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PRINCIPLES OF EQUAL-CHANNEL ANGULAR SHEET EXTRUSION (ECASE): APPLICATION TO IF-STEEL SHEETS

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Abstract: The present study reports the principles of a new system, "*equal-channel angular sheet extrusion (ECASE)"*, which has been designed and manufactured for continuous processing of IF-steel sheets. IF-steel sheets with 1.2 mm thickness and 200 mm width were processed using this system following route-A up to eight passes at room temperature. Microstructural evolution and mechanical properties were investigated as a function of number of passes. The ECASE process increased considerably both σ_y and σ_{UTS} values of IF-steel sheets. The σ_y after one pass was nearly twice as high as that of the as-received one. After eight ECASE passes, the σ_y and σ_{UTS} reached to about 499 MPa and 525 MPa, respectively, which were 2.6 times and 1.9 times higher than those of the as-received ones. However, the processed sheets show limited tensile ductility, which needs to be enhanced with further appropriate processes to be utilized in practice. It can be concluded that the use of ECASE provides a simple and effective procedure for improving the strength of IF-steel sheets.

1. INTRODUCTION

Severe plastic deformation (SPD) is one of the most effective methods to fabricate ultrafine-grained (UFG) steels having submicrometer or even nanometer grain sizes [1]. Among the SPD techniques, equal-channel angular extrusion/pressing (ECAE/P) is the most successful procedure to date because of its inherent advantages: uniform deformation through the billet cross section, large billet sizes and efficient grain refinement and microstructural control via different combinations of processing routes [2]. The UFG materials produced by ECAE have superior mechanical properties compared to coarse-grained (CG) counter parts. In general, higher strength with moderate ductility [3,4], improved impact toughness [5-6] and extended fatigue life [7,8] have been validated for wide range of metallic materials after multi-pass ECAE. Such experiments in mechanical properties seem to be beneficial for producing high strength and light-weight components [9].

The ECAE technique in its original form has certain handicaps for commercialization making it a batch-type technique that provides low product yield [10,11]. In order to make ECAE process more applicable to the mass production, few continuous ECAE processing techniques have been proposed. Conshearing [12], continuous constrained strip shearing (C2S2 or CCSS) [13], and continuous fric-

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tional angular extrusion (CFAE) [14] have been recently reported as continuous ECAE processes to produce UFG sheet materials. In these methods, in general, a modified ECAE die placed at the end of rolling mills. Required feeding force for the process is provided by the friction between sheet sample and mill surfaces. Hence, in order to reach enough feeding force, different combination of the mill systems, i.e. one large mill and satellite mills in conshearing, two mills in C2S2, and one mill supported with a static block in CFAE, are used. In addition, some precautions are taken, such as roughening the mill surfaces, in order to gain more driving force [15]. One of the characteristic features that distinguish these methods from each other is the amount of deformation applied per each pass in-between the mills during the feeding stage. In the C2S2 and conshearing, sheet thickness decreases plastically in-between the rolling mills in the feeding step, and then initial thickness is recovered via shearing at the corner of the ECAE die. Such feeding procedure causes complicated and somewhat heterogeneous strain distribution in sheet samples.

To date, continuous ECAE methods have generally been applied to non-ferrous metals including 1050 [14-15], 1100 [12,16], 7050 [17] Al alloys, and AZ31 Mg alloy [18-19]. As considering the manufacturing industry, many types of steels are widely used in the sheet forms. Among them, interstitial-free (IF) steels are generally used in the sheet forms for automobile panels that could have benefit from both high strength and adequate ductility in order to form light, fuel efficient, and durable car bodies. The CG IF-steel sheets exhibit excellent drawability and high planar isotropy due to its ultra low interstitial content [20]. However, they have relatively low strength because carbon and nitrogen atoms in solution of IF-steel are captured by titanium and/or niobium during baking process [21]. Considering the single-phase ferritic microstructure of IF-steel, very limited strengthening methods can be applied to IF-steel for enhancing its properties. Therefore, strengthening IF-steel via grain refinement is the most viable method since UFG materials tend to have high strength without significantly sacrificing ductility [21]. Conventional ECAE processed IF-steels demonstrated UFG microstructure and strengthening with adequate plasticity, achieved with the aid of post-ECAE annealing [7,8,21].

If the ECAE can be successfully applied to IF-steel sheets in a continuous manner, then it would also be possible for controlling their mechanical properties and formability. Therefore, a couple of studies have been conducted on processing of IF-steel sheets via modified ECAE tools [21,22]. Yan *et al*. [22] applied the CFAE method to IF-steel sheet samples with the dimensions of 2mm · 20~50 · 1000 mm up to 8 passes using an ECAE die with a channel angle of 120°. Jin *et al*. [21] applied the C2S2 method to IF-steel sheets with a thickness of about 1 mm with similar ECAE die parameters. Both of these reports [21,22] were mainly focused on the texture evolution and microstructural refinement of IF-steel sheets after processing. However, the change in mechanical properties of IF-steel sheets after multi-pass continuous ECAE, and their relation to the microstructure has not yet been investigated. In addition, there is limited information on the continuous ECAE processing systems. Thus, any effort focusing on the improvement of current ECAE systems deserves attention for their insertion into the industrial practice.

In this present work, we introduce the principles of a modified ECAE sheet processing method named "*equal-channel angular sheet extrusion (ECASE)"*, designed and constructed for producing UFG IF-steel sheets with improved strength in a continuous manner. Mechanical properties (room temperature tensile response and hardness) of the Ti-stabilized IF-steel sheets along with the microstructural evolution were investigated after multi-pass ECASE following route-A.

2. EQUAL-CHANNEL ANGULAR SHEET EXTRUSION (ECASE): THE TOOL AND PROCESSING

The schematic representation and the picture of the ECASE system designed and constructed are shown in Figs. 1a and 1b. Fig. 1c shows the picture of IF-steel sheet samples in the as-received and ECASE-processed states. The ECASE system consists of two main sections including the feeding (or driving) and the ECAE die (or processing) units. In feeding unit, two pairs of mills placed closely one after another to provide required driving force for the ECAE process. The diameter and the width of the mills are 80 mm and 180 mm, respectively. The main center part of mill surfaces was finished via grinding in order to decrease the surface roughness and obtain smooth surface finish on the processed samples. The driver sides of the mill surfaces were further machined to obtain a jaw-face-like surface in order to increase the driving force, as shown in Fig. 1a. The diameter of each driver side is machined 0.05 mm larger than mill diameter, and its width is chosen as 20 mm. The gap in-between two vertical mills was adjusted so that the sheets are subjected to

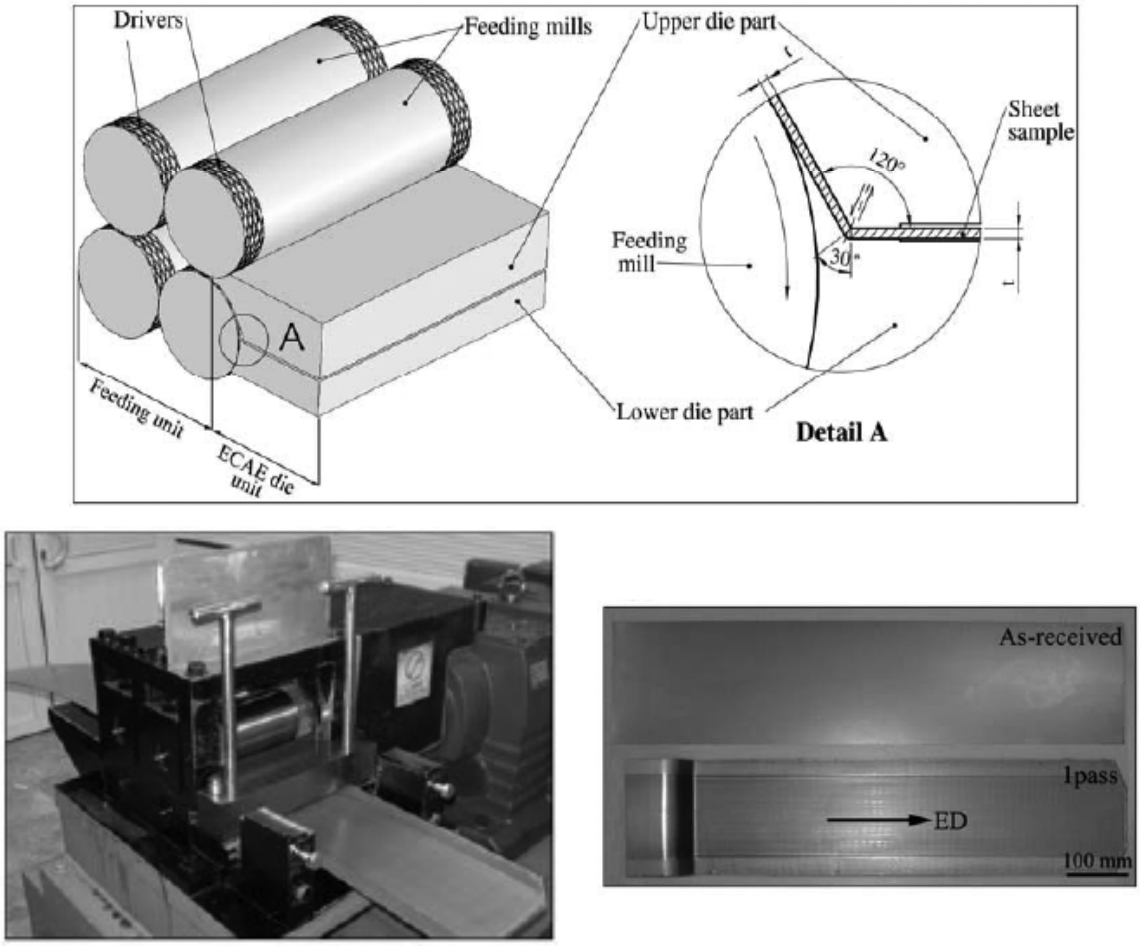

Fig. 1. (a) A schematic representation and (b) the picture of the *equal-channel angular sheet extrusion (ECASE)* system. (c) shows the picture of sheet samples before and after one pass ECASE.

elastic strain only during feeding through first and second mill sets. In addition, total compressive strain of the sheet samples is provided by first and second mill sets in order to increase feeding stability. Both mill sets were synchronized by an electromechanic system to prevent any misfeeding.

A modified ECAE die system was placed at the end of the feeding unit (Fig. 1a). This system was fixed by combining two steel blocks (upper and lower die parts in Fig. 1a), and the inlet and outlet channels were formed by carefully adjusting the gap in-between them. The inlet channel of the die is bounded with upper die part and mill surface. The die angles as the main geometric parameters of the system were chosen as 120° for the die angle (Φ), and 30° for the outer corner curvature angle (Ψ). These geometrical parameters were determined by adjusting the channel geometry to obtain better processing results. For this purpose, many tests were made with the different die angles, and these angles given above were found to be the best ones among them to gain sufficient deformation results on IF-steel sheets. Considering the existence of the oblique radius and dead zone, the equivalent shear strain induced by the ECASE die is about 0.65 in each ECASE pass according to the formula given in [23]. It should be mentioned that the system presented here was designed and built in lab-scale, but it could be easily adapted to the industrial production by scaling up. Furthermore, this system was produced especially for the processing of steel sheets, but it can also be easily applied to other sheet materials.

Table 1. Chemical composition of Ti-stabilized IF-steel sheets (wt.%).

C	Si	Mn	P	S	Ti	Fe
0.004	0.012	0.20	0.012	0.009	0.10	Balance

3. EXPERIMENTAL STUDY

3.1. The ECASE processing of IF-steel sheets

In this study, Ti-stabilized IF-steel sheets were used for ECASE processing with a nominal composition given in Table 1. The IF-steel sheets were supplied from ERDEMIR, Inc., Zonguldak-Turkey. The sheets were initially produced via cold rolling after the slabs had been hot rolled. Then, the sheets were annealed at 790 °C. The samples for ECASE with a thickness of 1.2 mm, width of 200 mm and length of 800 mm were cut from these sheets. The sheet ECASE process was conducted at room temperature up to eight passes following route-A, in which the sheet orientation maintained the same in successive passes. Feeding (processing) speed was chosen as 0.18 $m \cdot s^{-1}$ and standard mineral oil was used to reduce the friction between die channels and sheet samples.

3.2. Microstructural examination

Optical microscopy (OM) was used to investigate the microstructural evolution of IF-steel sheet samples. The specimens for optical microscopy were prepared from the transverse and flow sections of the ECAE-processed sheet samples (Fig. 2). The specimens were then mechanically grinded down to 1200 SiC grit and polished with 1mm and 0.3 mm alumina paste followed by etching with Marshall's reagent [24].

3.3. Mechanical behaviors

The effect of ECASE process on the mechanical response of IF-steel sheets was examined through room temperature tensile tests and hardness measurements. Room temperature tensile tests were conducted at a strain rate of about 0.00735 s^{-1} using dog-bone shaped flat specimens with a nominal gauge section of 25x6x1.2 mm. The tensile specimens were machined from the processed sheet samples, the tensile axis of which was laying parallel to the extrusion direction (Fig. 2). Tensile tests were conducted under monotonic loading using an Instron 3382 test frame with a video type extensometer for monitoring the strain during the experiment. Stress-strain curves and average tensile properties (the strength and ductility values) of the sheets were determined using three to five companion specimens.

The micro-hardness measurements were performed on both flow and transverse planes (Fig. 2), and the average hardness values and their variation along the thickness were determined. The Vickers hardness measurements were done with a load of 0.98 N for a dwell time of 10 s using a Struers Duramin-3 micro-hardness tester.

4. RESULTS AND DISCUSSION

4.1. Microstructure

Optical micrograph of as-received IF-steel sheet is shown in Fig. 3. The microstructure consists of equiaxed and coarse-grained (CG) ferritic structure with an average grain size of about 30 μm. Figs. 4a-d show the microstructure of IF-steel sheets processed by six and eight ECASE passes following route-A. These micrographs mainly show the morphological changes in microstructure occurred during ECASE. The macro-structure of the grains is mostly retained, and their long-axis aligns mostly with the inclination plane and its inclination angle from the extrusion direction decreases with the number of passes. From Figs. 4b and 4d, the grains incline at an angle of about 46° after six passes and 38° after eight passes towards the axis of the die exit channel (*x*-axis). The morphological changes are in agreement with those obtained in bulk ECAE processing following route-A in the literature [5,6,25]. The optical microstructural examinations can provide information, to some extent, about microstructural alterations leading to the change in mechanical properties of IF-steel sheet after ECASE, but further TEM/EBSD investigations are needed on the microstructural evolution for clarifying the grain refinement mechanisms in more detail. Because, grain

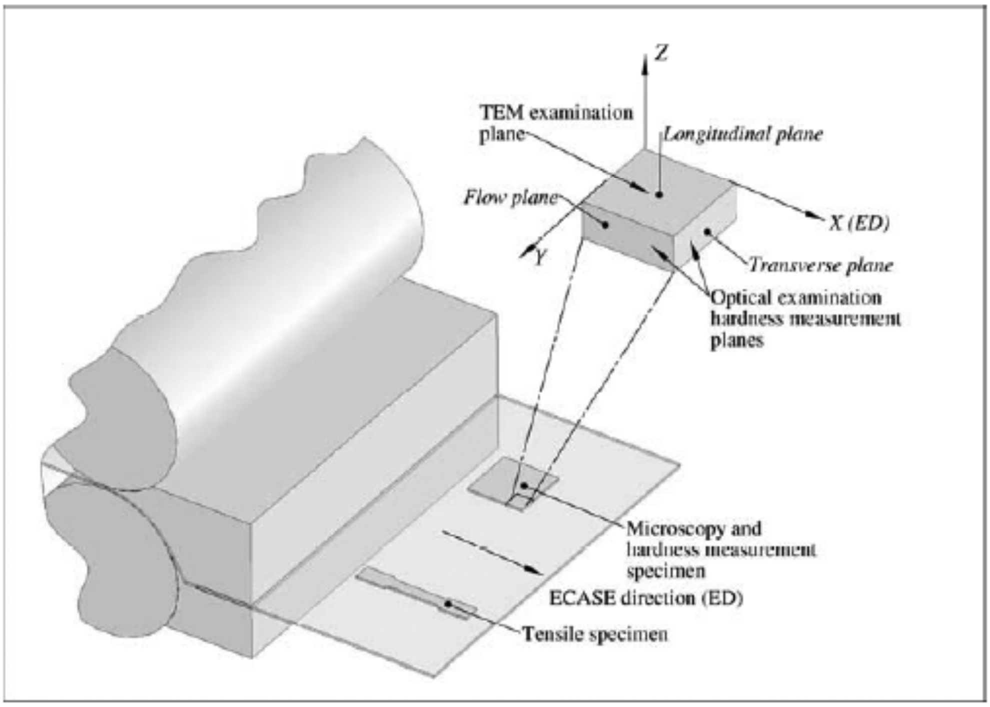

Fig. 2. A schematic describing the location/orientation of the test specimens in the ECASE processed sheet sample and the planes on which the microstructural examinations performed.

refinement via ECAE process starts with the formation of dislocation cells with low angle grain boundaries [26-28]. The microstructural alterations during ECASE is now under investigation.

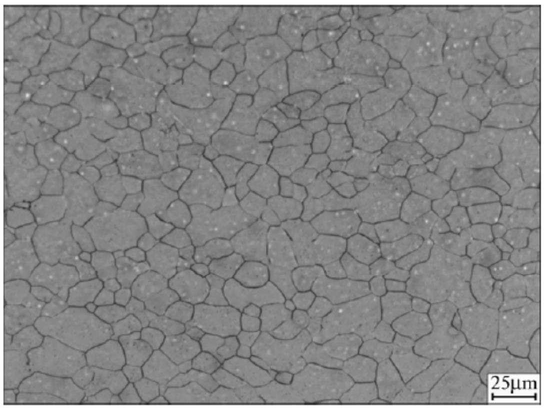

Fig. 3. Optical micrograph showing the coarse-grained and equiaxed microstructure of as-received IF-steel sheet.

4.2. Mechanical response

The effect of multi-pass ECASE on the tensile engineering stress-strain curves of IF-steel sheet specimens is shown in Fig. 5. The figure show that the as-received CG IF-steel sheet exhibits significant strain hardening and correspondingly large elongation, which is mainly due to the high strain hardening capacity of the starting material. After ECASE, the characteristic feature of the stress-strain curves of ECASE-processed IF-steel sheet samples changes significantly. In general, the stress-strain curves of processed sheet specimens show the maximum strength at the early stage of deformation, followed by macroscopic necking. This means that limited strain hardening occurs in the UFG microstructure as compared to that of the CG microstructure, which leads to a relatively early start of stress drop together with a localized neck formation. This behavior is essentially similar to that reported for the ECAE-processed bulk IF-steel [20]. It is well known that [1,9,26,29-31] early necking right after the onset of yield is mainly due to the low work hardening rate of the SPD materials in general, unless there are other means to provide high strain hardening rate such as bimodal grain size distribu-

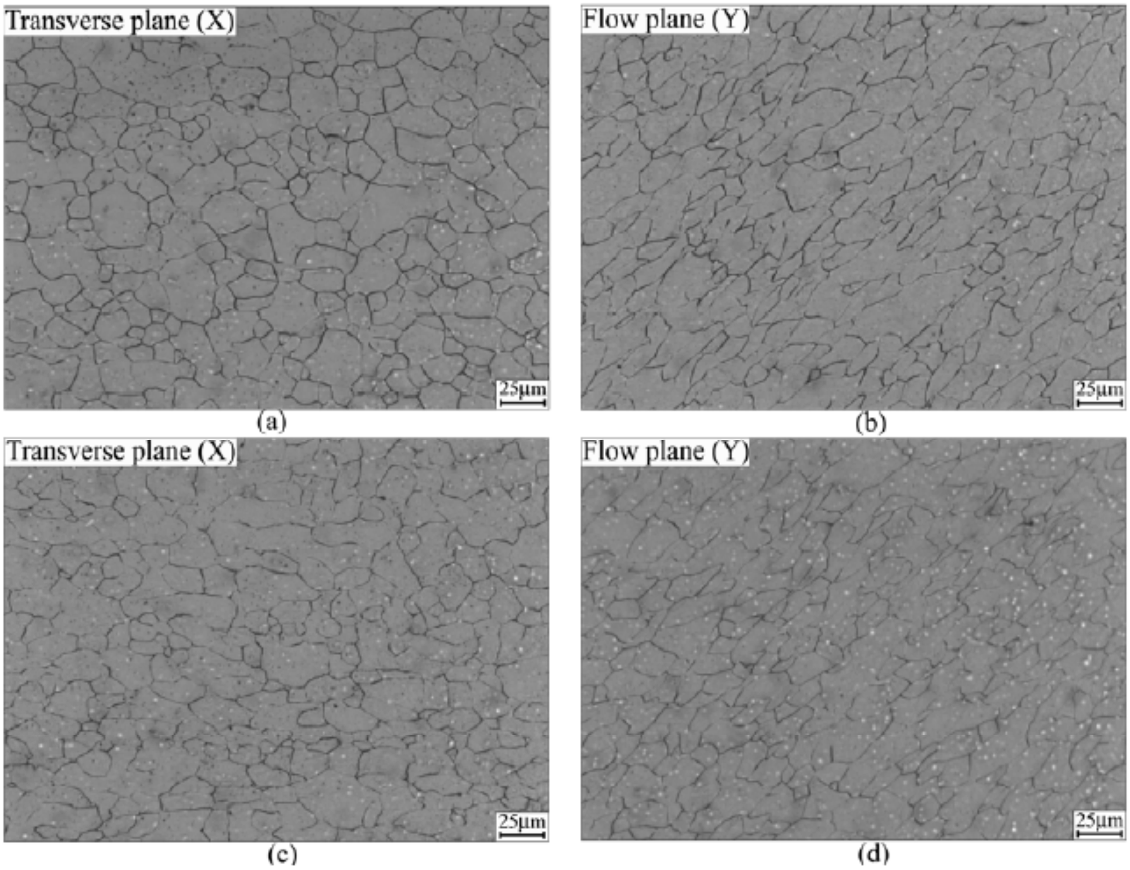

Fig. 4. Optical micrographs showing the deformed microstructure of IF-steel sheets after ECASE processing following route-A in the transverse and flow plane cross-sections (Fig.2): (a),(b) six passes and (c)-(d) eight passes.

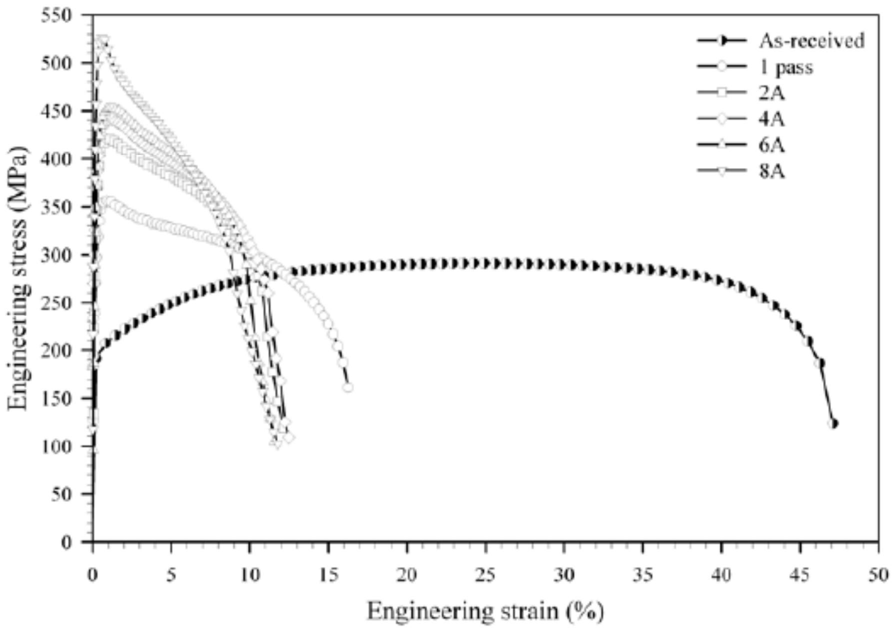

Fig. 5. Engineering stress-strain curves of the IF-steel sheets processed by multi-pass ECASE following route-A at room temperature.

tion. Decrease in work hardening rate in UFG materials compared to CG counterparts is attributed to the low density of the mobile dislocations and dynamic recovery due to the trapping of lattice dislocations that carry intergranular strains into grain boundaries. Du to the trapped mobile dislocations inherited from SPD, dislocation density in the grain interiors decreases upon further loading under uniaxial loading. Hence, reduction in the strain hardening rate of UFG microstructures leads to plastic instability dominated tensile deformation mode.

The summary of the mechanical properties taken from the stress-strain curves of IF-steel sheets is given in Table 2. In general, the ECASE process increases both yield strength (σ_Y) and ultimate tensile strength (σ_{UTS}) values of the CG IF-steel sheets. In addition, the σ_Y and σ_{UTS} values get closer to each other upon ECASE due to the loss of strain hardening capacity after processing. Even after only one ECASE pass (equivalent strain of 0.65), the strength of the IF-steel sheet increases considerably as seen in Table 2. The σ_Y of the specimen after one pass is nearly twice as high as that of the as-received one. The σ_{UTS} also shows a substantial increase from 283 MPa in the as-received condition to 377 MPa after one pass. With increasing number of ECASE passes, the strength values increase continuously, and after eight passes (equivalent strain of 5.28) the σ_Y and σ_{UTS} reach to about 499 MPa and 525 MPa, respectively, which are 2.6 times and 1.9 times higher than those of the as-received material. Also, while the σ_{UTS}/σ_Y ratio is 1.45 in the as-received IF-steel sheet, this ratio decreases suddenly after the first pass (1.01) and stays almost constant up to eight passes. However, the ECASE causes significant decrease in ductility of IF-steel sheets. As seen in Fig. 6 and Table 2, the CG IF-steel sheet exhibits significant strain hardening behavior and correspondingly large total elongation of about 46%. Half of the total elongation of the as-received materials occurs in the region of uniform deformation. After one ECASE pass, the elongation to failure (ε_f) decreases to about 15.8%. A large amount of this elongation comprises the non-uniform deformation. The elongation to failure decreases slightly with increasing number of passes. However, the uniform elongation (ε_u) was still low and was not effected considerably with further passes (Table 2).

The high strength with relatively low ductility is a typical feature for single-phase metals with UFG microstructure [1-2,28-32]. High strength of UFG IF-steel sheets can be attributed to the decreasing grain size (grain boundary strengthening) and the effect of severe plastic deformation that causes high density of dislocations leading to the formation of low angle grain boundaries at the grain interiors (dislocation strengthening) [26,31]. Limited ductility of the UFG IF-steel sheets can be explained with the characteristic features of the sub-grain structure that formed via severe plastic deformation. As mentioned before, SPD via ECAE forms UFG structure that surrounded with boundaries at a state of high energy. Because of the small grain size, the sources generating dislocations are located closely to high energy grain boundaries which annihilate dislocation [28,33]. In the case of the single-phase materials like IF-steel, this structure limits the dislocation interactions and storage, and consequently restricts strain hardening capacity leading to inadequate ductility [28]. The previous studies [28,31,33] showed that the ductility of UFG single-phase materials can be improved by post-deformation annealing because of decreasing the energy of the grain boundaries leading to decrease in effectiveness of the dynamic recovery, and by establishing bimodal grain size distribution that leads to strain accommodation in larger grains. The post-deformation annealing of UFG IF-steel sheets is currently underway in order to establish a reasonable combination of strength and ductility after the ECASE process.

Table 2. Strength and ductility values of IF-steel sheets in the as-received and ECASE-processed conditions.

Processing conditions	*Tensile properties*				
	σ_y (MPa)	σ_{UTS}(MPa)	σ_{UTS}/σ_y	ε_u(%)	ε_f(%)
As-received	194±12.0	283±12.0	1.45±0.04	23.9±3.6	46.0±0.5
1 pass	372±12.0	377±12.8	1.01±0.001	1.2±0.04	15.8±0.5
2A	402±16.6	410±17.7	1.01±0.01	1.3±0.08	12.6±0.5
4A	413±15.7	439±9.0	1.02±0.02	1.5±0.04	12.4±0.4
6A	447±8.6	460±8.9	1.02±0.02	1.5±0.07	12.3±0.5
8A	501±14.7	528±1.3	1.03±0.03	1.5±0.02	11.4±0.7

Table 3. The hardness values of the IF-steel sheets processed by multi-pass ECASE.

Processing conditions	*Hardness (Hv 1)*	
	Transverse plane	*Flow plane*
As-received	96±0.8	97±0.6
1 pass	136±2.3	136±3.2
2A	141±2.1	148±2.0
4A	153±1.9	156±2.3
6A	159±1.7	156±1.7
8A	163±1.6	160±2.1

The variation in the hardness as a function of the number of ECASE passes is given in Table 3. In general, the hardness of IF-steel sheets increases with increasing the number of passes on both transverse and flow planes. A significant increase (70%) in the hardness was achieved after the first pass of ECASE followed by a moderate increase in the hardness up to eight passes. In addition, both transverse and flow planes show almost the same variation in hardness with the number of passes. The increase in hardness can also be attributed to the UFG microstructure and high dislocation density from the ECAE process similar to the increase in flow strength values.

To monitor the microstructural homogeneity and/or anisotropy in mechanical properties after ECASE, the variation of hardness along the thickness of sheets was determined. Fig. 6 illustrates this variation on flow- and transverse-planes of processed sheets. From the Fig. 6, it is clear that the hardness is almost constant through the thickness before ECASE on both transverse and flow planes. However, the samples after ECASE show somewhat inhomogeneous distribution with wavy profile along the thickness on both planes. This anisotropic behavior in hardness after ECASE may be due to the non-uniform plastic strain condition [34].

5. SUMMARY AND CONCLUSIONS

Ti-stabilized IF-steel sheets were processed using a modified ECAE system, so-called "*equal-channel angular sheet extrusion (ECASE)*". After processing, mechanical properties of the IF-steel sheets along with accompanying microstructural evolution were studied. The main findings and conclusions of this study can be summarized as follows:

- Continuous shear deformation was successfully applied to the IF-steel sheets using the ECASE system at room temperature.
- The ECASE process substantially increased both yield strength and ultimate tensile strenght values of the IF-steel sheets. Yield strength after one pass was nearly twice as high as that of the as-received one. With increasing number of ECASE passes, the strength values increased continuously, and after 8 passes, yield and ultimate tensile strenght reached to about 499 MPa and 525 MPa, respectively, which were 2.6 times and 1.9 times higher than those of the as-received ones. However, the ECASE caused a significant decrease in ductility
- The hardness of the ECASE processed IF-steel sheets increased with the number of passes,

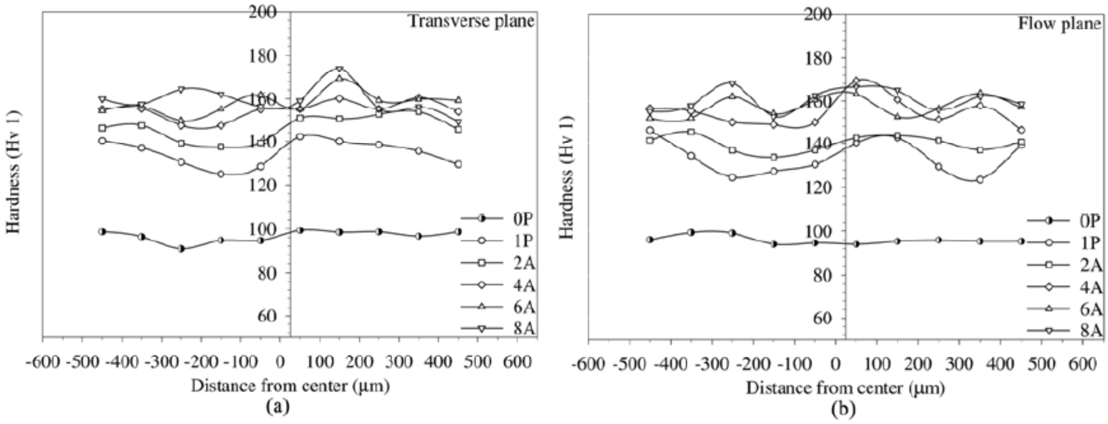

Fig. 6. Variation of hardness with the thickness of IF-steel sheets before and after ECASE process: (a) transverse plane and (b) flow plane.

and the specimen after eight passes demonstrated the highest hardness that is 70% higher than the initial value. However, the homogeneity in hardness along the sheet thickness somewhat deteriorated after ECASE.

· It can be concluded that the use of ECASE provides a simple and effective procedure for improving the strength of IF-steel sheets. However, further studies are needed, especially for improving the ductility and forming capability of the deformed sheets by post-deformation processes.

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