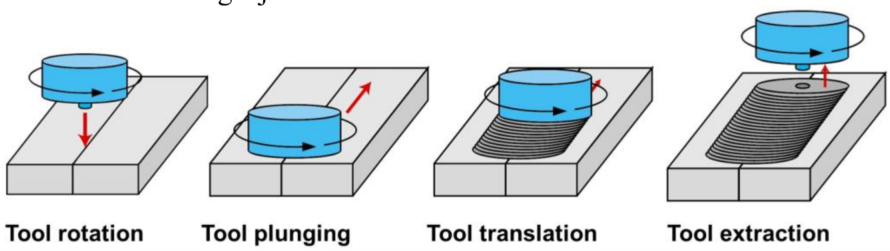

Figure 1. A schematic of FSW process

Due to the solid-state nature of the welding process, FSW avoids solidification defects inherent to conventional fusion techniques and thus routinely produce high-quality welds even in materials which are traditionally considered to be “unweldable”, e.g. aluminum alloys. Accordingly, FSW has considerable industrial potential and widely used in transportation industry.

It is important to emphasize that the welded material undergone very large strains at high strain rate and elevated temperature. Material performance at such extreme deformation conditions is not studied well. Hence, FSW represents also a substantial academic interest, and significant research effects have been undertaken during the last two decades to explore the microstructural behavior of friction-stir welded materials. The present work attempts to provide a brief but comprehensive overview of the current state-of-the-art in this area.

2. Material flow and crystallographic texture

Material flow is one of the key issues in FSW. Due to the specific character of FSW, the welded material normally experiences a combination of rotation- and translation motions (Figure 1). Additionally, the material may also undergo a vertical flow along the tool height. Thus, the material actually follows a complex helical trajectory. On the other hand, the rotation component is well accepted to predominate and therefore the FSW straining mode is close to the simple shear [3].

Considering a specific mushroom-shaped design of the welding tool, the character of the material flow (as well as a degree of the imposed strain and even the welding temperature) is principally depended on the depth location. Specifically, the material flow at the upper surface of the welded sheets is governed by the tool shoulder whereas that in the sheets interior is driven by the tool probe (Figure 2).

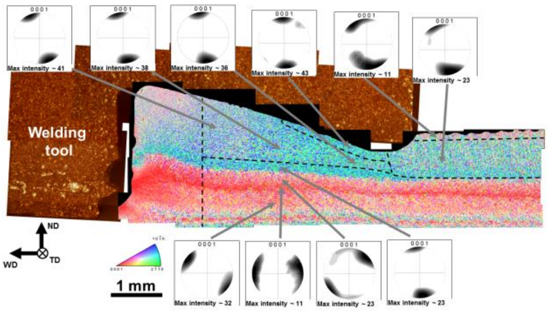

Figure 2. EBSD orientation map showing inhomogeneous texture distribution in thickness direction of friction-stir welded AZ31 magnesium alloy. WD, ND and TD are welding direction, normal direction and transverse direction, respectively. After Suhuddin et al. [9].

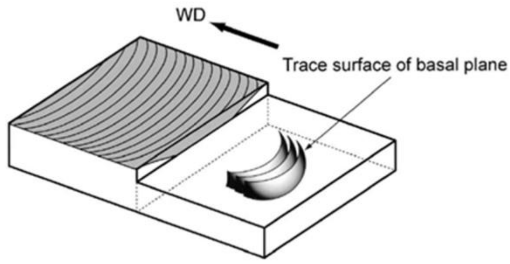

Figure 3. A schematic showing spatial distribution of shear planes within stir zone. WD is welding direction. After Park et al. [12].

FSW typically results in a distinct texture which is typically close to the typical simple-shear orientations [3]. In some cases, however, a formation of recrystallization textures has been reported [4]. In face-centered cubic (FCC) metals, the produced texture was found to be sensitive to the stacking fault energy (SFE). Specifically, a reduction in SFE leads to a transition from $B/\bar{B}\{112\}<110>$ [e.g. 5, 6] to $A/\bar{A}\{111\}<110>$ orientations [e.g. 7]. In body-centered cubic (BCC) crystals, $D_2(11\bar{2})[111]$ texture forms [8]. In hexagonal metals, the evolved texture depends on the c/a ratio. Specifically, magnesium alloys are characterized by a predominance of the *B*-fiber {0001}<uvtw> texture associated with the basal slip [e.g. 9]. In alpha-titanium, on the other hand, the texture is typically dominated by the $P_1\{1\bar{1}00\}<11\bar{2}0>$ attributable to the prism slip [10]. It is also worth noting that the FSW-induced texture in the wrought magnesium alloys is typically very sharp with the peak intensity sometimes achieving ~100 times random [11].

It is important to emphasize that the rotation of the welding tool during FSW gives rise to a variable orientation of the shear direction and the shear plane across the weld zone, shown in the schematic in Figure 3 Accordingly, the texture distribution in the friction-stirred materials is normally not uniform [e.g. 12].

3. Grain structure development

The FSW-induced recrystallization mechanism has been long time one of the research hotspots. The extensive research has demonstrated that grain structure development during FSW is a relatively complex phenomenon which normally includes several stages and is often driven by several mechanisms. These typically include geometrical effect of strain, grain subdivision and discontinuous recrystallization (Figure 4 & 5) but, sometimes, an activation of mechanical- or annealing twinning as well as the grain convergence is also possible [5-11, 13, 14].

The mutual contribution of these of these mechanisms depends primarily on crystal structure and stacking fault energy (SFE) of a particular material but may be also influenced by the temperature of the FSW process. Specifically, the grain structure development during FSW of cubic metals with high SFE is usually governed by the subdivision mechanism [e.g. 5, 6, 8]. In FSW metals with low SFE, in contrast, the key microstructural mechanism is the discontinuous recrystallization [e.g. 7]. In metals with intermediate SFE, e.g. in pure copper, a transition between these two mechanisms has been observed depending on the welding temperature [15]. In hexagonal metals, the microstructural evolution was found to be substantially influenced by crystallographic texture. Specifically, a development of a very sharp texture in stir zone may promote a partial grain convergence [9, 14].

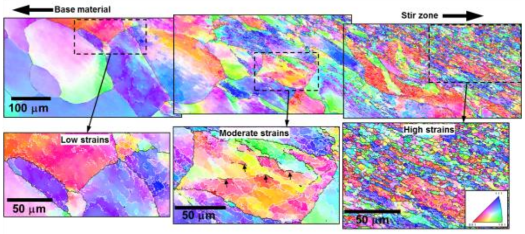

Figure 4. EBSD orientation map showing grain subdivision during FSW of pure iron. Arrows exemplify the transformations of low-angle boundaries to high-angle boundaries. After Mironov et al. [8]

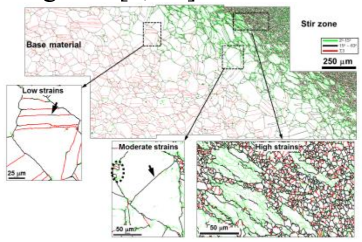

Figure 5. EBSD grain-boundary map showing discontinuous recrystallization during FSW of superaustenitic stainless steel. Arrows show prior-annealing-twin boundaries. Circle indicate grain-boundary bulging. After Mironov et al. [7]

4. Precipitation phenomena

Since commercial alloys often contain second-phase particles, the investigation of precipitation phenomena occurring during FSW attracts significant interest. The extensive research over the last two decades has conclusively demonstrated that a significant temperature gradient inherent to the FSW process gives rise to the complex particle behavior [2, 16]. In the microstructural regions exposed at relatively low temperatures, an essential coarsening of the constituent dispersoids is usually found; this normally leads to the loss of their coherent relationship with matrix. In the microstructural areas influenced by the relatively high heat input, the precipitates often dissolve. Depending on the cooling rate, the dissolved dispersoids may partially re-precipitate back (sometimes, in a form of solute clusters) during weld cooling cycle. Since the welded material normally contains high density of crystal defects (dislocations, subgrain- and grain boundaries), the re-precipitation may occur in a heterogeneous manner.

5. Phase transformations

During FSW of Ti-6Al-4V alloy and carbon steels, material flow may occur in the high-temperature phase filed and the final weld structure develops via the phase transformations occurring during weld cooling cycle. It has been found that these are essentially influenced by the large deformation experienced by the high-temperature phase [17, 18]. Specifically, a significant grain refinement as was as a formation of a distinct simple-shear texture in this phase may result in a pronounced variant selection occurring during the subsequent phase transformation. This, in turn, may give rise to the transformation temperature in the low-temperature phase. Moreover, a formation of a developed substructure in the high-temperature phase leads to local deviations from a characteristic orientation relationships between the phases.

6. Thermal stability

A characteristic of friction-stirred materials is a relatively low stability against abnormal grain growth [19]. This process involves a catastrophic growth of few grains which eventually consume the entire weld zone (Figure 6) and thus may essentially degrade weld properties. This undesirable process has been observed in various alloys thus presumably being a more or less common property of the FSWed materials. It is often reported that the abnormal grain growth often initiates from peripheral regions of stir zone, typically from its upper surface or the weld root, as shown in Figure 6. The origin of this phenomenon is still unclear, however.

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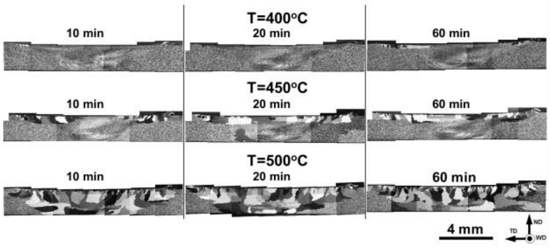

Figure 6. Optical micrographs illustrating abnormal grain growth in friction-stir welded aluminum. WD, ND and TD are welding direction, normal direction and transverse direction, respectively. After Mironov et al. [20]

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