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Flow behaviour of magnesium alloy AZ31B processed by equal-channel angular pressing

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Abstract. Magnesium alloys are characterised by their low density, high specific strength and stiffness. But, the potential application of Mg is limited by its low room-temperature ductility & formability. Formability can be improved by developing an ultrafine grained (UFG) structure. Equal channel angular pressing (ECAP) is a well known process that can be used to develop an ultrafine grained microstructure. The aim of this study was to investigate the flow behaviour of AZ31B magnesium alloy after ECAP. The specimen was subjected to three passes of ECAP with a die angle of 120° using processing route Bc. The processing temperature was 523 K for the first pass and 423 K for the subsequent two passes. The microstructure characterisation was done. Compression tests of ECAPed and annealed specimens were carried out at strain rates of $0.01 - 1s^{-1}$ and deformation temperatures of 200 – 300°C using computer servo-controlled Gleeble-3800 system. The value of activation energy Q and the empirical materials constants of A and n were determined. The equations relating flow stress and Zener–Hollomon parameter were proposed. In the case annealed AZ31, the activation energy was determined to be 154 kJ/mol, which was slightly higher than the activation energy of 144 kJ/mol for ECAPed AZ31.

1. Introduction

Severe plastic deformation (SPD) describes a group of metal-working techniques where very large strains are imposed without introducing any significant changes in the overall dimensions of the work-piece. Ultra fine grained materials (UFG) processed by SPD techniques possess improved strength[1] and super plasticity at lower temperatures. Many different SPD processing techniques have been developed .These techniques include equal channel angular pressing (ECAP)[2], high-pressure torsion (HPT)[3], accumulative roll bonding (ARB)[4], Groove pressing (GP) etc.

In Mg alloys, the Mg-Al-Zn (AZ) series are low cost alloys together with good strength, and ductility. But, Mg has low room-temperature ductility & formability. This is the result of the restricted number of independent and easily operated slip systems owing to its close packed hexagonal structure. SPD techniques lead to grain refinement and to significant improvements in the strength and ductility[5]. So there is a potential for improving the mechanical properties of AZ31 by subjecting these materials to severe plastic deformation.

In the present work, a Mg–3%Al–1%Zn alloy was processed by ECAP upto 3 passes using route B_c and its flow behaviour is compared with annealed AZ31. The purpose of this is to study the influence of finer grain size produced by ECAP on flow behaviour during subsequent processing.

2. Experimental procedure

Commercial AZ31 plates of 18 mm were machined into rods of 15 mm diameter and 110 mm length. Then the samples were annealed at 345°C for 1 hour. An ECAP die having a channel diameter of 15 mm and with an internal angle 2φ between the two parts of the channel as 120° was used. Angle ψ, the outer arc of curvature at the point of intersection of the two channels was 30°. The die was constructed from H11 tool steel and it was placed within the furnace with heaters surrounding the die. The temperature for each pressing was controlled using a thermocouple which was placed at a distance of 5 mm from the die channel wall. The die was held at required temperature for 10 min for stabilisation. A plunger attached to a hydraulic press was used for pressing. The samples were subjected to three passes of ECAP and through route Bc, in which the work piece was rotated 90° clockwise along its longitudinal axis between adjacent passes. The processing temperature was 250°C for the first pass and 150°C for the subsequent two passes.

For compression tests, cylindrical samples with 10 mm diameter and 15 mm height were machined from annealed and ECAPed samples. Compression tests were carried out at strain rates of 0.01 - 1s^{-1} and deformation temperatures of 200, 250 and 300°C using computer servo-controlled Gleeble-3800 system. The sample was resistance heated to deformation temperature at a heating rate of 5°C/s and held at that temperature for 60s. The samples were deformed to half of their original height which corresponds to a true strain of about 0.7.

Microstructural observations were carried out by optical microscopy (OM).

3. Results and discussion

3.1 Flow stress behaviour

The flow curves obtained for annealed and ECAPed AZ31 at temperatures of 200 -250°C and strain rates from 0.01 – 1 s^{-1} are shown in Figure 1 and 2. The flow stress increased to a peak value and then decreased as the strain is further increased. The increase in stress can be attributed to work hardening after yielding. It is followed by dynamic flow softening (dynamic recovery and dynamic recrystallisation) which can reduce the effect of work hardening.
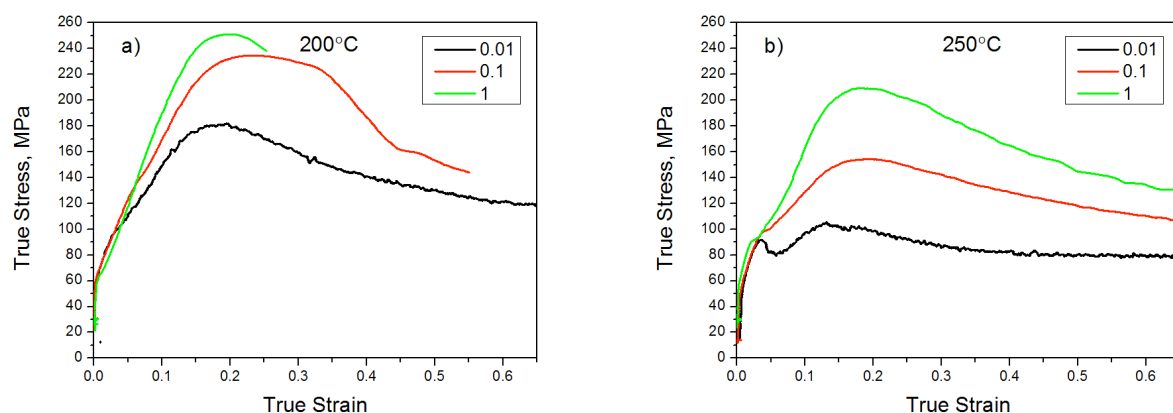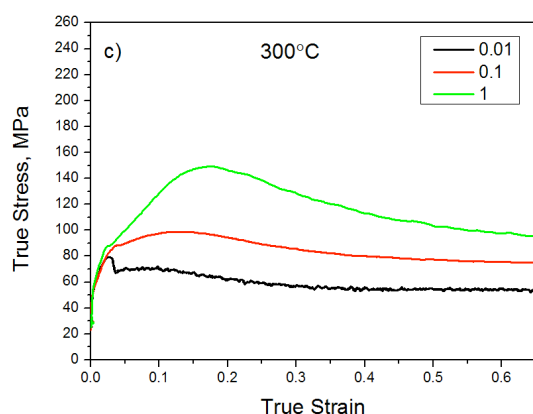
Figure 1: True stress–true strain curves of Annealed   AZ31 magnesium alloy during hot compression deformation a) 200°C b) 250°C c) 300°C
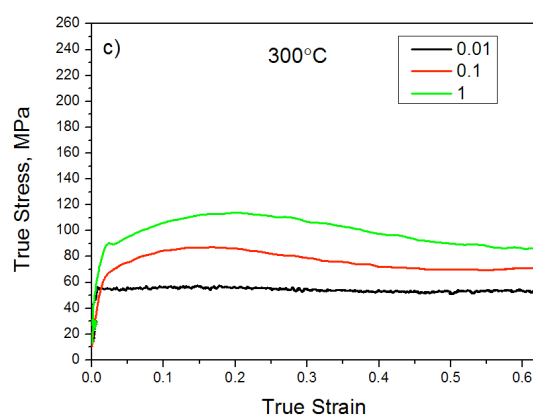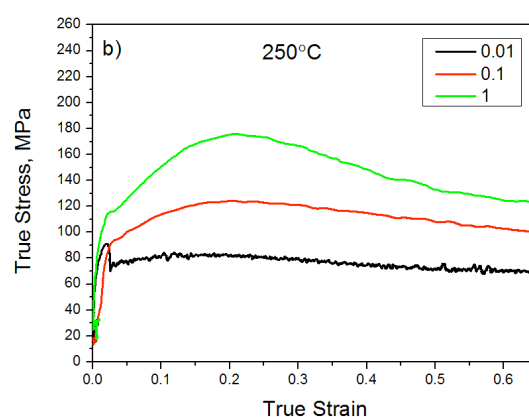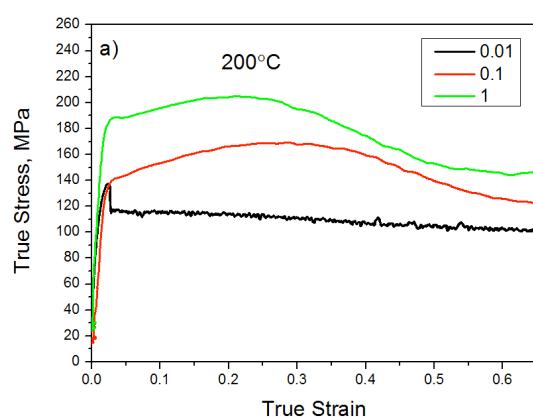

Figure 2: True stress–true strain curves of ECAPed   AZ31 magnesium alloy during hot compression deformation a) 200°C b) 250°C c) 300°C

The increase in stress and sudden drop at low strain at the strain rate of $0.01s^{-1}$ appear to be due to flow softening. Further tests are required to ascertain either it is flow softening or an artefact of hot compression.

3.2. Constitutive equations

Several constitutive equations have commonly been applied in hot working for description of the deformation process[6].

$$Z = \dot{\varepsilon}\, exp\left(\frac{Q}{RT}\right) \tag{1}$$

$$Z = A\left[sinh\,(\alpha\sigma_p) \right]^n \tag{2}$$

Where, Z is the Zener−Hollomon parameter, Q is activation energy for hot deformation, R is the gas constant, A and α are material constants, n is a constant closely related to the strain rate, $\dot{\varepsilon}$ is the strain rate, T is the deformation temperature(K) and σ_p is the peak stress (MPa).

By combining the equations (1) and (2), the following relation is obtained.

$$ln\dot{\varepsilon} = \left(lnA - \frac{Q}{RT}\right) + nlnsinh(\alpha.\sigma_p) \tag{3}$$

By using linear statistical regression methods, the average values of n and α are determined as 5.44 and 0.01, respectively for annealed samples. For ECAPed samples, values for n and α are 6.25 and 0.01 respectively.

Figure 3 shows the variations of peak stress with 1/T. The value of Q is calculated from the slope of the linear regression line (Q/nR). From the average value of intercept, the value of A can be estimated.
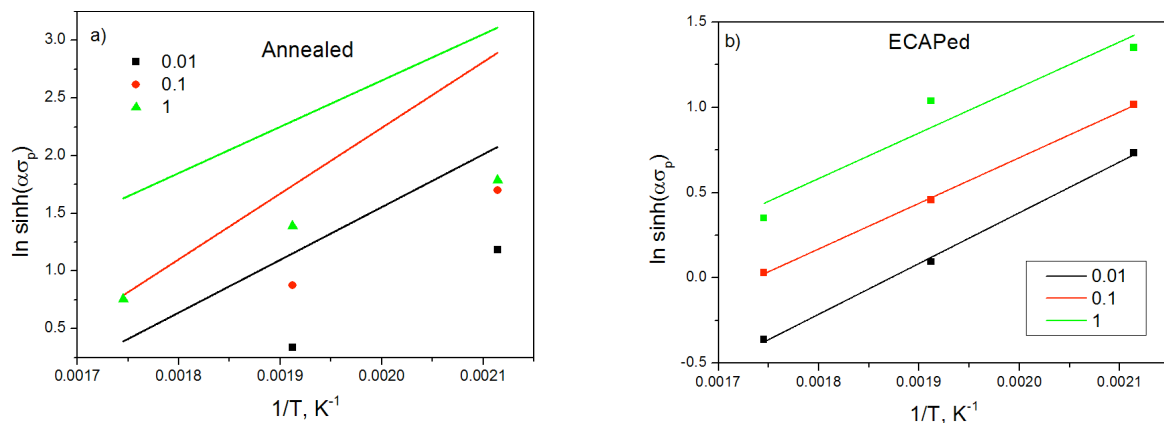

Figure 3: Variation of hyperbolic sine function of peak stress and 1/T for determination of constants of A and Q for a) Annealed and b) ECAPed AZ31
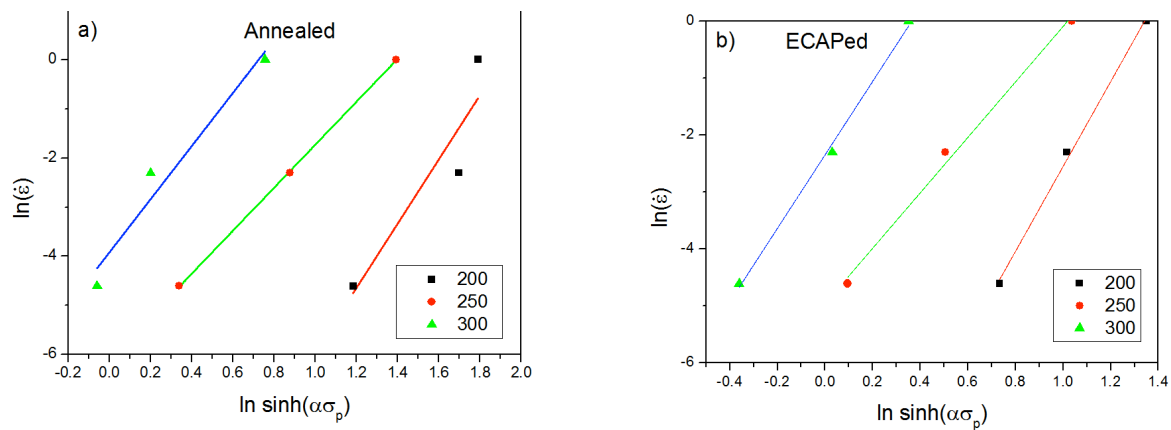
Figure 4 : Variation of hyperbolic sine function of peak stress and strain rate for determination of constants n and α for a) Annealed and b) ECAPed AZ31

The values obtained for the annealed and ECAPed AZ31 in Table1.

Table1: Material constants of Annealed and ECAPed AZ31

	N	A (MPa^{-1})	A (s^{-1})	Q (kJ/mol)
Annealed AZ31	5.44	0.01	6.21×10^{14}	154
ECAPed AZ31	6.25	0.01	4.53×10^{12}	144

These values of Q are very close to the previously reported values of 158 kJ/mol[7] and 147 kJ/mol[8]

Thus the Zener−Hollomon parameter for annealed AZ31 can be expressed as

$$Z = \dot{\varepsilon}\, exp\left(\frac{154000}{8.314T}\right) = 6.21 \times 10^{14}\left[sinh\,(0.01\sigma_p)\right]^{5.4} \tag{4}$$

For the ECAPed material the equation is,

$$Z = \dot{\varepsilon}\, exp\left(\frac{144000}{8.314T}\right) = 4.53 \times 10^{12}\left[sinh\,(0.01\sigma_p)\right]^{6.25} \tag{5}$$

Fig. 5 shows the relationship between the peak stress and the Z parameter. The peak stress increased with increasing the Z parameter for both annealed and ECAPed AZ31.
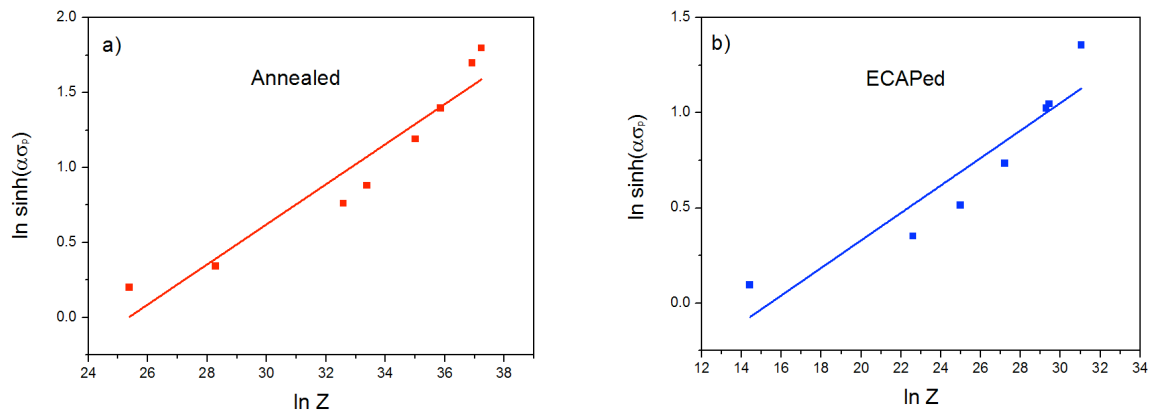
Figure 5: Relationship between the peak stress (σ_p) and the Z parameter for a) Annealed and b) ECAPed AZ31

The variation of peak stress with temperature and strain rate is shown in Figs. 6 and 7. The peak stress increased with decreasing deformation temperature and increasing strain rate. Comparing annealed and ECAPed AZ31, it is noted that the peak stress is reduced for ECAPed material due to larger number of fine grains. These fine grains had a softening effect on the hot deformation behaviour of AZ31.
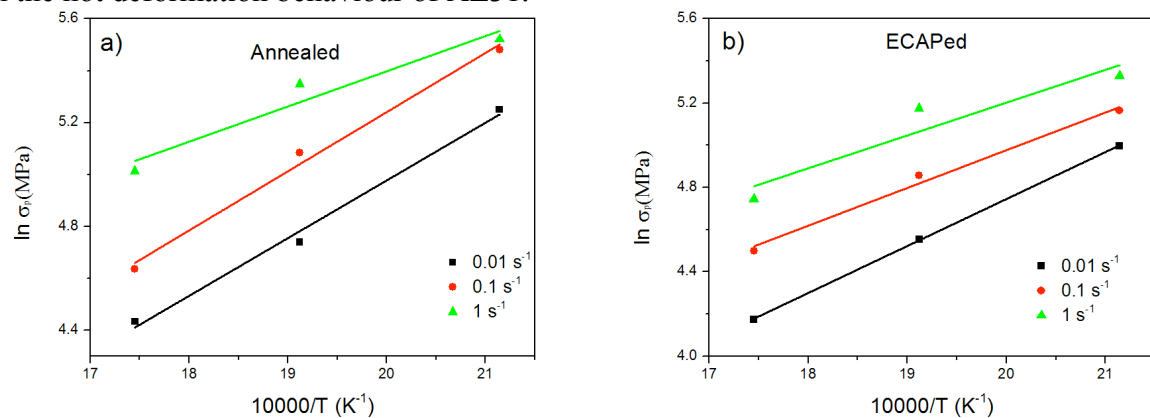

Figure 6: Effect of deformation temperature on the peak stress for a) Annealed and b) ECAPed AZ31
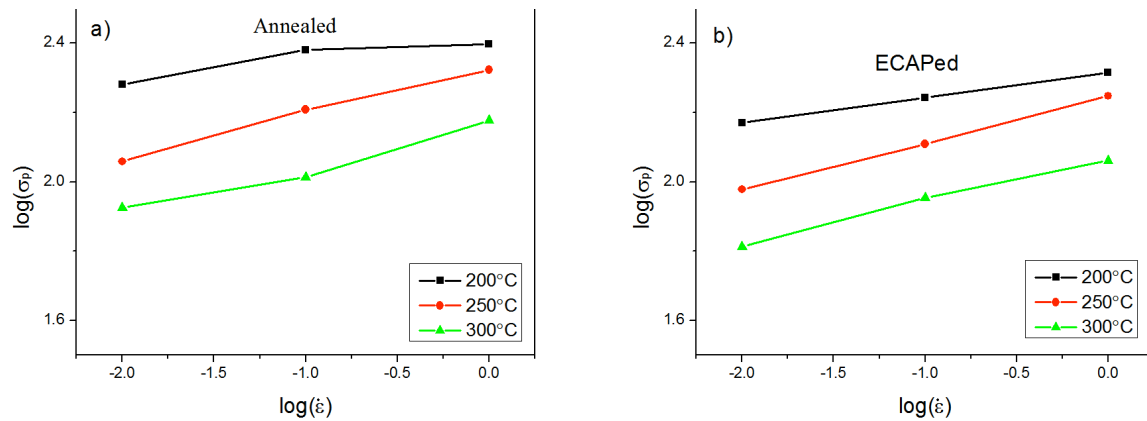
Figure 7: Effect of strain rate on the peak stress for a) Annealed and b) ECAPed AZ31

The variation of peak strain on deformation temperature and strain rate for annealed and ECAPed AZ31 alloy is shown in Figs. 8 and 9. It is noted that peak strain is decreased with temperature at lower strain rates of 0.01 and 0.1 s^{-1} while it almost remained constant at higher strain rate of 1 s^{-1}. From Fig. 9 it is evident that peak strain depended strongly on strain rate.
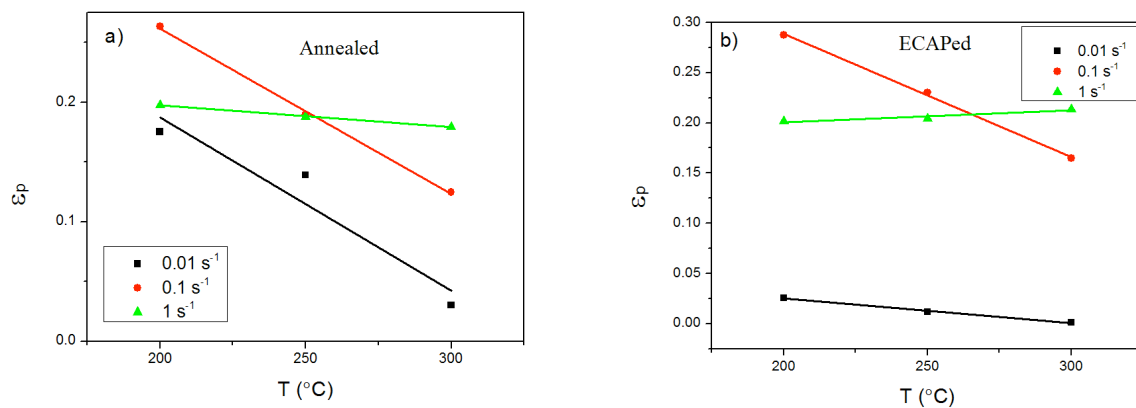

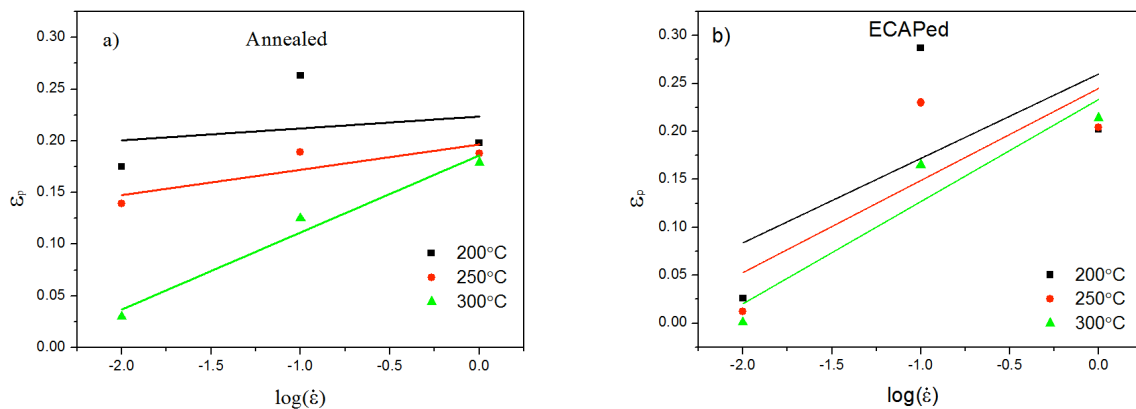**Figure 8**: Effect of deformation temperature on the peak strain for a) Annealed and b) ECAPed AZ31

Figure 9: Effect of strain rate on the peak strain for a) Annealed and b) ECAPed AZ31

The relationship between the peak strain and the Z parameter is shown in Fig. 10. For both annealed and ECAPed material, the peak strain increased with increasing the Z parameter.
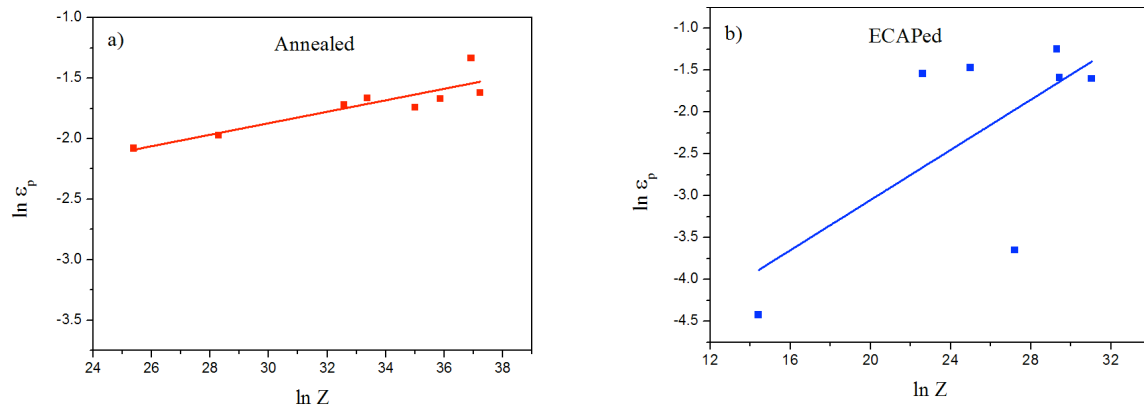

Figure 10: Relationship between the peak strain (ε_p) and the Z parameter for a) Annealed and b) ECAPed AZ31

The scattered data points in Figs. 9b and 10b can be attributed to uncertainty in estimating peak strain for the strain rate of 0.01 s^{-1}.
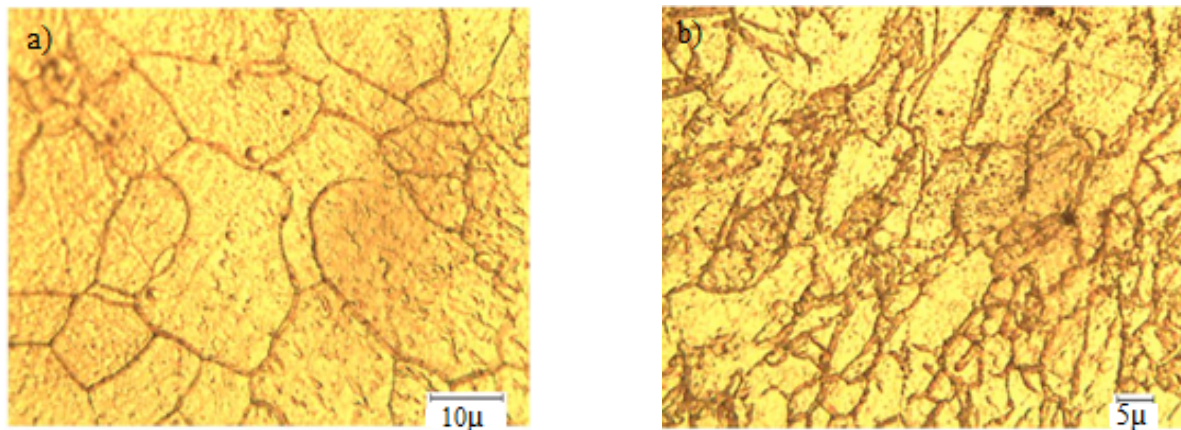
3.3 Microstructural Observations

Figure 11: Optical Micrographs of samples a) Annealed b) ECAPed

The microstructural evolutions during hot deformation were characterized by optical microscopy. Grain sizes were measured according to the ASTM E112 standard. Fig. 11 shows the optical micrographs of annealed and ECAPed AZ31.The initial grain size for annealed samples was measured as 29 μm. The grain size of ECAPed sample reduced to 2.8 μm.

4. Conclusions

Hot deformation behavior of annealed and ECAPed AZ31 was analyzed by means of constitutive equations.

1. The relation between the flow stress and Zener–Hollomon parameter was successfully analyzed. The value of apparent activation energy, Q, and the materials constants of A and n were determined.

2. The values of peak stress and flow stress were related to the Z parameter and pertaining equations were proposed.

3. The average grain size of the material reduces from 29 μm to 2.8 μm after 3 passes of ECAP.

4. The activation energy of annealed AZ31 was determined as 154 kJ/mol, which was slightly higher than the activation energy of 144 kJ/mol for AZ31 after three passes of ECAP.

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