Investigation of mechanical properties and fracture surfaces of 5086 Al-based alloy processed by equal channel angular pressing in different routes

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ABSTRACT

This paper aimed to experimentally investigate the influence of equal channel angular pressing in the two rotational routes A and B_C on the mechanical properties of Al 5086 alloy. The specimens were processed up to 10 passes at 150 °C in a die with 120° internal angle. To evaluate the mechanical properties of the specimens, uni-axial tensile and hardness tests were performed. The results showed that in all passes, route B_C had a higher effect on the simultaneous improvement of strength, elongation, and hardness. The fracture surface was investigated using scanning electron microscopy (SEM). The results showed that increasing the number of passes led to the raising of the number of dimples and the better distribution of them for both routes. The textures were also studied using the X-ray diffraction (XRD) analysis. The results showed the dominant texture altered from (111) to (220) plane by increasing the number of passes through both routes.

1-Introduction

Nowadays, improving the mechanical properties of alloys is considered an essential condition for using them in more sensitive applications. Meanwhile, the equal-channel angular pressing (ECAP) process is known as a kind of severe plastic deformation (SPD) [1-7]. Low cost, workability for various alloy systems, even intermetallic compounds and production of ultra-fine grain structures in bulk specimens are some of the most significant advantages of this process. In this method, the specimen is pressed through two intersecting channels having the same cross-sections with a die channel angle which can be chosen to be between 0-180 degrees. While the specimen is passing through the exit channel, a severe shear stress is applied, causing the grain refinement; thus, the mechanical properties are improved. This method can be a good alternative for enhancing Al-Mg alloys that are widely used in aerospace, marine and ship industries as a light structural material. Among these alloys, the 5086 Al-based alloy is preferred due to its relatively acceptable strength, good corrosion resistance, and machinability. It is obvious that improving the mechanical properties can result in broadening the potential applications. The processing route is one of the most important aspects in ECAP [8-10]. Any A, B_C, B_A, and C routes can have different mechanical properties due to variations in the strain direction. The effect of different routes has been investigated in various alloys [11-18]. For instance, it has been identified that

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in a 90 degree die for pure Al, route B_C improves the mechanical properties more effectively [19-20]. With regard to the aforementioned researches, the efficiency of different rotation routes in producing optimum microstructure using a 90 degree die is summarized as A < B_A < C < B_C [21]. It is worth mentioning that this conclusion is not accepted for all alloy systems in every condition. Cubic element analysis is one of the methods used to interpret this phenomenon, as examined by some researchers [22]. Furthermore, the geometrical relations between the shear planes are another method of analysis to investigate this parameter. In this method, researchers have come up with various controversies regarding the angles of shear in each pass, which could be a reason for the higher efficiency of route B_C. However, the results of some studies have shown that in a 120 degree die, route A plays the most important role in the improvement of the mechanical properties of some specific Al-based alloy systems [19, 23]. Therefore, none of the four routes can be decisively introduced as the most effective way in different die angles. It is believed that one of the most important parameters in defining the influential route is temperature. In the present study, the effects of routes A and B_C on the mechanical properties of 5086 Al-based alloy were investigated in a 120 degree die at 150 °C. In addition, the effects of such routes on the fracture surface and texture of the specimens were compared.

2- Experimental procedures

In this paper, 5086 Al-Mg alloy was used with the nominal chemical composition represented in Table 1.

To conduct the ECAP process, cylindrical specimens of 20 mm in diameter and 80 mm in height were prepared by machining; then, they were annealed at 450 °C in the atmospheric condition for homogenization. Subsequently, they were entered into a die with 120° internal angle and 20° curvature angle.

Fig. 1 shows the schematic of ECAP die used in this research. The temperature of the process was chosen to be 150 °C in routes A and B_C and Nano-MoS_2 was used as the high temperature lubricant to reduce friction. The pressing speed was 1 mm/s which was kept constant during the process. To study the mechanical properties, hardness and tensile tests were employed. Hardness measurements were performed on a section parallel to the extrusion axis with 10 kg load for 10 s. A Hounsfield tensile system (model H20KS) was used for performing the tensile tests according to ASTM standard [24].The tests were performed at room temperature with 2 mm/min rate. To investigate the microstructure, the specimens were electro-polished in a solution containing 6 ml of HCl, 80 ml of ethanol, and 14 ml of distilled water at 60 V for 5 seconds. The microstructure of the specimens was observed using orientation image microscopy, which is a scanning electron microscope, equipped with an electron back scattered diffraction (EBSD) system. To study the texture of the specimens, an X-ray diffractometer was employed using X'PERT MPD with 30 kV and 30 mA current. Finally, a secondary electron microscope was used to investigate the fracture surface of the specimens.

3- Results and discussion

3-1- Mechanical properties

Fig. 2 represents variations of hardness versus the number of passes in both routes A and B_C. As can be seen, hardness was increased from 62 to 91 HV by the first pass and decreased to 88 HV after the second pass through route A. Consequently, it was stabilized after a slight increase for the next passes. The reason for decrement after the first pass could be attributed to the high stacking fault energy in this alloy and the subsequent high rate of dynamic recovery in the specimens [25]. Through route B_C, the hardness value was increased from 91 to 107 HV after the second pass, indicating the more effectiveness of route B_C, as compared to route A.

Table 1. Chemical composition of 5086 Al-Mg alloy

Elements	Zn	Cr	Mn	Cu	Fe	Si	Mg	Al
Chemical Composition	0.101	0.096	0.612	<0.05	0.441	0.169	3.95	Remnant

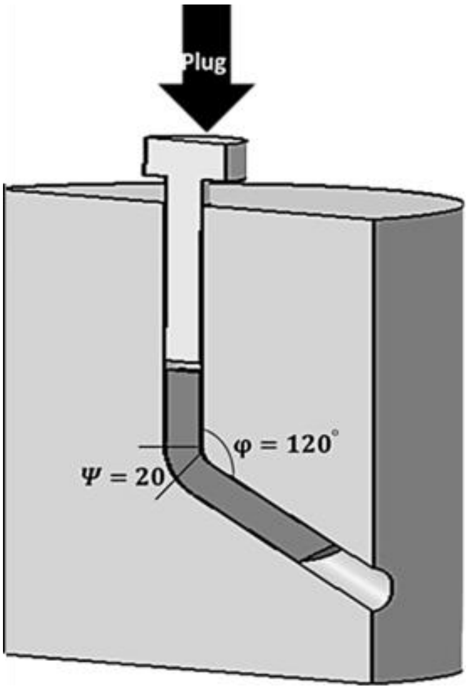

Fig. 1. Schematic of the ECAP die.

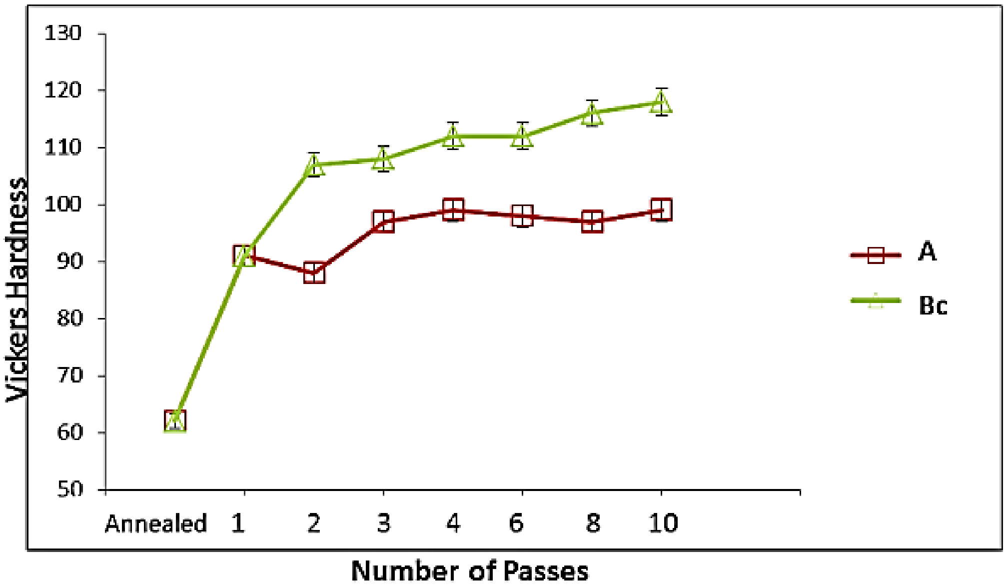

Fig. 2. Variations of hardness relative to number of ECAP pass in both routes A and B_C.

A considerable increase in the initial passes in both routes and a decrease in the slope of the increasing hardness in the next passes could be due to work hardening occurring by increasing the number of passes. Fig. 3 demonstrates variations of tensile strength for annealed and processed specimens by increasing the number of passes for both routes. As can be seen, tensile strength was increased to 300 MPa after the second pass and then was reduced to about 288 MPa for route A, while it was increased to 315 MPa for route B_C. By increasing the number of passes, the tensile strength had the same trend in both routes. The fourth pass occupied the highest tensile strength for both routes, indicating the higher work-hardening. Then, soft working drastically minimized tensile strength and after the eighth pass, work hardening dominated over again. Comparing the two routes, it can be seen that route B_C played a more important role in increasing the tensile strength. As it will be discussed in the next section in more detail, the reason could be the difference in the conditions of recrystallization occurrence in the two routes. Fig. 4 depicts the elongation percentage in various passes. As can be seen, the trend of variations was approximately the same for both routes. At the eighth pass the soft working was increased (Fig. 3) and elongation reached to maximum for both routes. Then it was reduced to its minimum in the final pass due to the increment of work hardening.

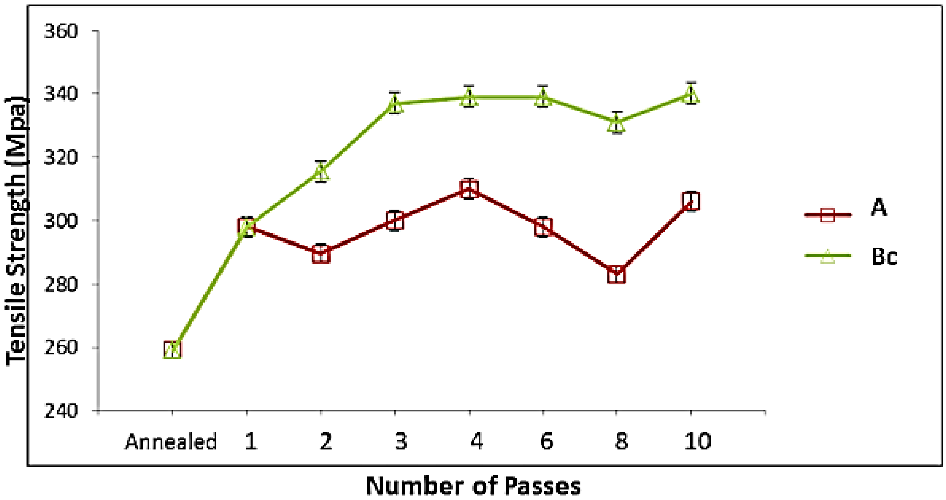

Fig. 3. Variations of the tensile strength relative to the number of ECAP pass in both routes A and B_C.

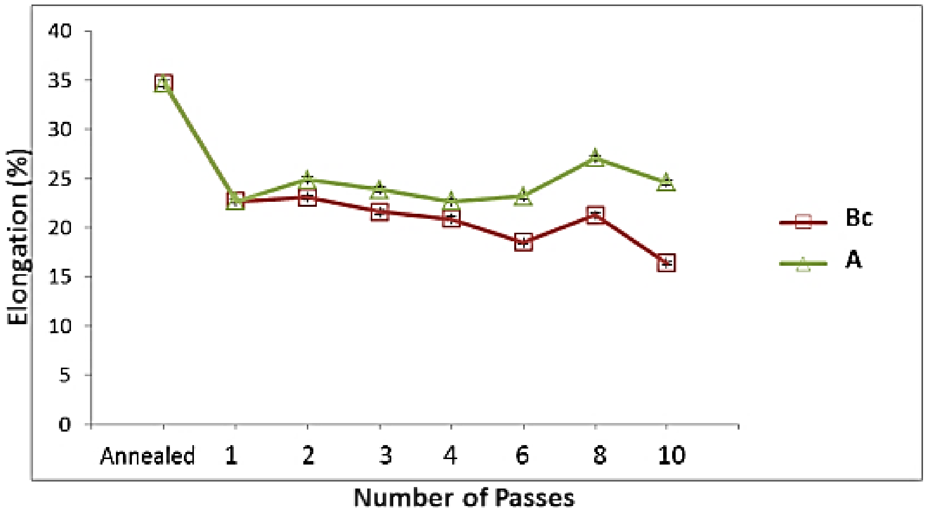

Fig. 4. Variations of elongation relative to the number of the ECAP pass in both routes A and B_C.

3-2- XRD analysis

The effect of the number of passes on the texture parameters is discussed in this section. The texture study was performed using a selection of 6 peaks in the diffraction patterns of specimens and comparing them with the random specimen (annealed). The texture parameters were calculated using Equation 1. In this equation, n is the number of planes, I is the intensity of the peak in the target specimen, and I^0 is the intensity of the peak in the random specimen [26].

$$T.P = \frac{\left(\frac{I_{hkl}}{I^0_{hkl}}\right)}{1/n \sum_1^n \left(\frac{I_{hkl}}{I^0_{hkl}}\right)} \quad (1)$$

If the obtained parameter is less than or equal to 1, the specimen has the random texture in that plane; However, if it is higher than 2, a dominant texture in the microstructure is indicated.

Figs. 5, 6 and 7 display the diffraction patterns and texture evolution by increasing the number of passes through both routes, respectively. As can be seen from the annealed specimen, the highest peak intensity was related to the planes (111) and (331), respectively; however, after the first pass, the intensity of plane (111) was significantly reduced. On the other hand, the intensity of plane (220), which was relatively low for the annealed specimen, was drastically elevated. Another point to be mentioned in these figures is the intensity increment of plane (400) after the eighth pass through both routes. This may be due to the rotation of grains during the application of severe stress or the occurrence of recrystallization. Since the grains can rotate only at temperatures higher than 0.5 Tm, the probability of recrystallization occurrence is greater in this condition.

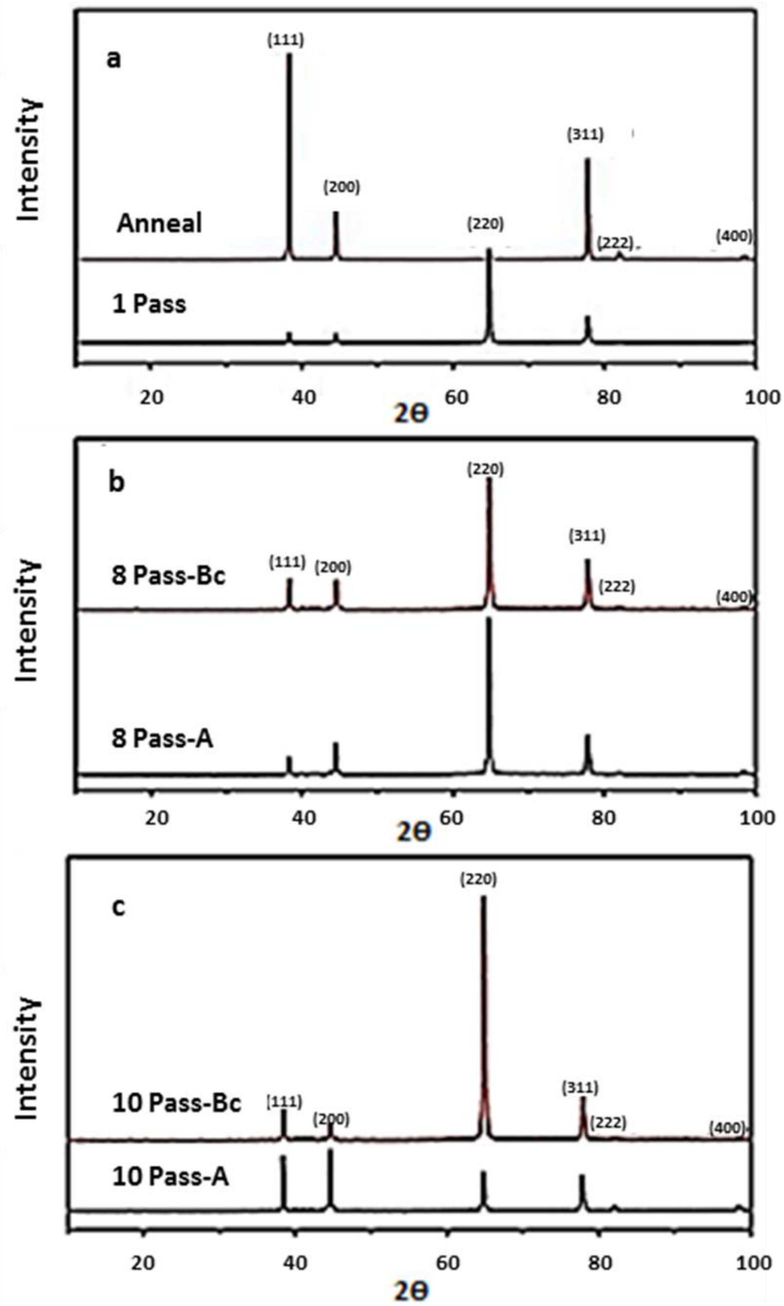

Fig. 5. Diffraction pattern of a) annealed specimen, b) 8 passes and c) 10 passes in routes A and B_C.

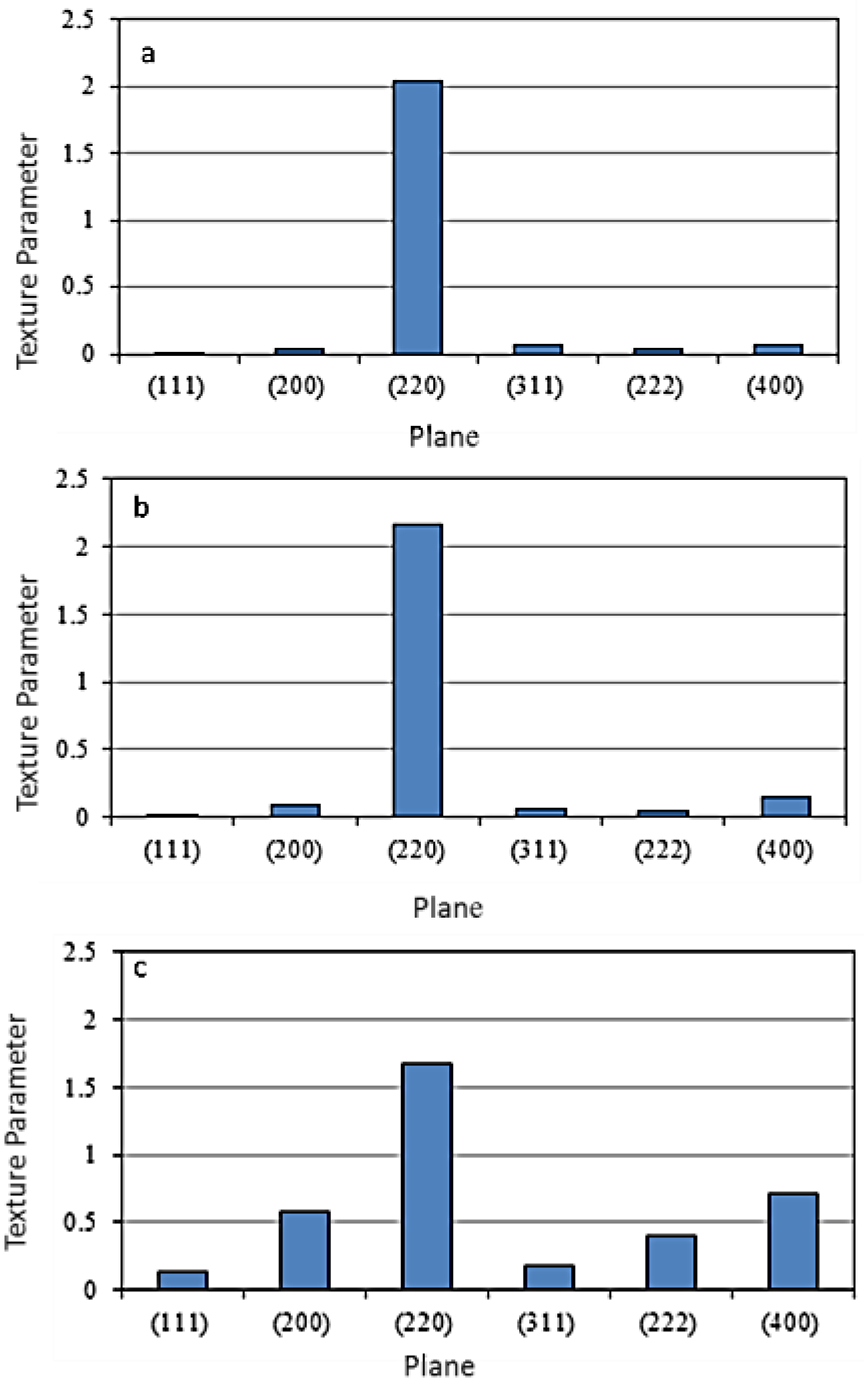

Fig. 6. Variations of texture parameter a) 1 pass, b) 8 passes and c) 10 passes in route A.

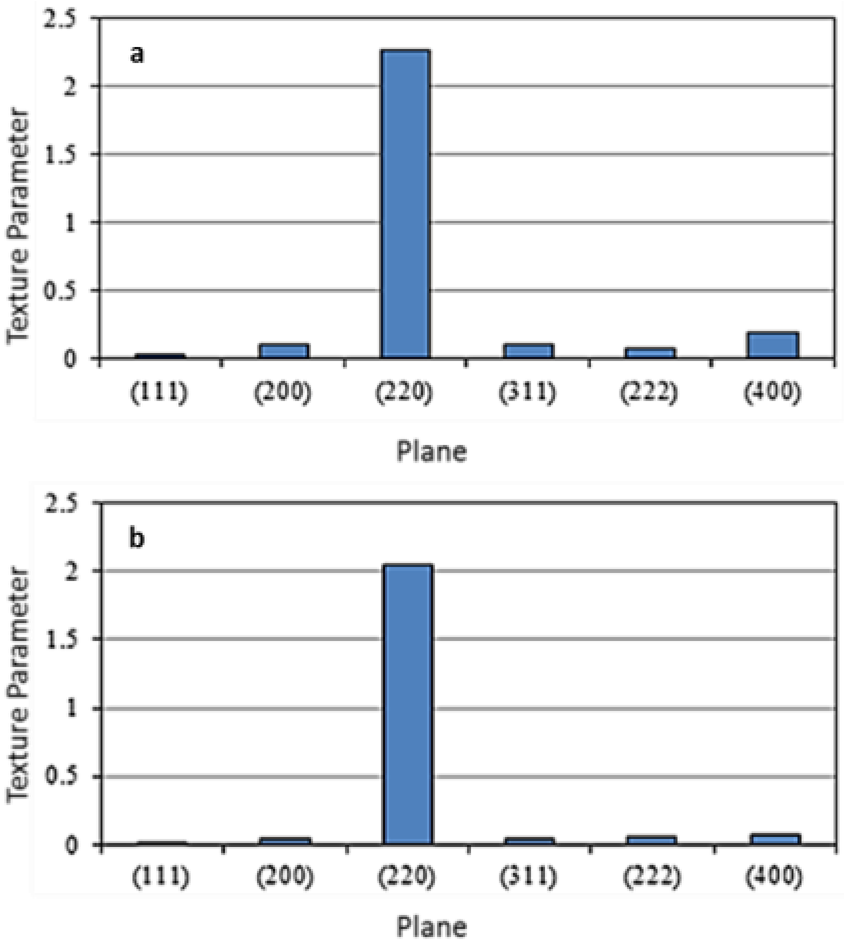

Fig. 7. Variations of texture parameter a) 8 passes and b) 10 passes in route B_C.

Fig. 8 shows the situation of specimens in different passes in the ECAP die through both routes. The shear stress is applied only along a particular plane in route A due to the non-rotation of specimens. It can lead to energy increment and provide the driving force for recrystallization. While in route B_C the shear stress is applied to different planes due to the rotation of specimen in each pass that can facilitate dynamic recovery and decrease energy. In Fig. 6 it was observed that in contrast to route B_C, the parameter intensity of plane (400) increased after the tenth pass through route A, indicating the initiation of deformation in the recrystallized grains, However, it decreased in route B_C. The results obtained from Fig. 4 also confirm this phenomenon. It was observed that elongation increased in the eighth pass and then reduced, indicating severe work-hardening. Fig. 9 shows the microstructures of specimens in the annealing condition and after the eighth pass as the first pass in which recrystallization occurred. As can be seen, equiaxed recrystallized grains were created after the eighth pass that their average size reaches to 1 ± 0.3 µm.

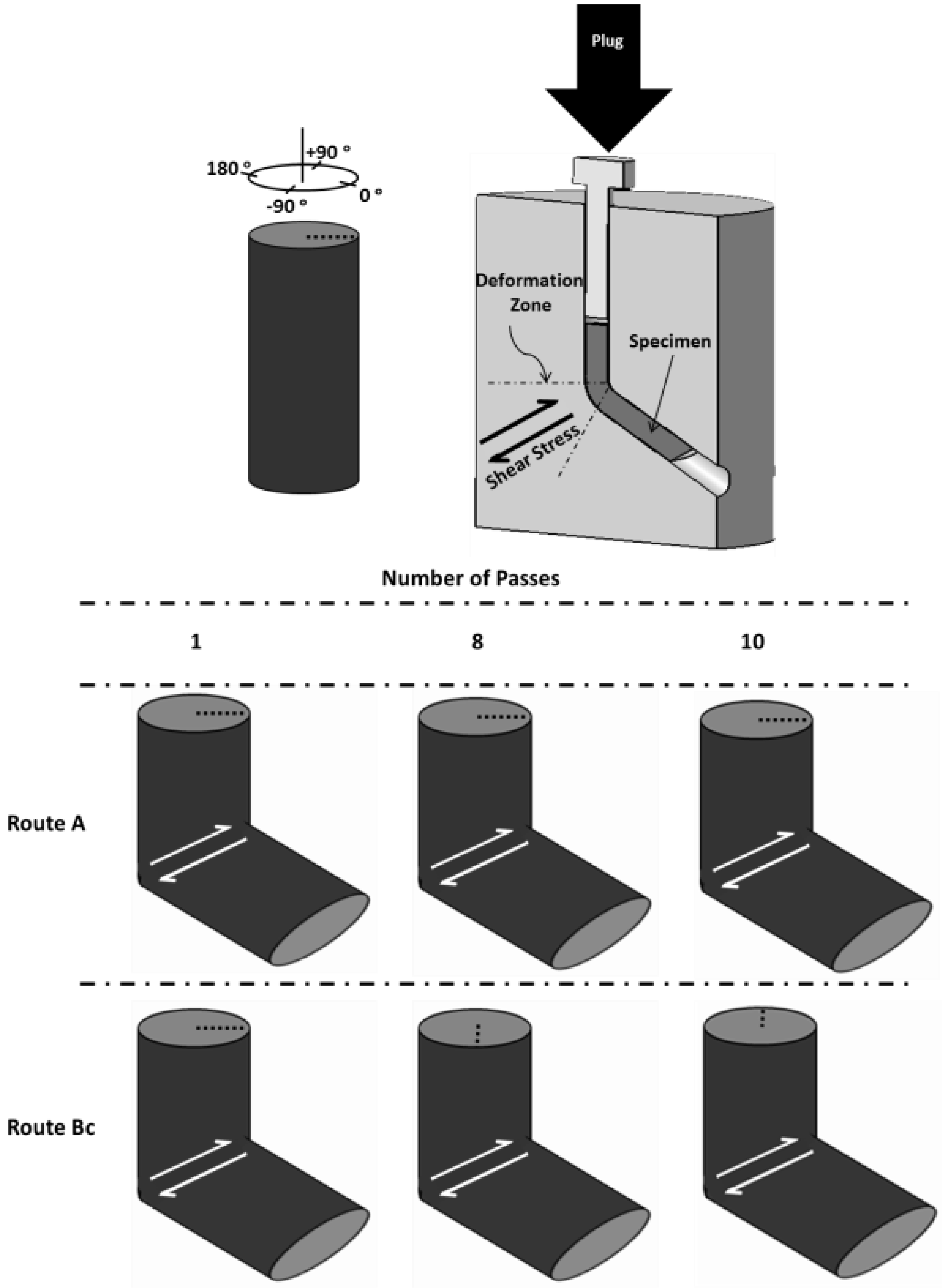

Fig. 8. Situation of the specimens in the ECAP die in routes A and B_C.

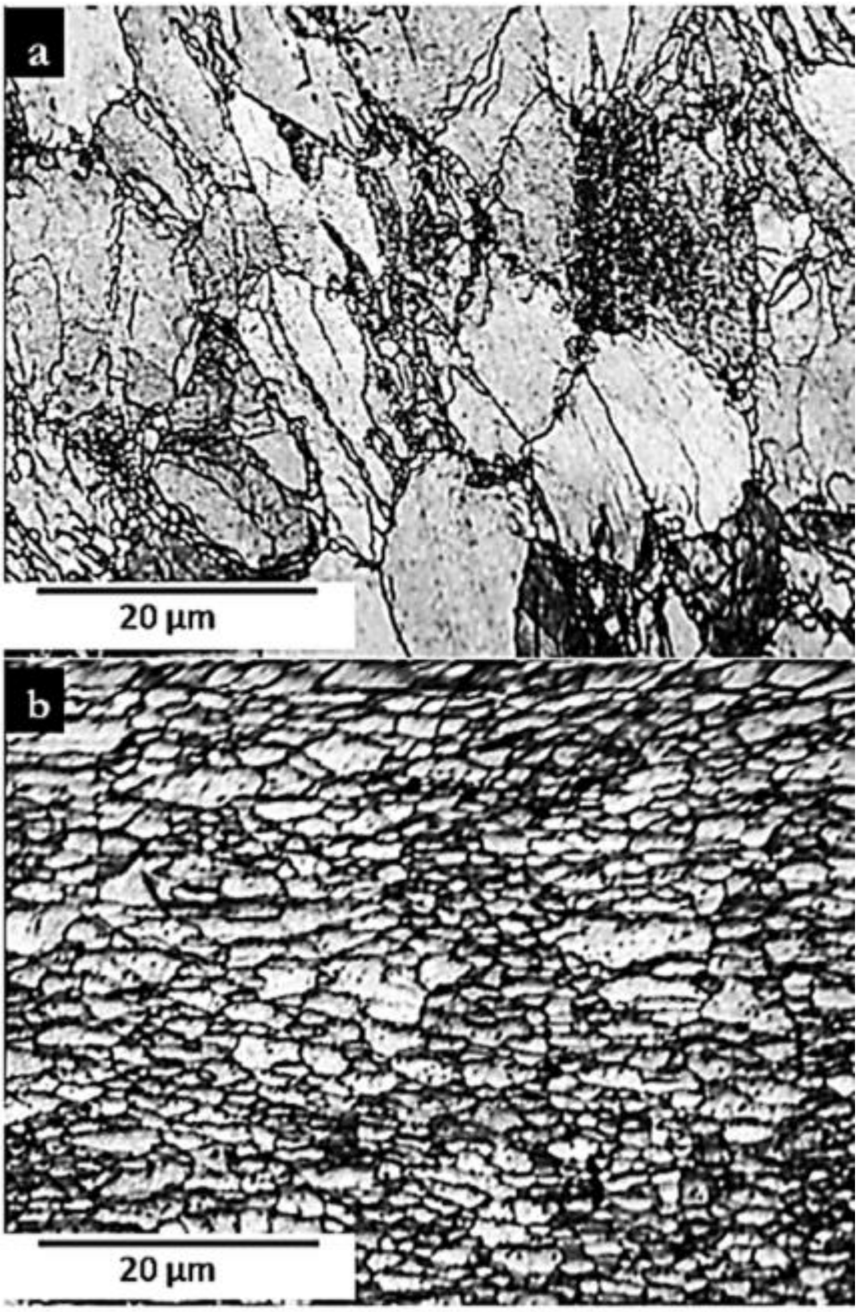

Fig. 9. EBSD images of microstructure a) annealed specimen and b) eighth pass of the ECAP process in route A.

3-3- Fractography

Fig. 10 shows the fracture surfaces of the annealed and processed specimens through route A after the tensile test. It can be seen that the annealed specimen was comprised of coarse and stretched dimples showing shear deformation in the microstructure. This behavior is usually seen in the plane stress conditions and materials with high fracture toughness [27]. According to Figs. 10b to 10h, the stretched dimples were reduced by increasing the number of passes and they tended toward more equiaxed sections.

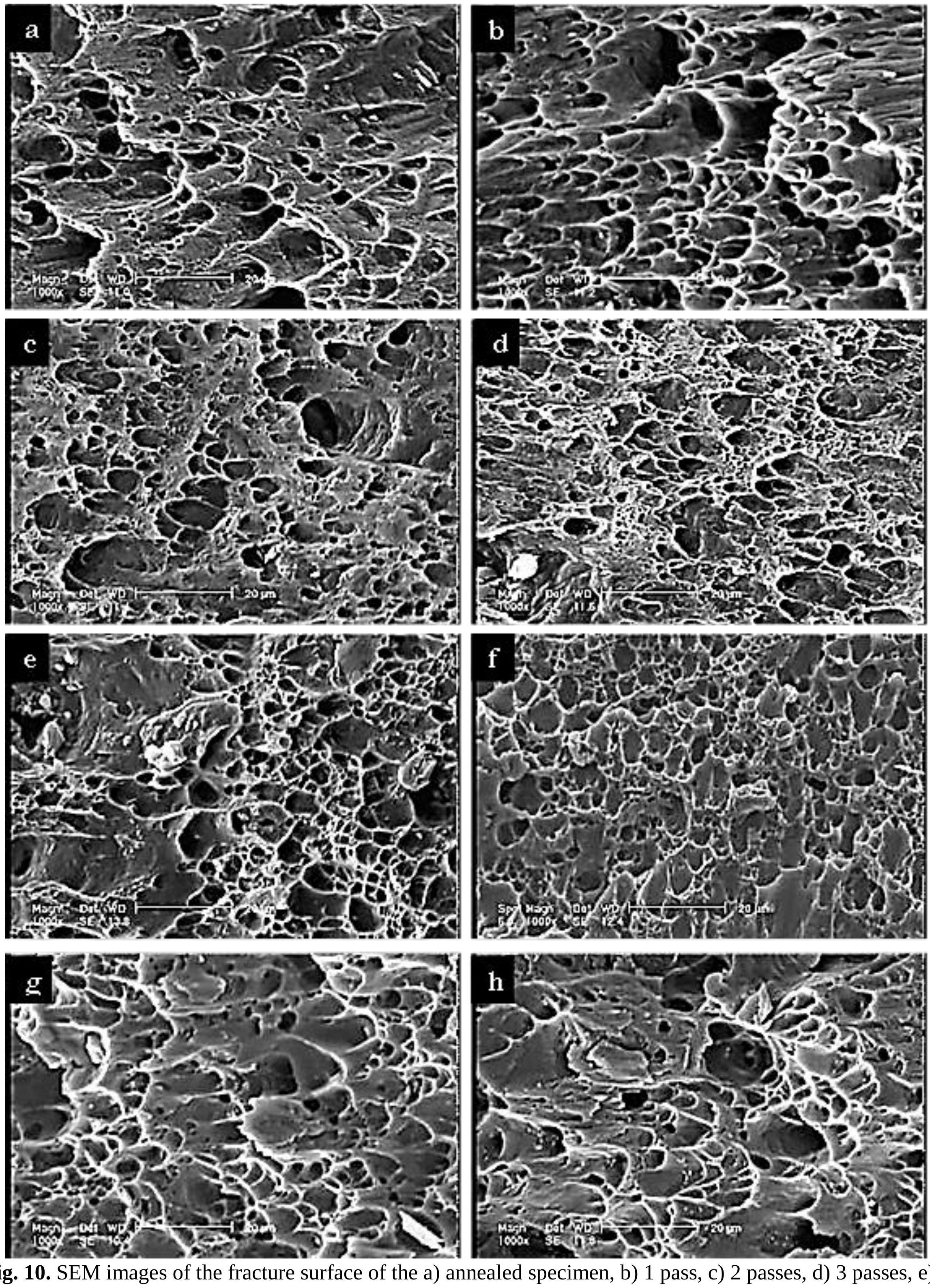

Fig. 10. SEM images of the fracture surface of the a) annealed specimen, b) 1 pass, c) 2 passes, d) 3 passes, e) 4 passes, f) 6 passes, g) 8 passes and h) 10 passes in route A.

These morphological changes could be a sign of insufficient shear deformation in the microstructure for stretching the dimples. Additionally, tri-axial stress components were possibly high enough around the voids resulting in the alteration of two-axial to tri-axial stresses

[27]. Also, it can be seen that the density of dimples increased by increasing the number of passes. Fig. 11 displays the fracture surface of the tensile specimens after the ECAP process through route B_C. As can be seen, the fracture surfaces in this route are almost similar to route A. However in this route, the dimples are more uniform in size and less elongated. This could be attributed to the better distribution of strain and a more homogeneous grain size in the microstructure. Also, less stretched dimples shows that the three-dimensional stresses have dominated and two-dimensional stress has a less contribution in deformation.

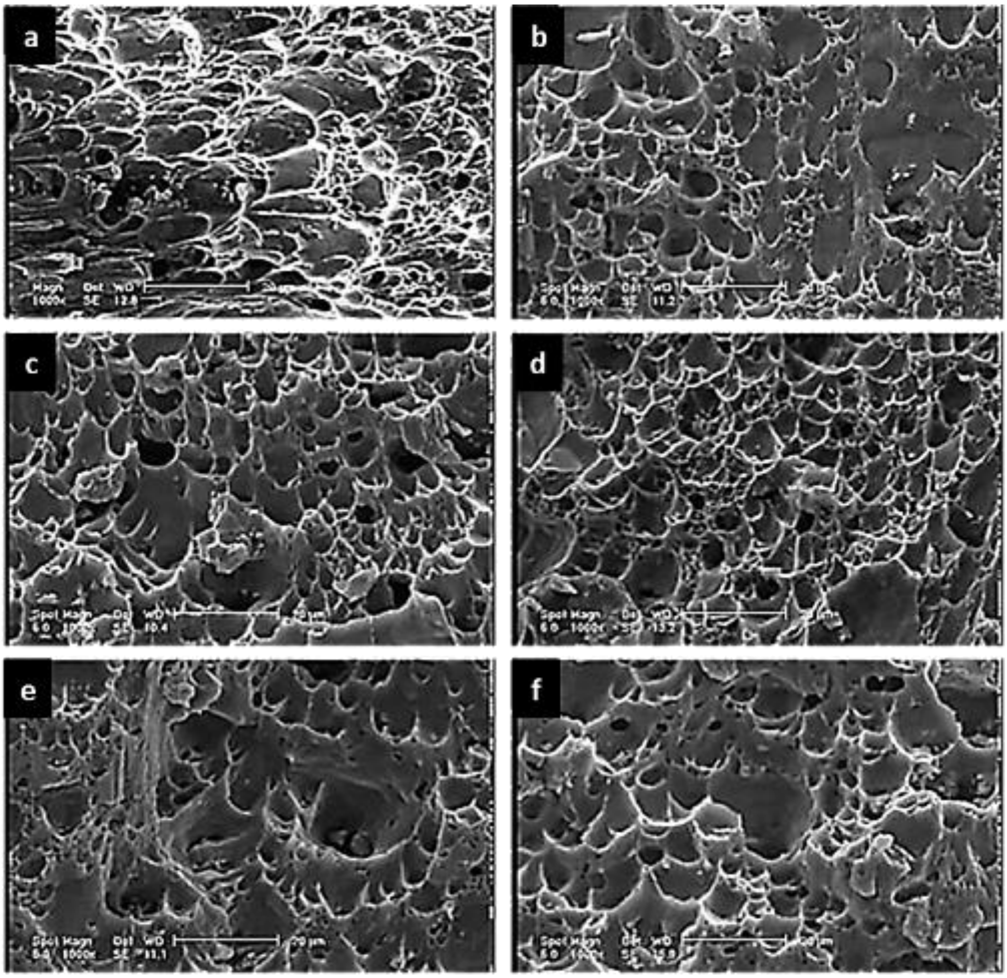

Fig. 11. SEM images of the fracture surface of the a) 2 passes, b) 3 passes, c) 4 passes, d) 6 passes, e) 8 passes and f) 10 passes in route B_C.

4-Conclusion

It was observed that hardness and tensile strength in route B_C were higher compared with route A. The texture analysis by means of XRD revealed that in route A, the intensity of plane (111) was significantly reduced and the intensity of plane (220) was drastically elevated. Also, it was shown that the intensity of plane (400) was increased after the eighth pass, while the intensity of the dominant planes was decreased in route B_C, indicating a more uniform microstructure. Fractography studies proved the increase in the number of dimples by increasing the number of passes for both routes. Fracture behavior in route B_C was fairly similar to that of the specimens in route A, while in route B_C, the dimples distribution was more uniform.

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