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Microstructure evolution and texture development in a friction stir-processed AISI D2 tool steel

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ABSTRACT

Crystallographic texture developments during friction stir processing (FSP) of AISI D2 tool were studied with respect to grain sizes in different tool rotation rates. Comparison of the grain sizes in various rotation rates confirmed that grain refinement occurred progressively in higher rotation rates by severe plastic deformation. It was found that the predominant mechanism during FSP should be dynamic recovery (DRV) happened concurrently with continuous dynamic recrystallization (CDRX) caused by particle-stimulated nucleation (PSN). The developed shear texture relates to the ideal shear textures of D1 and D2 in bcc metals. The prevalence of highly dense arrangement of close-packed planes of bcc and the lowest Taylor factor showed the lowest compressive residual stress which is responsible for better mechanical properties compared with the grain-precipitate refinement.

1. Introduction

Microstructure and texture evolution is one of the imperative key issues to have a better understanding of friction stir welding/processing (FSW/P). Knowing the potential advantages of these two technologies, numerous research efforts have recently been made to understand the details of structural progress during FSW/FSP; so far, such research attempts have been focused mainly on fcc metals such as aluminium alloys [1–3]. On the contrary, a reduced amount of attention has been given to bcc materials [4,5]. It has convincingly been established that the microstructure evolution during FSW/P is a very complex process driven by geometric effects of strain, grain subdivision and thermally activated high angle grain-boundary migration. The electron back-scattered diffraction (EBSD) technique has been considered as a powerful tool, developing better understanding of microstructural advancements and it also enhanced prediction behaviour of material after FSW/P [6]. Although many authors have claimed that FSW/P leads to formation of a refined, low-aspect-ratio grain structure including a significant fraction of high angle boundaries (HABs) [7,8]. However, other studies [9,10] have reported that considerable amount of retained low angle boundaries (LABs) (up to 40%) exists after FSW/P of steels. It has also been revealed that the strain field encircling the rotation tool is predominantly simple shear in nature, so the texture progressed in the stir zone may be described in terms of ideal simple shear components, with the shear plane normal and shear direction aligned approximately perpendicular to and tangential with either the pin column surface or the flow lines in the stir zone, respectively [11,12].

Because of lower temperature experienced during FSW/P compared to conventional welding technique and surface treating, lower residual stresses remain in welded or processed materials [12]. However, there are different opinions about dominant source of the residual stress. For instance, previous study [13] reported that both friction heat and plastic deformation introduce residual stress during FSW of stainless steel. Thereafter, Woo et al. [14] proved that in FSP of 6061 aluminium alloy, the plastic deformation has rather effected than the frictional heating. On the contrary, Buffa et al. [15] proved that the effect of generated heat is more dominant. It calls for a comprehensive study of the effect of FSP rotation rate on residual stress of processed samples in order to find out the origin of residual stress and the consequent properties. Alternatively, Hatamleh et al. [16] have related these different residual stresses results to different material thicknesses, used parameters and the kind of clamping fixtures used to hold the plates in place during FSW/P. Considering these controversial claims about microstructure revolution comprising grain boundaries style, residual stress

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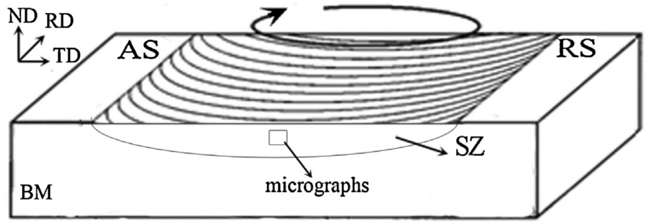

Fig. 1. Schematic of the FSP setup. The rectangular shows the location of the micro-analysis.

and obtained texture after FSW/P needs to be intensively investigated as to how these revolutions happen during vigorous plastic deformations at high temperatures.

Although, previous researches claimed that grain refinement during FSW/P is responsible for mechanical properties improvement [17,18], our previous studies in nanohardness measurements [19] showed that the grain refinement does not accompany with improved mechanical properties. Consequently, it seems that not only microstructure refinement, but also texture plays a significant role on the mechanical properties. Furthermore, relatively little attention has been paid to how grain refinement occurs and what kinds of phenomena are dominant for the grain refinement during FSP. The present study focuses on the mechanisms of grain refinement during FSP of AISI D2 steel, and also, the related texture. For these purposes, the EBSD technique in conjunction with scanning electron microscopy equipped with a field emission gun (FESEM) was employed to provide in-depth insight into microstructural evolution.

2. Experimental procedure

Sheets of as-annealed AISI D2 cold-worked die steel, with the chemical composition of 11.40Cr–1.49C–0.82Mo–0.79V–0.40Si–0.35Mn–0.31Ni–bal Fe (in wt pct), were used. The top surfaces of the plates were mechanically ground using 80-grit emery cloth to remove oxide and contaminants, degreased with ethanol and then subjected to FSP setup. The FSP tool, made of WC-Co, had a columnar shape with a 16 mm diameter shoulder and no pin. Fig. 1 shows schematic image of FSP with the defined directions of normal direction (ND), transverse direction (TD) and rolling direction (RD) and the selected area of microanalysis studies. The FSP was accomplished in position control, using 3° tool tilt angle (α) and 0.1 mm tool penetration into 3 mm thick AISI D2 plates. A constant traverse speed of 385 mm/min and four different tool rotation rates of 400, 500, 600 and 800 rpm were used as the processing parameters. Ar gas was used for surface shielding during FSP.

As-processed specimens were sectioned transverse to the FSP direction and mechanically polished and etched with Nital solution. The microstructures of the specimens were characterized by optical microscope and scanning electron microscopy (SEM) using a field-emission type gun (Hitachi S-4300SE) equipped with electron backscatter diffraction (EBSD) system operated at 15 kV. The section of the specimen for microstructural observation was polished mechanically and then polished under the silicon colloidal solution. The obtained EBSD data were analysed by TSL-OIM analysis software ver. 5.3. All the microstructures of the FSPed specimens were observed from TD of the sheets. Using Cameca Camebax SX50 apparatus (Cameca, Gennevilliers, France), electron probe microanalysis (EPMA) was done to quantitatively measure the composition across the matrix and the carbide particles of FSPed samples. X-ray diffraction was used to measure the residual stress in samples using the multiple exposure technique. Residual stress measurements accomplished on FSPed samples with X-ray diffraction (XRD) with

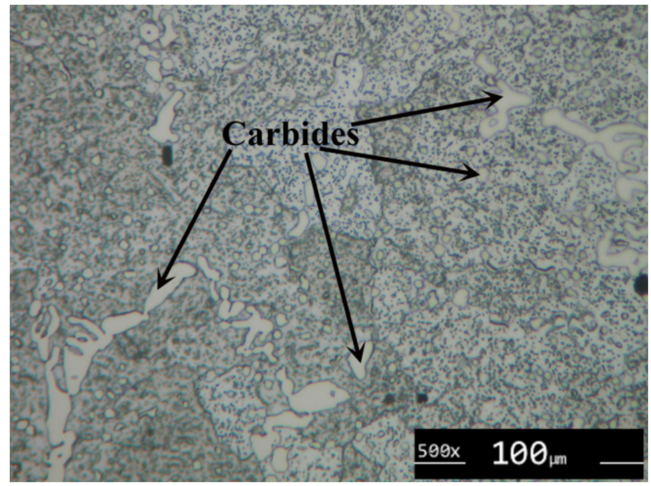

Fig. 2. OM image of the BM.

Cr–K_{α} radiation with a mean penetration depth of 5 μm from surface. Since the primary and largest residual stress in FSW/P occurs in the longitudinal or weld-line direction [13,15], in this research, the residual stress was measured in longitudinal direction. The residual stress was calculated based on the general Hook's law [20].

3. Results and discussion

An optical microscope image of the base material (BM), exhibiting the ferrite matrix and the large carbide particles, is illustrated in Fig. 2. The SEM images of stir zones (SZs) of the FSPed samples at different rotation rates of 400–600 rpm are shown in Fig. 3(a)–(c). They indicate that all regions consist of a microstructure having the ferrite matrix and fragmented carbides originated from the primary large carbides of the BM.

In Fig. 3(d)–(f), the ND orientation colour maps of SZs with different tool rotation rates of 400–600 rpm obtained by EBSD measurements and analysis are shown. The colours in the orientation maps indicate the crystallographic directions of each point parallel to the transverse direction (TD) of the sheet (the normal direction of the observed plane), according to the stereographic triangle shown in the figure. It has been demonstrated that using tool with no pin during FSP, the shear stress generated by the forward motion of the tool works is concentrated near the upper surface of the SZ [21]. So, the shear plane normal (SPN) is always considered to be parallel to ND, while shear directions (SDs) are supposed to be tangential to SZ's boundary in each point. The direction of the shear stress imposed on the SZ after FSP is representative by grain orientations which is much more extensive in the SZ of the FSPed sample at rotation rate of 500 rpm (Fig. 3(e)). In fact, in this condition, FSP arrangement resulted in the formation of high density close-packed planes (CPPs) [22] (shown in green colour) aligned almost 45° to TD in all over the SZ. Comparing the SZ of the FSPed sample at rotation rate of 500 rpm with the SZs of the lower and higher rotation rates of 400 and 600 rpm exhibits lower density of CPPs and higher density of {1 0 0} and {1 1 1} (Fig. 3(d)–(f)). Considering the SZ of 600 rpm FSPed sample, it also seems that lengthening of the grains has been promoted by effective severe plastic deformation and friction heat obtained at higher rotation rates. It can be implied that the grain lengthening is caused by geometric requirements of strain and grain boundary sliding which is happening during superplastic deformation [23].

In grain boundary maps of Fig. 3(g)–(i), the LABs and the HABs are depicted as blue and red lines, respectively. It is obvious that the microstructure of all FSPed samples consists of a mixture of the