Microstructural refining during friction stir processing of SAF 2205 duplex stainless steel

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ABSTRACT

Friction stir processing (FSP) was conducted on a SAF 2205 duplex stainless steel at advancing speed of 50 mm/min and rotational speed of 400 rpm. Characterization of evolved material was studied using electron microscopy equipped with electron back scattered diffraction (EBSD) system. The results indicated that the severe plastic deformation and the heat generated during the FSP developed a very fine microstructure in the stir zone (SZ). It was found that the finest grains with average grain size less than 1 μm were formed in the bottom of the SZ where the material was more likely to receive the lowest temperature in both constituent phases of ferrite and austenite. Therefore, it can be inferred that the material in the bottom of the SZ was less affected from the heat generated by the shoulder. The presence of such severe deformation along with the elevated temperature during the welding procedure inside the SZ activates the occurrence of continuous dynamic recrystallization mechanism throughout the material which seems to be responsible for grain refinement. Moreover, 111 and 110 pole figures of both constituent phases demonstrated that the rotating tool broke the initial microstructure, modified the pre-existence rolling texture of the starting material, and introduced simple shear texture components into the SZ.

Keywords: *Stainless Steels, Ferrite, Austenite, Shear Texture, Continuous Dynamic Recrystallization.*

1. Introduction

Friction stir processing (FSP) is a solid-state processing technique on the base of friction stir welding which was invented and patented by TWI (A British research and technology institution) in 1991, which overcomes many of the problems associated with traditional fusion welding techniques. The FSP utilizes frictional heating along with forging pressure to produce high-strength microstructure. During the process, a specially designed tool plasticizes and mechanically stirs the material under the forging pressure to form a processed zone. As a result, the microstructure of the material is modified while FSP [1]. It is well accepted that the free energy of a crystalline material is increased during deformation by the presence of dislocations and interfaces, and a material containing these defects is thermodynamically unstable [2]. On the other hand, the presence of frictional heat during the processing, exposes the material to the annealing state, and provide some thermally activated processes such as dynamic recovery (DRV) and dynamic recrystallization (DRX) mechanisms through which the defects may be removed or alternatively arranged in configurations of lower energy. Therefore, the concurrence of the high temperature along with the severe plastic deformation in the stirred zone (SZ) results in a very fine recrystallized microstructure. The severe grain refinement during the FSP, has proposed the technique as a useful method for producing ultra-fine grain (UFG) and even Nano grain (NG)

materials. Grain size is considered as one crucial microstructural characteristics which greatly affect the mechanical and physical properties of the material [3,4]. Grain refinement which is usually occurred during the thermo-mechanical processing or cold work, enhances mechanical properties such as strength, wear, and ductility, through Hall-Petch relation without any modification of chemical composition of the base material [5]. It is also well accepted that the grain boundaries are prone barriers to slip of the dislocations [2]. Therefore, smaller grain size provide more barriers which impede the dislocation movements. Impeding the movement of dislocations hinder the onset of plasticity and hence increase the yield strength of the material. It is to be mentioned that the strength of such barriers effectively increases with the disorientation (misorientation angle) [6].

In this regard, there have been conducted some studies on the microstructure refining of duplex stainless steels (DSSs) using FSP or friction stir welding [7-12]. Saeid et al. [7] investigated the influence of welding parameters (including 50-250 welding speeds and 600 rpm rotational speed) on the microstructure and mechanical properties of a SAF 2205 duplex stainless steel (DSS). They reported that very fine microstructures developed in the SZs and indicated that the grain size at center of the SZs tends to decrease from 5 μm in the welded material with 50 mm/min to 1 μm in the welded material with 200 mm/min. These researchers also showed that further increase in welding speed beyond the 200 mm/min resulted in a groove like defect due to the insufficient heating. Mishra et al. [8] studied the microstructure evolution of friction stir processed 2507 super duplex stainless steel with rotational speed of 800 rpm and advancing speeds of 10, 25, 50, 100, 150, and 175 mm/min. they reported the formation of finest SZ microstructure for the processed material with 100 mm/min which was approximately larger than 5 μm. These researchers also reported the formation of rather larger grains with average size of 6.5 μm in the center of SZ at advancing speed of 50 mm/min. It is well accepted that at a constant advancing speed, the generated heat during the process tends to decrease with decreasing the rotational speed [1]. Therefore, this study aims to further investigate the microstructural characteristics of a FS processed SAF 2205 DSS with rotational speed of 400 rpm and advancing speed of 50 mm/min which seems to results in lower heat input and finer grains using

EBSD technique.

2. Experimental Procedure

The material used in this study was a 2 mm thick plate of SAF 2205 duplex stainless steel with dimensions of $2 \times 100 \times 100$ mm^3. The FSP process conducted in a bead on plate configuration at advancing speed of 50 mm/min and rotational speed of 400 rpm parallel with the rolling direction of the provided sample. The FSP tool was designated from a WC-based material with a conical geometry (the diameters of the shoulder, pin base, pin tip, and pin height were selected 16 mm, 4.5 mm, 3.5 mm, and 1.7 mm, respectively). Microstructural studies were conducted using a JSM-6400 JEOL scanning electron microscope (SEM) operated at 20 kV and equipped with a TSL EBSD system. The EBSD analysis was performed with step sizes of 0.1–0.5 μm on the cross section perpendicular to the processing direction (TD-ND plane). The sample for the EBSD analysis was mechanically ground, prepolished with 1 and 0.25 μm diamond pastes and finally electropolished by a solution consisting of 700 mL ethanol, 120 mL distilled water, 100 mL glycerol, and 80 mL perchloric acid at room temperature with a voltage of 35 V for 10 s. A TSL OIM analysis software was used for processing of acquired data.

3. Results and Discussion

Figure 1 shows phase maps obtained from the base metal (BM), thermo-mechanically affected zone (TMAZ), and the SZ. It is apparent from the maps that the phase morphology is changed along the joint from the BM towards the SZ. During the FSP process, the rotating tool broke up the initial lamellar structure of both constituent phases of the initial material in the TMAZ. Running from the TMAZ towards the SZ the material further deformed and the elongated structure of the TMAZ no more exist in the SZ and replaced with a fine equiaxed grains in both phases [10-12]. Another point to be noted is the evolution of the grain boundaries in the resultant regions. Figure 1 also shows the grain boundary maps through the processed regions. High angle grain boundaries (HAGBs), low angle grain boundaries (LAGBs), and coincidence site lattices (CSLs) boundaries are defined by black, red, and blue colors, respectively. This figure qualitatively showed that the frequency of LAGBs is increased in the TMAZ and the SZ. According to the EBSD data, BM consists of ferrite

with average grain size of 2.43 μm and austenite with average grain size of 2 μm which tend to decrease to submicron levels in the SZ. The average grain sizes of the ferrite and austenite phases are calculated to be 780 and 580 nm in the SZ, respectively.

Figure 2 indicates the grain size color coded maps of each constituent phases in the bottom of the SZ. This figure represent more information about the grain size distribution in the SZ. Grain size distributions showed that about the 60 % of the developed grains in the austenite phase are in the range of 148 nm – 1 μm which are defined with red color. It is also obvious from the figure that there have been generated submicron grains throughout the ferrite phase (approximately 37 % percent of the ferrite grains). This behavior also implied that the material in the bottom of SZ is probably less affected from the heat generated by the shoulder. Another point to be noted is that the larger grains are developed in the ferrite in comparison with the austenite. The formation of larger grains in the ferrite phase can be explained regarding its nature. Ferrite is a body centered cubic (bcc) structured

phase which provide lots of slip systems and high stacking fault energy (SFE). Higher SFE of ferrite facilitates the thermally activated phenomena like dynamic recovery and recrystallization at elevated temperatures. The kinetics of such softening mechanisms mainly depends on the temperature at which the deformation occur and the value of the SFE. The higher value of SFE in ferrite accelerated the occurrence of such mechanisms in comparison with the austenite. Therefore, grain growth can be occurred in spite of recrystallization in the ferrite phase during the cooling cycles after welding. Fast kinetic of recrystallization in ferrite provide the grain growth condition, i.e., during the same cooling cycle, ferrite after fast recrystallization has more time to grain growth phenomenon than that of austenite. Santos et al. [8] also reported the formation of larger grains in ferrite rather than the austenite during the friction stir welding of a typical duplex stainless steel.

A detailed statistical analysis of grain boundaries from the BM, TMAZ, and SZ is depicted in Fig. 3. The results showed the austenite is mainly composed of CSLs. Such boundaries tends to develop when a finite fraction of lattice sites coincide between the two adjoining lattices [3].
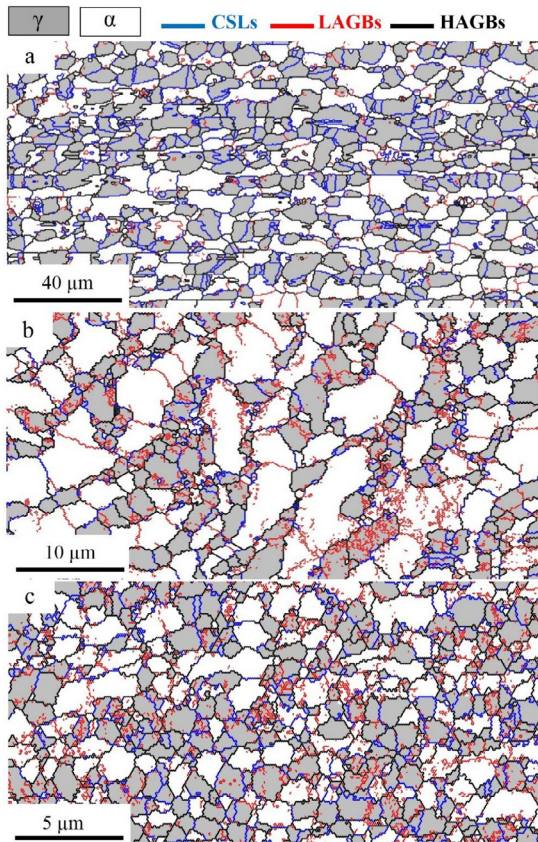

Fig. 1- EBSD phase and grain boundary maps: a) BM, b) TMAZ, and c) SZ.
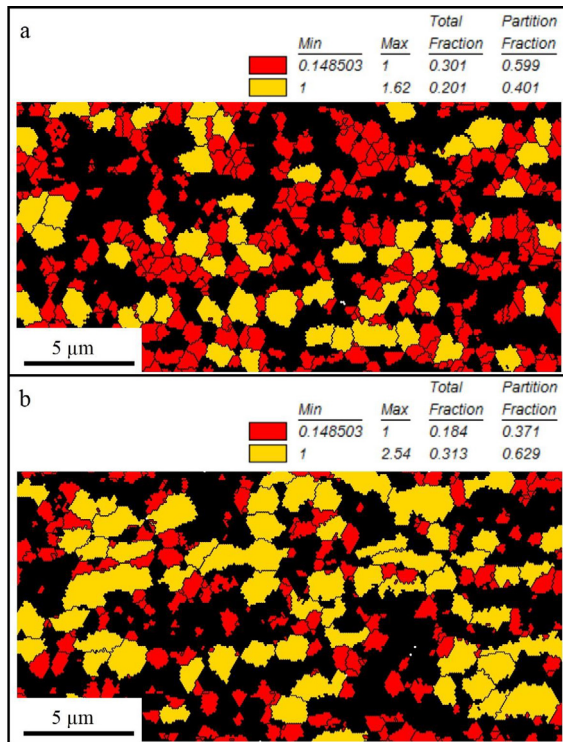

Fig. 2- Grain size color coded maps of constituent phases: a) austenite, and b) ferrite.

This type of high angle grain boundaries commonly develop in the fcc structured materials during the annealing process [13,14]. This behavior from the base suggests that the starting material is in the annealing state. It is also clear from the figure that the frequency of LAGBs is increased in the TMAZ in comparison with the BM. LAGBs commonly form during the dynamic recovery throughout the material. During the deformation large amount of dislocations are produced inside the material to sustain the applied deformation. High temperatures produced during the process assists their movements which eventually results in the formation of sub boundaries or LAGBs. It is also to be mentioned that the amount of generated LAGBs in ferrite is higher than that of austenite which can
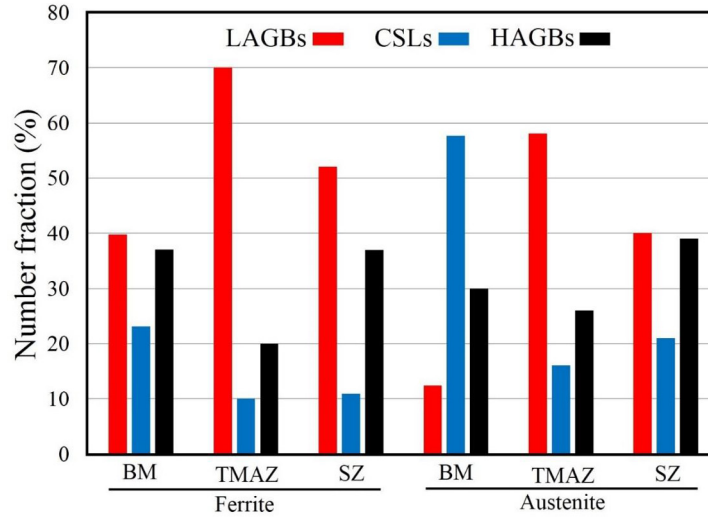

Fig. 3- Grain boundary character distribution from the resultant regions.
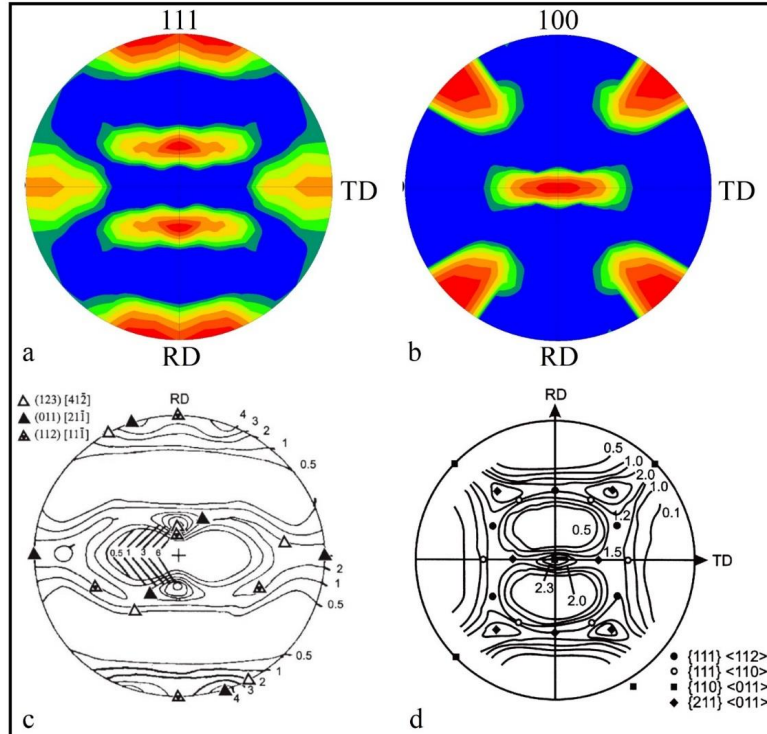

Fig. 4- EBSD data from the BM: a) 111 pole figures austenite phase, b) 100 pole figures of ferrite phase, c and d) 111 pole figures indicating the position of some ideal deformational orientations in FCC structured materials, and d) 100 pole figures indicating the position of some ideal deformational orientations in BCC structured materials [3].
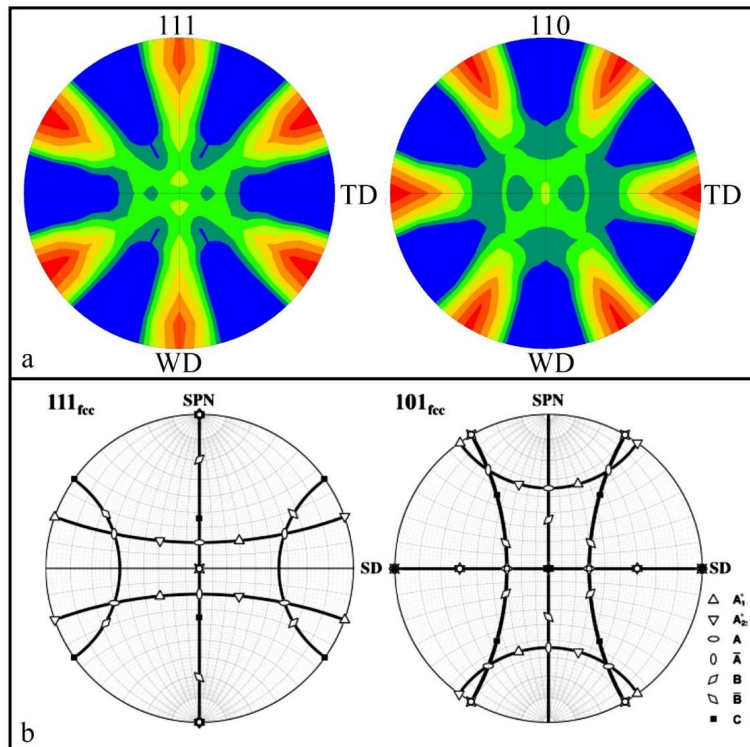
Fig. 5- 111 and 110 pole figures: a) obtained from austenite phase, b) common shear texture components in a FCC structured materials [16].
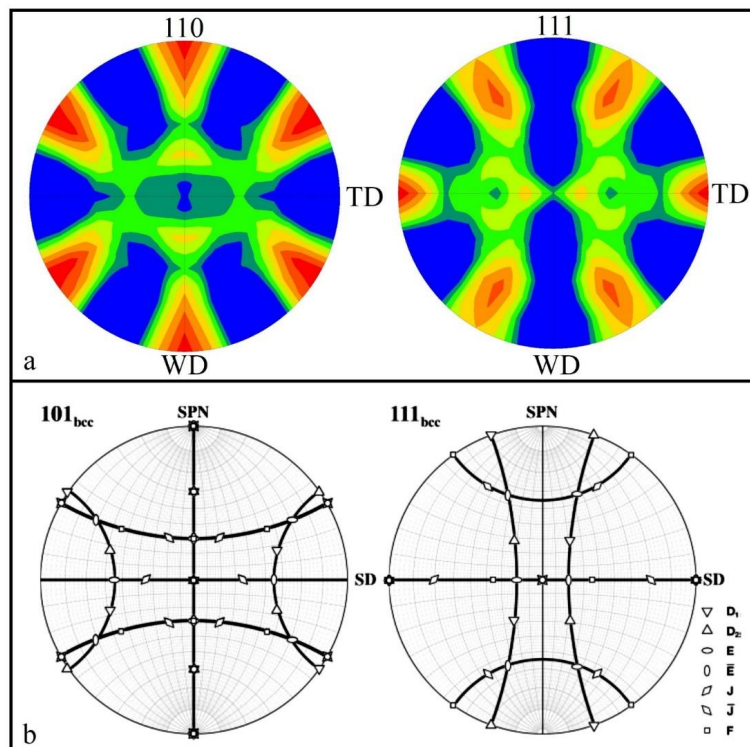

Fig. 6- 110 and 111 pole figures: a) obtained from ferrite phase, b) common shear texture components in a BCC structured material [16].

be related to the higher SFE of ferrite. Approaching the SZ, the fraction of LAGBs is decreased, and the fraction of HAGBs is increased in comparison with the TMAZ. This behavior implies that the HAGBs are developed at the expenditure of the LAGBs. HAGBs continuously can be established from the LAGBs through the occurrence of continuous dynamic recrystallization [3].

Texture analysis from the BM in figure 4 indicates that the starting material in both constituent phase of ferrite and austenite has rolling texture [3]. It is well approved that during deformation of a polycrystalline material the orientations of individual grains change relative to the directions of the applied stresses. This type of modification mainly takes place by the easy slip planes. These planes are re-oriented during the deformation so that the individual grains to be compatible with the external shape of the deformed material. Such rotations produce a preferred direction commonly called as texture [15]. Moreover, the slip phenomenon usually occur on the densely packed planes and orientations. Figures 5 and 6 show the 111 and 110 pole figures as densely packed planes and orientations of each constituent phase in the SZ of the material. Comparing the obtained pole figures (figure 5a and 6a) with the position of common shear texture components (figures 5b and 6b) approved the presence of simple shear texture in the SZ [16]. The formation of simple shear texture has been also reported in the SZ 304L austenitic [14] and SAF 2507 duplex [17] stainless steels the presence of deformation texture in newly developed microstructure approved the occurrence of CDRX mechanism. The later phenomenon tends to occur preserving the deformation texture.

4. Conclusion

The friction stir processed SAF 2205 duplex stainless steel was investigated using electron back scattered diffraction technique in the present study. The results showed that the base metal equiaxed microstructure severely deformed in the thermo-mechanically affected zone followed by the formation large amount of low angle grain boundaries. A very fine microstructure was developed in the stir zone (SZ) with the formation of large quantities of high angle grain boundaries

through the occurrence of continuous dynamic recrystallization (CDRX) mechanism. The presence of simple shear texture development in the SZ confirmed the occurrence of CDRX mechanism.

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