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PROCESSING OF GRADE A LOW CARBON STEEL BY EQUAL CHANNEL ANGULAR PRESSING

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ABSTRACT

The present study aims to analyze the effect of equal channel angular pressing (ECAP) on the microstructural and mechanical properties as well as the impact energy of low carbon steel. Grade A steel was processed using ECAP. One pass of ECAP did not cause a considerable decrease in the grain size of the steel. It brought about two different microstructures on the flow and transverse planes of an ECAP billet, instead. The microstructure consists of elongated ferrite and perlite grains aligned in a direction having mainly 45° angle with the extrusion direction on the flow plane while nearly equiaxed grains were formed on the transverse plane. These differences between the microstructures of two different planes of the ECAP sample are attributed to the share planes that are operative during ECAP. ECAP increased the hardness and strength values of the steel significantly due to the increase in the dislocation density during the process. However, it decreased the elongation to failure considerably. It was found that the impact energy of the ECAP-processed sample is dependent on the notch position of the Charpy impact test sample.

Keywords*:* Low carbon steel, Grade A steel, Equal channel angular pressing (ECAP)

DÜŞÜK KARBONLU GRADE A ÇELİĞİNİN EŞ KANALLI AÇISAL EKSTRÜZYON YÖNTEMİ İLE PROSES EDİLMESİ

ÖZET

Bu çalışmada eş kanallı açısal ekstrüzyon (EKAE) işleminin düşük karbonlu çeliğin mikroyapısal ve mekanik özellikleri ile darbe enerjisi üzerine etkilerinin incelenmesi amaçlanmıştır. Bu amaçla düşük karbonlu Grade A çeliği, (EKAE) işlemine tabi tutulmuştur. 1 pasoluk EKAE işlemi çeliğin tane yapısında önemli bir incelmeye neden olmazken, EKAE numunesinin akma ve dik kesit düzlemlerinde iki farklı mikroyapı oluşumunu beraberinde getirmiştir. Akış düzleminde ekstrüzyon doğrultusu ile 45° açı yapacak şekilde yönlenmiş ferrit ve perlit tanelerinden oluşan mikroyapının, dik kesit düzlemi üzerinde neredeyse eş eksenli tanelerden oluştuğu belirlenmiştir. EKAE numunesinin iki farklı düzleminin mikroyapıları arasındaki bu farklılık, EKAE işlemi sırasında aktif olan kayma düzlemleri ile açıklanmıştır. EKAE işlemi sırasında mikroyapıdaki dislokasyon yoğunluğundaki artıştan dolayı çeliğin sertlik ve dayanım değerlerinin önemli ölçüde arttığı görülmüştür. Ancak, EKAE işlemi kopma uzaması değerinin önemli ölçüde azaltmasına neden olmuştur. EKAE işlemine tabi tutulan numunenin darbe enerjisinin, Charpy darbe testi numunesinin çentik pozisyonuna bağlı olduğu belirlenmiştir.

Anahtar kelimeler*:* Düşük karbonlu çelik, Grade A çeliği, Eş kanallı açısal ekstrüzyon (EKAE)

1. INTRODUCTION

Low carbon steels have gained special attention for being used in transportation industries like the automotive and railway sectors. Their low cost, high formability and excellent weldability make them attractive materials for such applications [1]. In these applications total weight of the vehicles is an important criteria affecting the fuel consumption. It is well known that decreasing weight is an effective way to decrease total fuel consumption. One of the ways to reduce weight is to use lightweight materials like aluminum alloys in these applications instead of low carbon steel. However, this solution significantly increases the production cost of the vehicle and thus affects the competitive capacity of the vehicle in the market adversely. Improving the mechanical properties of low carbon steels in any manner, hence the specific strength, may be another solution to decrease the total weight of the vehicles and structures.

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It is well known that mechanical properties of low carbon steels can be optimized by heat treatment and/or imposing strain or decreasing grain size via plastic deformation techniques [2]. Besides the conventional plastic deformation techniques like rolling, extrusion and forging, severe plastic deformation (SPD) techniques have been proposed in recent years [3-11]. It has been well established that significantly higher strain can be imposed to the material by SPD methods as compared to the conventional plastic deformation techniques. Furthermore, ultrafine-grained materials having grain sizes in submicron levels can be achieved by SPD methods. Equal channel angular pressing (ECAP) [5-8], torsional straining (TS) [9] and friction stir processing (FSP) [10, 11] are the main SPD techniques. ECAP is one of the most commonly used techniques since it makes possible to achieve bulk ultrafine-grained (UFG) materials. Another advantage of ECAP comparing to other SPD techniques is that this process can also be applied to the materials in the sheet form which is mostly used in the automotive industry [8].

Although there are some studies on the ECAP processing of low carbon steels [12-15], none of them aimed to analyze the effect of ECAP on the microstructural and mechanical properties of Grade A steel which is one of the widely used low carbon steels especially in the shipbuilding industry [16]. Therefore, the main purpose of this study is to analyze the effect of ECAP on the microstructural and mechanical properties as well as the impact energy of low carbon Grade A steel. For this purpose, Grade A steel was subjected to ECAP at 200 °C. After the ECAP process, the microstructural changes and the effect of ECAP on the microstructure, room temperature (RT) tensile behavior and impact energy of the steel were investigated.

2. EXPERIMENTAL PROCEDURE

The material used in the present study was a Grade A low carbon steel having a chemical composition of 0.16 wt pct C, 0.18 wt pct Si, 0.7 wt pct Mn, 0.011 wt pct S, 0.18 wt pct P, 0.09 wt pct Cr, 0.14 wt pct Mo, 0.04 wt pct Cu, 0.04 wt pct V, and balance Fe. In order to improve the strength of the initial hot rolled material, it was subjected to one pass ECAP at 200 °C using an ECAP die having 90° cross-section angle (Φ) and 0° outer curvature angle (Ψ). The ECAP sample having $13 \times 13 \times 130$ mm^3 dimensions was covered with a graphite-based lubricant to reduce the friction between the billet and the channel walls during extrusion. Then the sample was placed into the ECAP die and waited for ~5 min to ensure that the sample reached to the ECAP temperature of 200 °C. ECAP process was conducted with an extrusion speed of 1mm$\cdot$s^{-1}.

Optical microscopy (OM) and scanning electron microscopy (SEM) facilities were used to examine the microstructures of the low carbon Grade A steel sample before and after the ECAP process. The samples for microstructural examinations were extracted from the ECAP sample using the wire electrical discharge machining (wire-EDM). Then the samples were prepared using standard polishing techniques and etched in a 3 % Nital solution (3 ml HNO_3 + 97 ml C_2H_6O). Microstructural examinations were performed from two different planes of the ECAP sample; flow plane (FP) which lies parallel to the extrusion direction (ED) and transverse plane (TP) which is perpendicular to the extrusion direction (Figure 1).

Mechanical properties of the sample before and after the ECAP process were determined using hardness and uniaxial tensile tests conducted at RT. As in the case of microstructural examinations, hardness measurements were performed on both flow and transverse planes of the ECAP-processed sample (Figure 1) using a Vickers micro-hardness tester. Load and dwell time for micro-hardness measurements were chosen to be 500 g and 10 seconds, respectively. Dog-bone shaped tensile test samples having $1.5 \times 3 \times 9$ mm^3 gauge section dimensions were cut from the ECAP sample using wire-EDM. The samples were extracted from the ECAP sample where their longitudinal axes are parallel to the ED (Figure 1). Tensile tests were performed at 5×10^{-4} s^{-1} strain rate using an Instron-3382 electro-mechanical load frame having a video type extensometer. The tests were repeated at least three times for each sample to confirm the repeatability of the results.

The impact toughness of the low carbon Grade A steel for the initial and ECAP-processed conditions were evaluated by using the Charpy impact test system. Miniaturized Charpy V-notched samples having 3 mm × 4 mm × 27 mm dimensions and 1 mm-depth notch were cut from the initial and ECAP-processed samples with wire-EDM. The samples were extracted from the ECAP billets in two different positions, as shown in Figure 1, to analyze the effect of notch position on the ECAP sample on the impact energy.

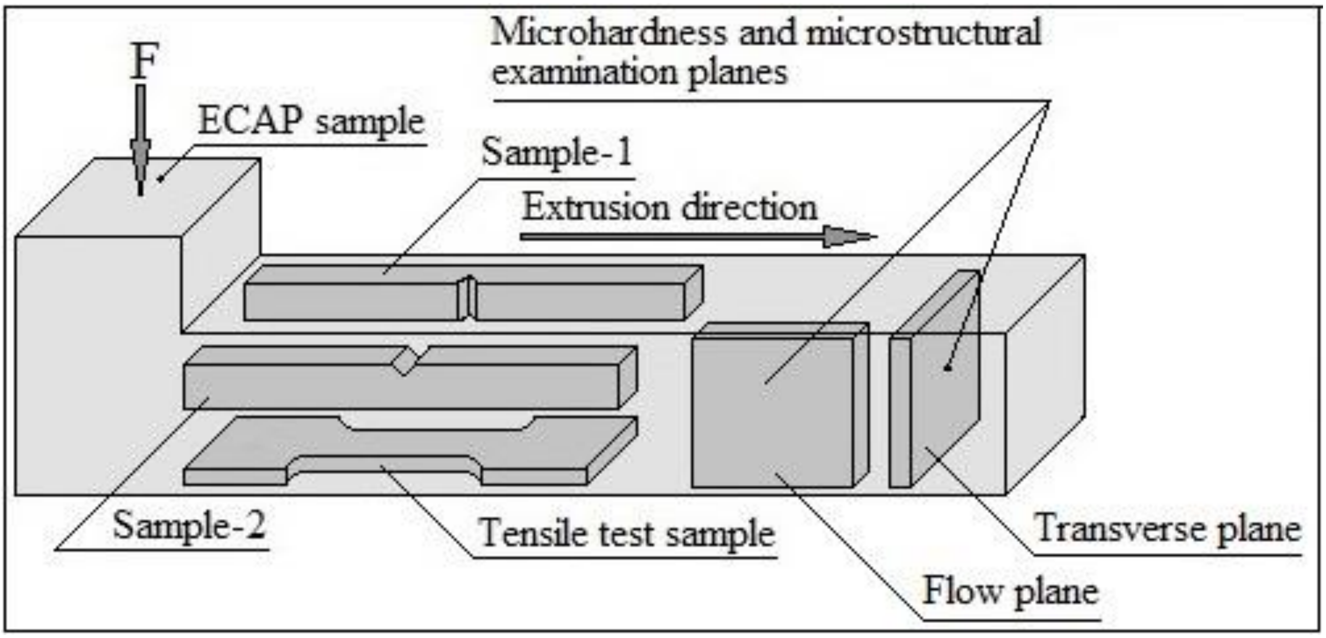

Figure 1. A schematic representation showing the location and orientations of the tensile test, impact test, microhardness and microstructural examination samples on the ECAP sample.

3. RESULTS AND DISCUSSION

Optical and SEM micrographs of Grade A steel at the initial hot rolled condition are given in Figure 2. The initial microstructure consists of coarse grained ferrite and pearlite grains. It is clear that the perlite phase having dark contrast in the optical micrograph slightly elongated along the hot rolling direction which aligns parallel to the page (Figure 2(a)). Also, the pearlite phases mainly accumulated along the boundaries of the ferritic grains having relatively equiaxed morphology (Figure 2(a) and (b)). The mean grain sizes of ferrite grains were measured to be 15±0.8 μm using the linear intercept method. Figure 3 shows the optical micrographs of the ECAP-processed steel taken from both flow and transverse planes of the ECAP sample. One pass of ECAP brought about a microstructure consisting of elongated ferrite grains with high aspect ratio aligned in a direction mainly having 45° angle with the ED. The mean width and length of the ferrite grains are measured to be 10±0.5 μm and 20±0.9 μm, respectively. Furthermore, the pearlite grains formed as long and continuous stringers aligned with the same direction as the ferrite grains (Figure 3(a) and (b)). On the other hand, the microstructure of ECAP-processed steel has a nearly equiaxed morphology on the transverse plane of the ECAP sample. Furthermore, the pearlite stringers coming from the initial hot rolled stage still exist in the microstructure of the transverse plane. The mean grain size was determined to be 13±0.6 μm on that plane (Figure 3(c) and (d)). These differences between the microstructures taken from two different planes of the ECAP sample arise from the nature of ECAP, and similar observations were also reported in some previous studies [6, 17, 18]. The grain boundaries in the flow plane lying at approximately 45° to the extrusion direction is consistent with the shearing characteristics of single pass ECAP as shown in references [6] and [17]. It was shown theoretically that the share plane on the flow plane of the ECAP die has an angle of ~45° with the extrusion direction. Thus the grains on the flow plane of the sample elongate along the theoretical shear plane at the intersections of the vertical and horizontal channels of the die after one pass of ECAP as in the case of the present study. On the other hand, the flow plane lies parallel to the extrusion direction on the transverse plane. Therefore, such an orientation of the grains was not observed on that plane [6, 17, 18].

The hardness, strength and elongation to failure values of the low carbon Grade A steel before and after the ECAP process are summarized in Table I. It is clear that, there is no considerable difference between the hardness values measured from flow and transverse planes of the ECAP billet. The hardness of steel increased from 126 HV0.5 to 276HV0.5 after ECAP process. ECAP processing of low carbon steel increased the strength values significantly. The yield and tensile strength of the steel increased from 265 and 443 MPa to about 330 and 800 MPa, respectively, by means of ECAP. On the other hand, ECAP results in a considerable decrease in the elongation to failure as compared to the unprocessed steel. While the elongation of the steel was measured to be 37% at the initial stage, it decreased to 13 % after one pass of ECAP. As stated before, ECAP process did not lead to a considerable grain refinement in the Grade A steel in the present study. On the other hand, it increased the strength of the steel significantly. Thus, this significant increase in the strength values of the steel cannot be fully attributed to the grain refinement. It was reported in an earlier study that Grade A steel that was processed by FSP and having 3 μm grain size showed lower tensile strength than the ECAP-processed sample of the present case [2,19]. It was stated that dynamic recrystallization occurred during the FSP due to the high temperature at the process region, and thus limited increase in the dislocation density occurred in the microstructure of the steel after FSP. Therefore, increase in the strength of the steel was mainly attributed to the grain refinement while strain hardening effect was mentioned to be limited (Hall-Petch effect) [2, 19]. On the other hand, the steel was processed at the cold deformation region in the present study since ECAP was applied to it at 200 °C. Therefore, it can be said that significant increase in the dislocation density occurred due to the high imposed strain. Thus, significant increase it the strength values and considerable decrease in the elongation to failure of the steel was achieved by ECAP process although limited grain refinement occurred in the present study.

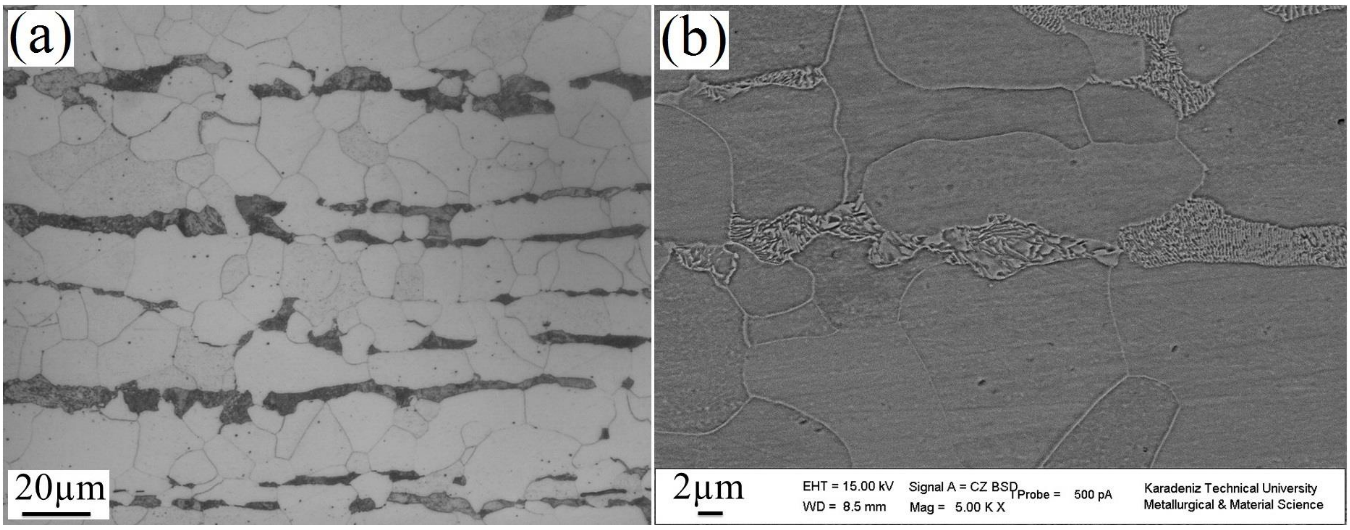

Figure 2. (a) Optical and (b) SEM micrographs showing the initial mirostructure of Grade A steel.

Impact energies obtained from the Charpy impact tests are given in Table II. At the initial stage impact energy of the low carbon steel was determined to be 5.80 J. The ECAP resulted in decrease in the impact energy of the sample in both planes. The impact energy was observed as 4.50 J in Sample-1. However, Sample-2 shows significantly lover impact energy comparing to initial sample and Sample-1. Its impact energy was measured as 1.65 J. In order to investigate the reason of the different impact energies obtained from the initial sample, Sample-1 and Sample-2, the fracture surfaces of the impact test samples were examined with SEM. Macroscopic images of the fractured samples and some presentative SEM images showing the morphology of the fracture surface of both initial and ECAP-processed samples (Sample-1 and Sample-2) after impact tests are given in Figure 4. The fracture characteristics of initial sample and Sample-1 are quite similar to each other. In general, these samples did not break completely during the impact test (Figure 4(a) and (d)), and both samples show a ductile fracture mode with dimple-like fracture surface (Figure 4(c) and (f)). However, the initial sample shows finer dimples comparing to that of Sample-1 due to the its more ductile behavior (Figure 4(c)). On the other hand, Sample-2 shows completely different fracture behavior as compared to two other samples (Figure 4(g)-(i)). This sample was completely broken during the impact test and divided into two pieces (Figure 4(g)). Sample-2 shows a typical brittle fracture with quite smooth fracture surface without any plastic deformation signs. No dimples and tearing edges are observed on the fracture surface of that sample (Figure 4(i)). Another implication from the fracture surface and macroscopic image of the fractured Sample-2 is that fracture occurred through a smooth plane which is almost parallel to one face of the notch of the fracture test sample (Figure 4(g) and (h)). Looking at the position where Sample-2 was extracted from the ECAP sample, one side of its notch appears to be parallel with the grains oriented in the flow plane (Figure 1 and Figure 3(a) and (b)). When the macroscopic view of the Sample-2 and SEM image of the fracture of that sample are taken into account, it is seen that the fracture occurs along this plane. In other words, the fracture in this sample occurs along the oriented pearlite grains on the flow plane. Due to the brittle behavior of the perlite phase, the impact energy in this sample was very low compared to the two other samples. Thus, it is seen that the mechanical properties of the low carbon steel sample subjected to one pass of ECAP are depends on the direction where the grains oriented

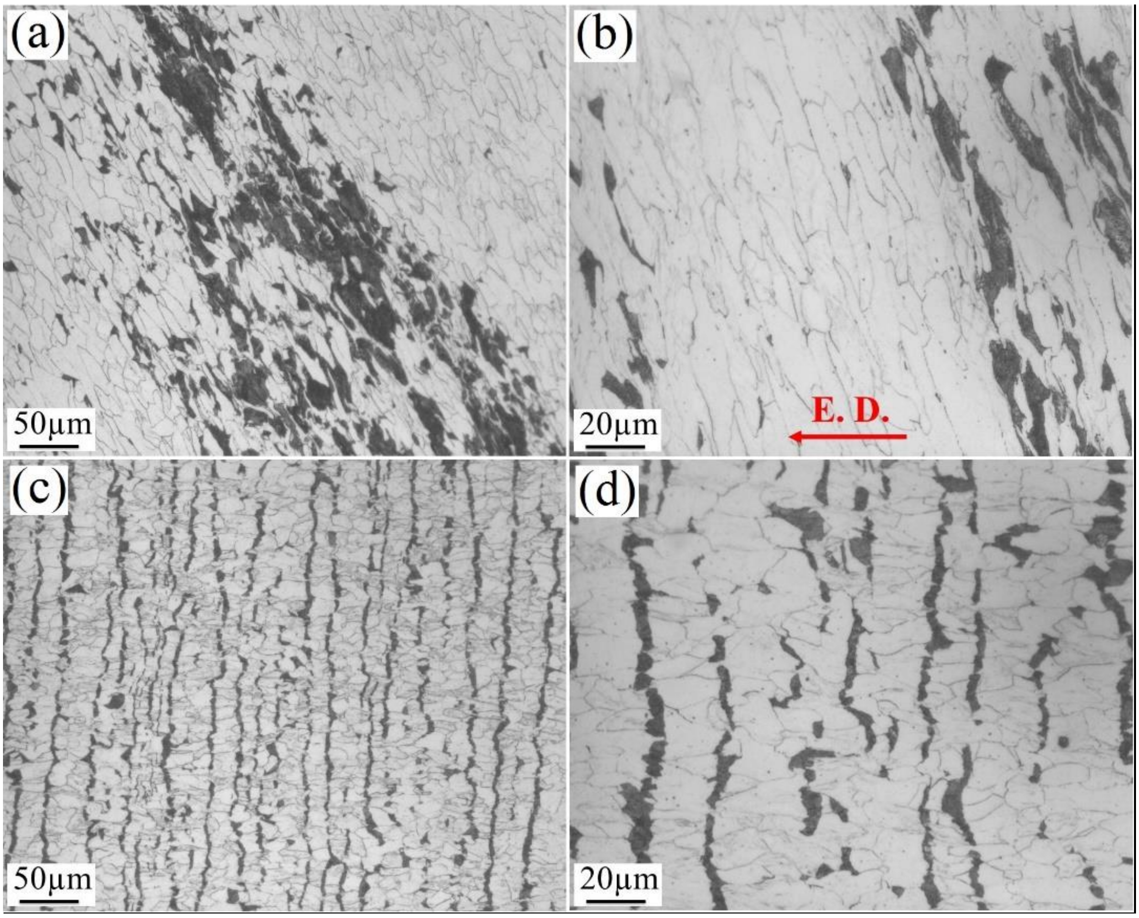

Figure 3. Optical micrographs showing the microstructure of ECAP-processed Grade A steel (a)-(b) Flow plane, (c)-(d) Transverse plane.

Table 1. Mechanical properties of the initial and ECAP-processed low carbon steel samples.

	Microhardness (HV0.5)	Yield strength (MPa)	Tensile Strength (MPa)	Elongation (%)
Initial	126 ± 4	265	443	37
After ECAP	273 ± 8 (FP) 280 ± 7 (TP)	330	800	13

Table 2. Impact energy values of the low carbon steel samples.

	Impact Energy (J)
Initial	5.80
Sample-1	4.50
Sample-2	1.65

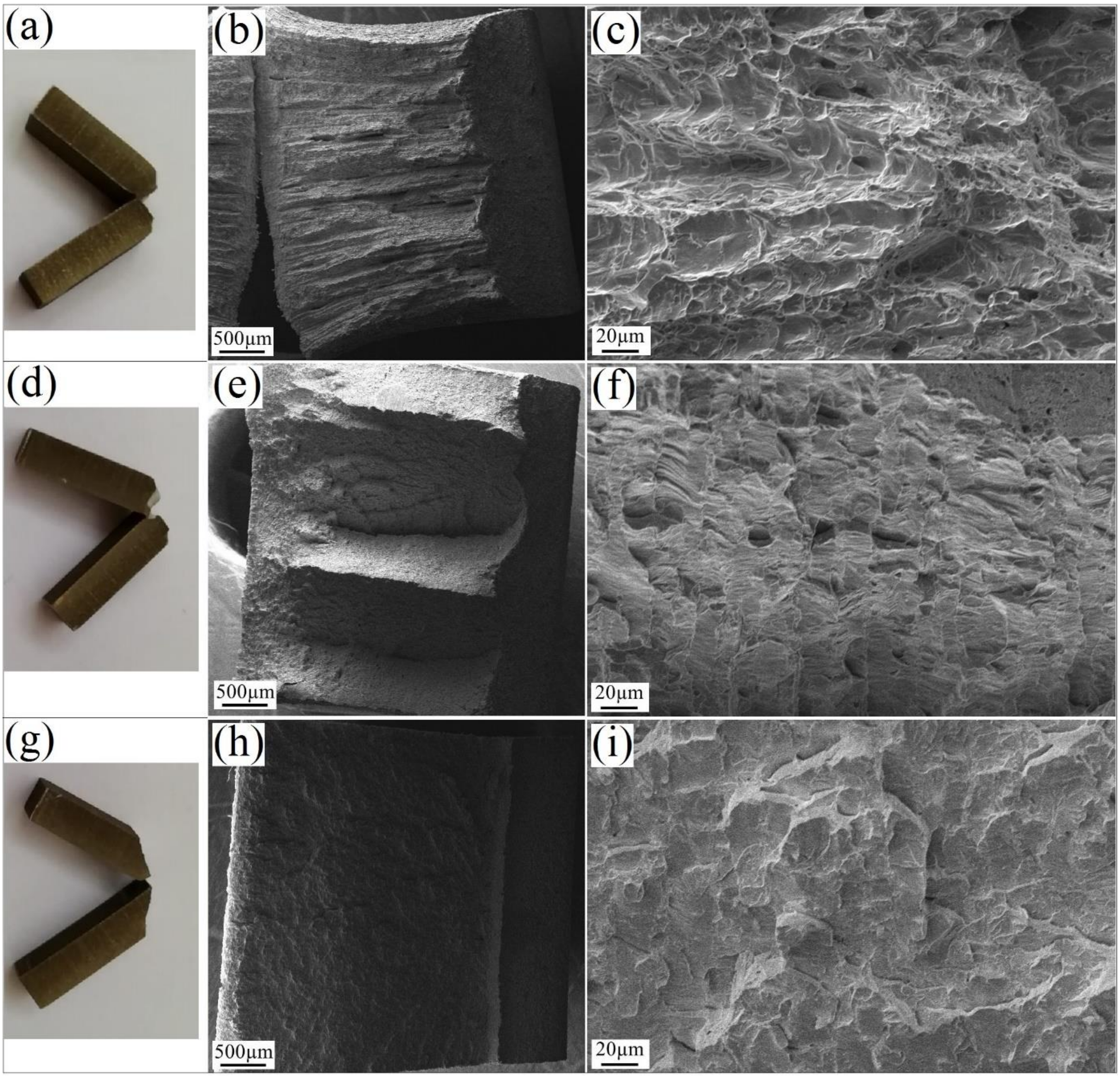

Figure 4. Macroscopic images of the fractured samples and some presentative SEM images showing the morphology of the fracture surface of both initial and ECAP-processed samples: (a)-(c) initial sample (d)-(f) Sample-1, and (g)-(i) Sample-2.

4. CONCLUSIONS

In this study, the effects of ECAP on the grain size, tensile behavior and impact energy of low carbon Grade A steel were investigated. The main findings and conclusions can be listed below:

1. One pass of equal channel angular pressing (ECAP) does not cause a significant decrease in the grain size of the steel. It brings about a microstructure consisting of elongated ferrite and perlite grains aligned in a direction mainly having 45° angle with the extrusion direction (ED) on the flow plane of the ECAP billet. The mean width and length of the ferrite grains are measured to be 10±0.5 μm and 20±0.9 μm, respectively. On the other hand, microstructure of ECAP-processed steel has a nearly equiaxed morphology with 13±0.6 μm grain size on the transverse plane of the ECAP billet. These differences between the microstructures taken from two different planes of the ECAP sample are attributed to the share planes that are operative during the ECAP.

2. The hardness of steel increases from 126 HV0.5 to 273HV0.5 after ECAP process. ECAP processing of low carbon steel increases the strength values significantly. The yield and tensile strength of the steel increase from 265 and 443 MPa to about 330 and 800 MPa, respectively, after ECAP process. On the other hand, ECAP results in a considerable decrease in the elongation to failure as compared to the unprocessed steel. While the elongation of the steel is measured to be 37% at the initial stage, it decreases to 13 % after one pass of ECAP.
3. The significant increase in the hardness and strength values of the steel is attributed to the strain hardening due to the significant increase in the dislocation density by means of high imposed strain during the ECAP process.
4. Impact energy of the ECAP-processed sample is dependent on the notch position of the Charpy impact test sample. The dependency of the impact energy on the notch position arises from the oriented microstructure of the ECAP-processed steel.

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