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Microstructure and Mechanical Properties of Semi-continuous Equal-channel Angular Extruded Interstitial-free Steel

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Abstract: An innovative method called semi-continuous equal-channel angular extrusion (SC-ECAE) has been developed to produce ultrafine grained steel by inducing severe plastic deformation. In contrast to the external forces that are exerted on specimens in traditional ECAE, the driving forces are applied on the dies in the novel SC-EACE process. Commercial interstitial-free steel sheets with width of 160 mm and thickness of 2 mm were processed repeatedly to various passes at room temperature using this method. The microstructural evolution was characterized using high-resolution electron backscatter diffraction (EBSD), and the mechanical properties were investigated by tensile testing. The EBSD images indicated that the fraction of high-angle boundaries (HABs) began to increase gradually after four passes; after six passes, elongated HAB structures with nearly submicron-scale average spacings were formed. The tensile testing results showed that strengthening was accompanied by a decrease in tensile ductility, but no significant anisotropy was observed. After 10 passes, a final HAB fraction of about 90% and an overall grain size of 0.55 μm, yield strength of 638.7 MPa, an ultimate tensile strength (UTS) of 710.3 MPa, and a total elongation of 12.0% were obtained.

Key words: severe plastic deformation; semi-continuous equal-channel angular extrusion; IF steel; ultrafine grained structure; EBSD

Grain refinement is one of the most basic and important methods for microstructural control in metallic materials. The research boom in severe plastic deformation (SPD) techniques has been prevalent for many years because of the ability of these methods to produce ultrafine microstructures and even nanoscale microstructures. SPD techniques include equal-channel angular press (ECAP)[1,2] or equal-channel angular extrusion (ECAE)[3], high-pressure torsion[4], accumulative roll bonding[5,6], and asymmetric rolling[7]. These methods are also attractive in the steel industry, and many attempts to introduce SPD methods, such as continuous constrained strip shearing[8] and ECAP-conform[9] and continuous frictional angular extrusion[10], to steel production have been made[11,12]. However, the potential of these techniques is still being explored, and some disadvantages such as limited scalability, high scrap rate, high load requirement, and low productivity remain challenging. As one of the novel methods based on SPD, semi-continuous equal-channel angular extrusion (SC-ECAE) incorporates ECAE to achieve severe deformation[13], while allowing the easy processing of large specimens by exerting the external forces on the dies instead of on the specimens. The main benefits of SC-ECAE are its capability to process large materials to various extents, high productivity, low scrap rate, and reduced extrusion force requirement. The main objective of the present investigation is to refine the microstructure and improve the mechanical properties of interstitial-free steel using SC-ECAE.

1 Experimental

The principle of the SC-ECAE method is shown in Fig. 1. The first extrusion channel is composed of Die A and Plane C, and the second channel is made up of Die A and Die B. The second channel is kept shorter than the first one to reduce the resistance to the specimen exerted through the second channel. The

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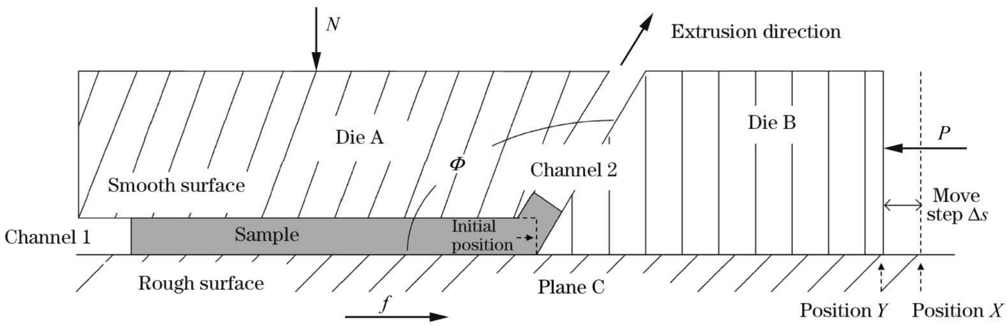

Fig. 1 Schematic of SC-ECAE

contact surface between Die A and the specimen is ground as smooth as possible to reduce the friction; in contrast, the contact surface between Plane C and the specimen is rough. The process is as follows. First, the specimen is fed to the initial position in the first channel and held in place by the force N exerted on Die A. Second, Die B is moved by force P from Position X to Y, which is defined as step Δs. Under this condition, the specimen is pushed through the extrusion angle Φ and it enters the second channel, covering the distance Δs. Third, the forces N and P are released, allowing Die A and Die B to return to their initial positions. Subsequently, the above process is repeated until the entire specimen has gone through the extrusion angle, which is called one pass. The specimen is processed through various accumulative passes with the orientation remaining constant throughout. The advantage of this method is that several types of forces act on the dies instead of the specimen. Thus, it is easier to apply each force, allowing the specimen size restrictions to be loosened. This can greatly enhance the workability, in particular for the processing of sheets. Thus, SC-ECAE can potentially meet the requirements for practical applications.

A pilot SC-ECAE setup was recently established for the present investigation. Commercial interstitial-free (IF) steel sheets with thickness of 2 mm, width of 160 mm, and length of 1000 mm were used for the SC-ECAE processing. The chemical composition of the investigated material is given in Table 1. The material was cold rolled and annealed at 820 ℃ for 40 min, giving a fully recrystallized starting microstructure with an average grain size of 24 μm. Deformation was conducted at room temperature with a rate of 0.01 m/s; the detailed parameters are shown in Table 2. The sheets were processed to varying numbers of accumulative passes (up to 10), giving a maximum equivalent true strain of 4.8, with the sheet orientation remaining constant throughout. Plane C was mechanically roughened to enhance friction, and an MS2 spray was employed to lubricate the interface between the specimen and Die A. The deformation structures of the SC-ECAE-processed sheets were examined by FEG-SEM equipped with high-resolution electron backscatter diffraction (EBSD) on the transverse direction (TD) plane after mechanical polishing and electropolishing. The EBSD data were analyzed using HKL-Channel5 software. The mechanical properties were tested by a Zwick Z100 tensile tester.

Table 1 Compositions of the material mass%

C	Si	Mn	P	S	Cr+Ni+Mo
0.0014	0.006	0.134	≤0.020	≤0.005	≤0.01

Table 2 Parameters of SC-ECAE process

Pass number	2	4	6	10
P/kN	350	420	430	480
N/kN	550	650	700	750

2 Results and Discussion

2.1 Microstructural evolution

As shown in the SEM images in Fig. 2, the microstructural refinement generally intensifies with increasing the number of deformation passes. Severe plastic deformation, which was essentially caused by simple shear, was found in a narrow region along the intersectional plane of the two extrusion channels (referred to hereafter as the die shear plane) after every pass. In addition, the stresses on the TD planes of the deformation structures obtained from the samples processed to all levels of strain were reasonably uniform over the entire cross-sections of the specimens.

As shown in Fig. 2(a), the initial equiaxial grains began elongating after two passes. In the following