Original Article

Frictional angular rolling extrusion of interstitial-free steel sheets

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A B S T R A C T
Interstitial-free steel sheets were processed using a novel severe plastic deformation technique – frictional angular rolling extrusion (FARE), in order to produce ultrafine grained structures. The deformation was carried out at room temperature and individual sheet specimens were repeatedly processed to various passes. An overall grain size of 200 nm was achieved after eight passes (or an equivalent total strain of 5.3). The present paper reports the evolution of microstructures during deformation, which were examined and characterized using electron backscatter imaging and high resolution EBSD in a field emission gun SEM. The mechanisms of grain refinement are discussed.
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1. Introduction

In the last two decade or so, extensive research has been carried out in order to develop and optimize severe plastic deformation (SPD) techniques for commercial utilization. So far, of all the SPD techniques, equal channel angular pressing (ECAP) has attracted the most attention, due to its effectiveness of grain refinement and capability of producing UFG structures at scales large enough for structural applications [1–3]. However, the ECAP technique in its original form has disadvantages for commercial employment, such as limited scalability, high scrap rate and high load requirement. These limitations, plus its batch nature, result in low productivity and high material waste. Several attempts have been made to transform ECAP into a continuous process. For example, continuous constrained strip shearing (C2S2) [4] and ECAP-Conform [5] are methods for continuously processing sheets and rods to produce UFG structures. Although these techniques exhibit some useful features, they all use a long confined feeding passage for building up pressure on the workpiece to generate frictional extrusion force. This causes several problems and a major one is that the work-piece undergoes a reduction in thickness, or shape change, before entering into the die’s shear zone. Consequently, the material experiences a complicated deformation path and redundant strains. This results in reduced grain refinement effectiveness and excessive requirement for torque, imposing practical limitations for scale-up.

Frictional Angular Rolling Extrusion (FARE) was developed to overcome the above-mentioned problems [6] and has been successfully applied to process UFG aluminum sheets [7]. The
FARE technique, as schematically shown in Fig. 1a, involves the use of an ECAP based die assembly combined with several innovative steps, including the use of a frictional driving roll, which applies a normal pressure to the work-piece without plastic compression. Thus, processing can be done continuously, like rolling, and plastic deformation occurs by simple shear as it does in ECAP. The main benefits that the FARE technique offers include the capability of processing large volumes of material in various forms, high productivity, low scrap rate, and reduced extrusion force requirement, etc. The present paper reports the result of a feasibility study on the application of the FARE technique in the production of UFG steels, focusing on the microstructure evolution and mechanisms of grain refinement during the processing of an interstitial free steel (IF steel).

2. Experimental

Fig. 1 illustrates the principle of the FARE setup established for the present investigation. The driving roll rotates to provide a torque (M) and at the same time applies a pressing force (P) to the work-piece against its supporter. The first extrusion channel is virtually formed between the driving roll and the workpiece supporter whose working surface is made to match the curvature of the sheet on the driving roll. The second extrusion channel was a short slot, to minimize friction, in the stationary die assembly. The die angle was 120° and the configuration of the die assembly and the reference coordinates used in this paper are shown in Fig. 1b.

IF steel sheets, with dimensions of 2 mm × 20–50 mm × 1000 mm, were used for the FARE processing. The material was cold rolled and annealed 820 °C for 40 min, giving a fully recrystallized starting microstructure of an average grain size of 67 μm. Deformation was carried out at room temperature and at a rate of 0.6 m/min. The sheets were processed to a various accumulative number of passes of up to 8 following route A, i.e., the sheet orientation maintained constant throughout, giving a maximum equivalent true strain of 5.3. The driving roll was mechanically roughened to enhance friction and an MS2 spray was employed to lubricate the interface between the workpiece and its supporter, the working
surface of which was machined by spark erosion and polished to a finish of 0.5 \( \mu \text{m} \). The deformation structures of the processed sheets were examined in a FEG-SEM, with the help of backscatter imaging and high resolution EBSD. The examination was conducted on the TD plane after mechanical grinding and polishing to 0.5 mm and electropolishing in a solution of 20% nitric acid in methanol at \( -30^\circ \text{C} \) and 12 V for 60 s. EBSD data were analyzed by HKL-Channel5 software.

3. **Results and discussions**

3.1. **Process performance**

Using the setup illustrated in Fig. 1, the FARE processing of IF steel sheets performed successfully under a range of conditions. Deformation was found to be reasonably uniform over the sheet cross-section and the effect of surface friction was limited as shown in Fig. 2. A significant surface friction affected zone, with a depth of \( \sim 100 \mu \text{m} \), was only seen in the bottom surface, where the sheet is in contact with the stationary die surface, while at the top surface the microstructure was almost indistinguishable from the matrix. This phenomenon is a characteristic feature of the FARE process, due to the fact that the bottom surface experiences sliding contact with the support block, whereas the top surface moves at the same speed as the driving roll. As shown in Fig. 2, the surface damage was the worst after the first pass and was gradually healed to a certain extent with increased number of passes. This is probably because the starting material exhibited higher friction coefficient and less resistance to local tearing before being hardened upon extensive processing.

Fig. 3 shows the microstructure transition between first and second pass across the shear plane from a sample that was half-way through the 2nd pass processing. It can be seen that plastic deformation occurs in a narrow region (<350 \( \mu \text{m} \)) along the die shear plane (SP), as the microstructures outside of this region characterize the material flow pattern of either one pass ECAE or two, which suggests that the plastic deformation during the FARE processing occurred primarily by simple shear. This is desirable as simple shear exerts the highest amount of material spin among all possible deformation modes for a given strain and theoretically generates the most orientation distortion.

3.2. **Microstructure evolution**

The backscatter electron images in Fig. 4 show the evolution of fine scale microstructures with increased number of FARE pass. As shown in Fig. 4a, dislocation cell bands are the characteristic features of the microstructure after the first pass of FARE. The cell bands are approximately aligned with the die shear plane, i.e., at an angle of 60\(^\circ\) to the extrusion direction and the die shear plane, respectively.

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**Fig. 3** – FEGSEM backscattered image showing the geometry of the deformation zone in the simple shear plane.

**Fig. 4** – FEGSEM backscattered images showing the evolution of fine-scale microstructure with the increased number of FARE passes: (a) 1 pass, (b) 2 passes, (c) 3 passes, (d) 4 passes, (e) 6 passes, and (f) 8 passes. ED and SP indicate the extrusion direction and the die shear plane, respectively.
direction (ED). A relatively weaker second set of dislocation cell bands, aligned at an angle of about $10^\circ$ to ED was also observed. Both sets of dislocation cell bands exhibited varied densities in different grains. EBSD analysis revealed that the cell bands generated misorientations of about $2.96^\circ$ on average across their boundaries. The 2nd pass microstructure was composed of both cell bands and micro-shear bands (Fig. 4b). Upon deformation in the 2nd pass, the die shear plane cell bands formed in the 1st pass rotated roughly to be in line with the overall grain elongation direction. As shown in Fig. 5, the shear banding tool place along the die shear plane, cutting through the 1st pass cell bands. The shear bands are different form cell bands in a sense that they are associated with strain localization and generation of higher misorientations. In the 3rd pass, the microstructure was apparently compressed and a fiber structure developed as the initial grain structure was essentially destroyed. Shear banding in the die shear plane also took place in the 3rd pass (Fig. 4c), although the intensity was weaker than in the 2nd pass. A uniform, fine lamellar structure formed after four FARE passes as shown in Fig. 4d and little evidence of shear banding along the shear plane was detected. The lamellar structure was further compressed in the transverse direction and rotated toward ED during the following extrusion as shown in Fig. 4e and f. After eight passes, the spacing of the fine lamellar structure in the normal direction (ND) can be estimated from Fig. 4f to be $\sim 200$ nm.

The introduction of high angle boundaries (HABs) lies in the core of grain refinement during severe plastic deformation. In the present work, high resolution EBSD technique was used to determine the HABs developed after different FARE passes. Example for EBSD maps is shown in Fig. 6, illustrating the evolution of the deformation structure, particularly of HABs with strain. In the EBSD maps presented, HABs in black lines are defined as having misorientations higher than $15^\circ$ and low angle boundaries (LABs) in white lines are those misoriented between $1.5^\circ$ and $15^\circ$. Boundaries misoriented below $1.5^\circ$ were cut off due to the noise effect. The misorientation distribution, grain size and high angle grain boundary fraction determined from EBSD measurements as a function of FARE pass number are presented in Figs. 7 and 8. It can be seen from the figures that the dislocation substructures formed in the early stages of deformation only subdivided the initial grain structure by LABs misoriented a few degrees and that the fraction of HABs increased gradually with increasing strains. A significant fraction of HABs developed after the 3rd pass, although their distribution was still heterogeneous. An elongated, uniform HAB structure formed after six passes, and HABs became dominant with a fraction over 50%. For this microstructure, the

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**Fig. 5** - FEGSEM backscattered images showing the features of deformation bands and shear bands in a 2nd pass FARE microstructure.

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**Fig. 6** - EBSD orientation maps showing the evolution of deformation structure with the increased number of FARE passes: (a) 2 pass, (b) 4 passes and (c) 8 passes.
average spacing of HABs was at a submicron scale, converging with the length scale of the LAB substructure. With further two more passes applied (total strain of 5.3), a final HAB fraction of 61\% was obtained and the HAB spacing decreased to 0.39 µm, whereas the overall boundary spacing, including both HABs and LABs, was down to about 0.25 µm. As shown in Fig. 5, the microstructure became relatively more equiaxed and in some regions, pancake-like submicron grains are seen to have formed within the lamellar structure. This UFG structure occurred at a lower strain than that expected from conventional ECAP processing of the comparable IF steel [8], although the fraction of HAB area still showed some potential to increase, and grain aspect ratio to reduce, upon further deformation. Nevertheless, the overall trend of microstructural evolution and grain refinement observed in the present work is similar to that reported in previous ECAP studies [8–10].

3.3. **Mechanisms of deformation**

Grain refinement by severe plastic deformation is mainly attributed to the development of strain induced high misorientations via grain subdivision and this is true in the FARE processing. As shown above, grain subdivision in the first pass took place primarily by the formation of dislocation cell bands. Unfortunately, the misorientations associated with these cell bands are very low on average and no evidence has shown their direct contribution to grain refinement. However, careful EBSD examination revealed that shear banding occurred in many areas where the die shear plane cell bands intersected with the 2nd set of cell bands. Fig. 9a is an example of shear bands formed in such areas and it is seen that HABs have formed in association with the shear bands. EBSD analysis showed that the accumulative misorientation generated by shear banding was in the range of 5–25°. Such an orientation spread within a shear banding area is shown in the pole figure of Fig. 9b.

Deformation banding via orientation splitting was found to occur in the 1st pass during ECAP processing of fcc metals [11,12] but it was not so evident in the present deformation. This is not surprising because IF steel with a bcc lattice structure has 48 slip systems in operation during deformation, which is four times of the operating slip systems for fcc metals. The strain accommodation in bcc is therefore easier and orientation splitting is limited in the early stages of deformation. However, deformation banding via orientation splitting has been found to take place in IF steel at large strains in rolling [13]. This is in agreement with the observations in the present work. It was found that deformation banding was an important mechanism of grain subdivision in
Shear bands was of banding strain the operation leads shown varied in Fig. 9. This is a characteristic feature of deformation banding through orientation splitting, although the morphology of the deformation bands is not typical of those usually observed in rolling or plane strain compression. Shear banding was another important mechanism responsible for the generation of new HABs in the 2nd pass. Actually, the 2nd pass microstructure exhibited much higher density of shear bands than in the 1st pass. This is largely because there is always a strain path change from 1st pass to 2nd pass during the repetitive FARE and the simple shear in the 2nd pass can only occur on different operation slip systems, cutting through the cell bands formed in the 1st pass. The collapse of the cell bands leads to softening and promotes strain localization. As a result, shear banding occurred. EBSD measurements showed that, similar to the situation in the 1st pass, shear banding in the 2nd created a mixture of both low and high angle misorientations (5–35°). The area arrowed B in Fig. 9c shows the structure of HABs generated by shear banding in the die shear plane. Shear bands were also seen to form in the direction parallel to that of the 2nd set cell bands formed in the 1st pass (see arrow C in Fig. 9c). It should be pointed out that deformation banding tended to take place in grains with lower density of 1st pass cell bands, whereas shear banding took over in grains with intense cell bands. Shear banding was also observed in the 3rd pass together with orientation splitting in a less-defined mode. Grain refinement during the later stages of FARE was mainly due to the geometrical compression of the HABs generated in the first few passes, in response to the accumulative shear strain applied, which determined the HAB spacing. On the other hand, the breakup of the lamellar structure led to the formation of more equiaxed grain structures in the 8th pass. These are similar in principle to the findings during normal ECAP processing [1,2] and will not be discussed in detail here.

4. Conclusions

(1) IF steel sheets were successfully processed by novel frictional angular rolling extrusion (FARE) to various total number of passes.
(2) The FARE process displayed high effectiveness in grain refinement and a UFG grain structure with an average grain size of ~200 nm was obtained after eight passes with 61% of high angle boundaries in the microstructure.
(3) The plastic deformation in the FARE process showed similar features to those of ECAP and the material flow was substantially by simple shear. Although the sliding movement between the workpiece and the supporting surface caused some damages in the early stages of processing.

(4) The grain refinement mechanisms were found to be directly linked to the shear banding, deformation banding and the geometrical compression of microstructures.

Conflicts of interest

The author declares no conflicts of interest.

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