Materials and Design 103 (2016) 259–267

Contents lists available at ScienceDirect

Materials and Design

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

A comparison of crystallographic texture and grain structure development in aluminum generated by friction stir welding and high strain torsion

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ARTICLE INFO

Article history:
Received 2 March 2016
Received in revised form 15 April 2016
Accepted 17 April 2016
Available online 26 April 2016

Keywords:
Torsion testing
Crystallographic texture
FSW
EBSD
Grain structure

ABSTRACT

Crystallographic texture and grain structure of high strain torsion tested aluminum at 500 °C was investigated using the electron backscattering diffraction technique and compared with that of friction stir welded aluminum. The crystallographic texture of the torsion tested aluminum is dominated by simple shear texture components B, $\bar{B}$ and C with some evidence of A/$\bar{A}$ appearance. Key observations from the torsion test that may help explain the texture observations in the thick section friction stir weld are: 1) with increasing strain there is a reduction in C component and a more homogeneous mixing of the B/$\bar{B}$ components, equivalent to that observed on the retreating side of the weld, where the shear strain is expected to be the highest; 2. at lower levels of strain there is significant levels of texture component banding, similar to the advancing side of the weld; and 3. even at nominally the same shear strain, the torsion sample showed localised banding of C components, again similar to the advancing side of the weld. The grain structure developed in torsion is similar to that of the grain structure in the welding zone of FSWed aluminum, suggesting high strain torsion is an excellent method for simulating deformation of FSW.

1. Introduction

Friction stir welding (FSW) is a solid-state joining process developed by TWI, UK in 1991 [1] that has been successfully applied to a number of material types [2–8] in a wide range of industrial sectors [9–11]. The joint is formed by continuous sweeping of frictionally heated material from the front to the back of a forward moving rotating tool (shoulder plus probe), generating plastic deformation within the weld nugget zone (NG). Thus, the joint formation process can be considered to be shear induced high strain solid-state extrusion. This has led to significant work being undertaken to understand microstructure evolution within the NG as a function of tool design and process variables [3,8,12–27], and its subsequent impact on mechanical properties [2,8,12–15,25–33]. There has also been a number of investigations of crystallographic texture development in the NG, particularly for aluminum, for both thin and thick section welds [34–43]. In thin welds a number of different texture components have been reported. For example, the surface layer of 2 mm thick AA5754 and AA5182 has been reported to contain two texture components: $(118)[62\bar{1}]$ and a rotated cube component, $(00\bar{1})[120]$ [32]. A similar rotated cube component,{100}⟨011⟩, was also observed at the surface of 4 mm thick AA6063 but below the surface a {221}⟨114⟩ component was also seen, in addition to the {100}⟨011⟩ [41]. This is in conflict with observations for 4 mm AA6061 [38] in which {100} ⟨001⟩, {111} ⟨110⟩ and ⟨100⟩//ND components were identified in the surface region; ⟨111⟩//ND in the centre of the weld; and both ⟨100⟩//ND and ⟨111⟩//ND in the lower section of the weld. This is further conflicted by the analysis of Field et al. [43]who studied 6.35 mm thick AA6061 and AA1100 and stated texture appears to be largely alloy independent but there are significant through thickness texture gradients of face-centered cubic shear components. In thick section (>20 mm) welds it is generally accepted that texture components in aluminum are mainly of the shear type, dominated by the B fibre components. For example, Prangnell and Heason [39] and Fonda et al. [37,40], both investigating the texture of 25 mm thick AA2195, reported B fibre shear textures as the main components of texture. In addition, the authors [36] of the present study investigating the texture across the NG zone in 38 mm thick AA6082reported that in the probe-dominated region the textures are almost entirely the shear texture components of B/$\bar{B}${112}⟨110⟩/{112}<110>) and C {100}⟨110⟩, with the B and $\bar{B}$ in alternating bands. This observation was further confirmed [34]by examination of the texture through the thickness of stationary shoulder friction stir welded 6 mm thick AA6082, where, as long as the probe was dominating the formation of the joint, simple shear was dominating the texture. Thus, it can be said that the variation in texture

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http://dx.doi.org/10.1016/j.matdes.2016.04.056
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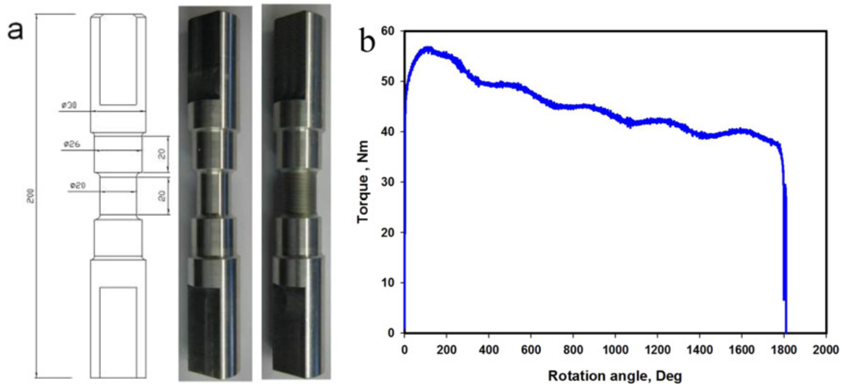

Fig. 1. a) Schematic drawing of the torsion test specimen dimensions and the specimen before and after torsion test. b) Torque versus rotation angle for torsion test.

observed in thin section FSWeds is most likely due to the shoulder that applies shear deformation in a plane perpendicular to the shear plane in the probe-dominated region, leading to more complicated texture components than observed in the simple shear condition generated by the probe.

Torsion testing is a widely used simple shear test for assessing the flow behaviour of materials and for simulating industrial working processes such as rolling, forging or extrusion. This is because large strains up to 100 can be readily imposed owing to the geometric and mechanical stability of the test at high temperatures [44,45]. Montheillet et al. [45]reported that for fcc metals at small strains and low temperatures texture is dominated by A components, $\{11\bar{1}\}\langle 110\rangle/\{\bar{1}11\}\langle\bar{1}\bar{1}0\rangle$, at intermediate strains and low temperatures the texture is dominated by the C component, and at high strains and high temperatures the texture is dominated by B components. Barnett and Montheillet [46] also reported that for AA1050 at 450°Cthe A_2^* component $\{11\bar{1}\}<112>$ drops from a volume fraction of around 5–7% at an equivalent strain of 2 to negligible levels at an equivalent strain of 4, whilst the C component increases in intensity up to a strain of 4 then decreases to half its maximum intensity at a strain of 7. However, the intensity of the B component increases steadily with increasing strain.

Hassan et al. [47] have used high strain torsion up to a strain of 20 at a strain rate of 0.005 s^{-1} to simulate the grain structure in the NG zone of friction stir welded 7010 aluminum alloy. They reported, with this very slow strain rate, that only at very high strain does a similar grain structure to that developed in the NG zone start to appear, suggesting that high strain torsion is an effective way of investigating microstructure evolution in FSW. They also suggested that the main mechanism of fine grain structure formation is by a form of geometric dynamic recrystallization and it is encouraged by heterogeneous plastic flow, as produced in the NG region of FSWed aluminum alloy [39,48]. In the current study, an equivalent strain of up to 9, at a strain rate up to 15 s^{-1}, has been applied to aluminum AA6082-T6 using the torsion test at 500 °C to compare the developed crystallographic texture and grain structure with that of the probe dominated region of FSWed aluminum AA6082-T6 under near equivalent deformation conditions.

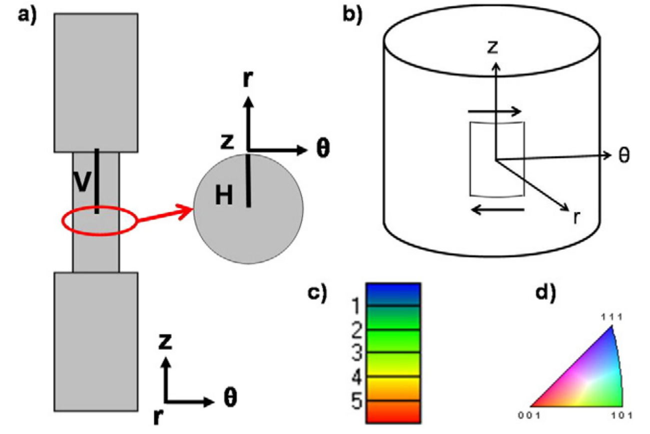

Fig. 2. Schematic drawing showing the positions (thick black lines named V and H) of the EBSD maps taken along the Z direction at 7.5 mm radius (map V) and along r direction (map H). b) The torsion test axes. c) colouring key for pole figures and d) colouring triangle key for inverse pole figure maps relative to r direction used throughout the paper.

2. Experimental work

A solid bar torsion test sample of dimensions illustrated in Fig. 1a was machined from AA6082-T6. A gauge dimension of 20 mm diameter and 20 mm long was used to give a wide range of strain variation from the center to the surface of the sample. Torsion testing was under taken using a servo-hydraulic testing rig, details of which have been described elsewhere [49]. The sample was heated to 500 °C and held for 1 min then rotated at a speed of 500 rpm for five rotations. After deformation, the specimen was immediately water spray quenched to help preserve the as-deformed microstructure, as well as to be closer to the cooling rates experienced in FSW of thick section aluminum, where the thermal mass is high, leading to high cooling rates. FSW was also conducted for 20 mm thick AA6082-T6 at a rotation rate of 500 rpm and traverse speed of 350 mm/min. A common Triflat™ design FSW tool was used; this tool has a 40 mm diameter scrolled shoulder with a tapered and threaded Triflat™ 19.5 mm long

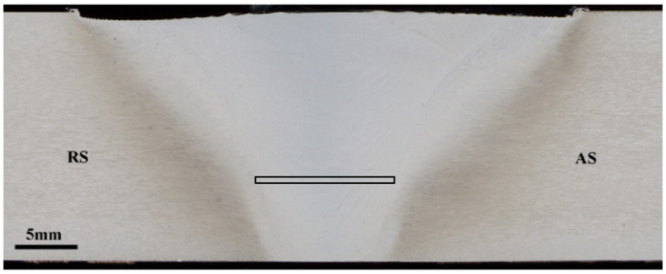

Fig. 3. Optical macrograph of the 20 mm thick FSWed AA6082-T6. The rectangle shows the area analysed with EBSD in the probe-dominated region of the NG zone. AS and RS are the advancing and retreating sides, respectively.