



HAL
open science

Grain growth activation energy of ECAP-processed Mg-Ce alloy: Effect of deformation temperature

Hiba Azzeddine, Salaheddine Sadi, Abdelkader Hanna, Thierry Baudin, François Brisset, Jose Maria Cabrera

► **To cite this version:**

Hiba Azzeddine, Salaheddine Sadi, Abdelkader Hanna, Thierry Baudin, François Brisset, et al.. Grain growth activation energy of ECAP-processed Mg-Ce alloy: Effect of deformation temperature. *Materials Today Communications*, 2023, 37, pp.107161. <10.1016/j.mtcomm.2023.107161>. <hal-04245387>

HAL Id: hal-04245387

<https://hal.science/hal-04245387v1>

Submitted on 17 Oct 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



HAL Authorization

Grain growth activation energy of ECAP-processed Mg-Ce alloy: Effect of deformation temperature

Hiba Azzeddine^{1,*}, Salaheddine Sadi¹, Abdelkader Hanna¹, Thierry Baudin², François Brisset² and Jose Maria Cabrera^{3,4}

¹ Laboratory of Materials and Renewable Energy, Faculty of Sciences, Mohamed Boudiaf University, 28000, M'sila, Algeria.

² Université Paris-Saclay, CNRS, Institut de chimie moléculaire et des matériaux d'Orsay, 91405, Orsay, France.

³ Department of Materials Science and Engineering, Technical University of Catalonia, 08019-Barcelona, Spain.

⁴ Fundació CIM-UPC, 08028 – Barcelona, Spain

* Corresponding author: Pr. Hiba Azzeddine, hiba.azzeddine@univ-msila.dz

Abstract

In the present work, the grain growth activation energy, Q was evaluated in a Mg-0.3Ce (wt. %) alloy after equal-channel angular pressing (ECAP) processing via route *Bc* for 4 passes at 300 and 350 °C and followed by isochronal annealing at 150, 250, 350, and 450 °C for 2 h. The results demonstrated that Q depends strongly on the deformation processing. The Q value was equal to 111.4 kJ/mol for the sample ECAP-processed at 300 °C. While the sample ECAP-processed at 350 °C shows the presence of two different Q values depending on the annealing temperature, $Q_I = 26.5$ kJ/mol in the low-temperature range (150–350 °C) and $Q_{II} = 120.7$ kJ/mol in the high-temperature range (350–450 °C). This behaviour was attributed to the resulting deformation microstructure and the occurrence of dynamic grain growth during ECAP processing at 350 °C.

Keywords: Activation energy; ECAP; Grain growth; Kinetics; Magnesium.

1. Introduction

Ultra-fine materials are characterized by superior mechanical properties and enhancement of superplasticity at elevated temperatures [1, 2]. Severe plastic deformation (SPD) including equal-channel angular pressing (ECAP) processing is one of the effective procedures to fabricate ultra-fine materials with submicrometer (0.1–1 μm) or nanometer (< 100 nm) scale grain sizes [3, 4]. Basically, in ECAP processing the material undergoes a high shear deformation by pressing it through an L-shaped die without any change in the cross-section area which permits repetition of the deformation [3]. Nowadays, ECAP processing is frequently used for processing diverse Magnesium Mg-based alloys such as AZ series [5-10] or Mg-containing rare-earth (RE) elements (Mg-RE) alloys [11-17]. The reports demonstrated that ECAP processing can significantly enhance the ductility and reduce the mechanical anisotropy of Mg-based alloys through exceptional grain refinement and texture modification [5-12]. For example, excellent ductility (elongation of 22.6%) and high strength (ultimate tensile strength of 417.2 MPa) were reached in a Mg-10.6Gd-2Ag (wt. %) alloy after ECAP processing at 350 °C for 8 passes [12]. However, the deformation and recrystallization behaviours of Mg-based alloys are greatly controlled by ECAP processing conditions such as strain level, strain path, and deformation temperature [5, 8, 14, 16]. It was reported recently that ECAP processing of a Mg-0.3Ce (wt.%) alloy at 300 and 350 °C for 4 passes led to similar dynamic recrystallization (DRX) fraction but with different grain size due to the occurrence of dynamic grain growth during ECAP processing at 350 °C [14]. Moreover, the annealed microstructure at 450 °C of the ECAP-processed Mg-0.3Ce alloy at low strain (1 ECAP pass) was found very heterogeneous due to the pinning effect of second particles and the absence of DRX [16]. While an increasing number of ECAP passes (2 and 4 ECAP passes) provided sufficient recrystallization nucleation sites which led to a more homogeneous microstructure after annealing at 450 °C [16]. It is well known that the thermal stability of SPD-processed alloys during subsequent annealing is important to maintain or even improve their excellent mechanical and physical properties [1, 18]. It has been reported that ECAP processing at 200 °C for 6 passes of a ZK60 alloy can achieve a superior superplasticity elongation in the temperature range of 177–200 °C. However, such superplastic behavior was vanished at 220 °C which has been attributed to the occurrence of grain growth [1]. Therefore, the recrystallization and grain growth kinetics must be inspected to control the mechanical properties of Mg-based alloys. The recrystallization and grain growth kinetics are typically evaluated by calculating the activation energy which controls the extent of the resistance to any

grain growth [19]. So far, limited studies can be found in the literature dealing with the evolution of microstructure and the corresponding mechanical properties of ECAP-processed Mg alloys containing RE elements (Mg-RE alloys) after annealing treatments [16, 20]. Consequently, the recrystallization/grain growth kinetics and information on the activation energies of ECAP-processed Mg-RE alloys are lacking. Hence, the present study aims to evaluate the activation energy of grain growth of a Mg-0.3Ce (wt.%) alloy after ECAP processing at 300 and 350 °C. The purpose of choosing a low content of Ce element (0.3%) is to obtain a low-cost and single-phase Mg-Ce alloy [21]. More information on the evolution of microstructure, texture and microhardness after ECAP processing and annealing treatments of the Mg-0.3Ce alloy can be found in references [14, 16].

2. Experimental procedure

The as-cast Mg-0.3Ce alloy was processed by ECAP via route *Bc* for 4 passes at 300 and 350 °C using a die having a channel angle of $\Phi = 90^\circ$ and an outer arc of curvature of $\Psi = 37^\circ$ as illustrated in Figure 1. More details on the ECAP die processing and deformation behaviour of the alloy can be found in the reference [14]. The deformed samples experienced isochronal annealing at 150, 250, 350, and 450 °C for 2h followed by air quenching.

The microstructure was revealed near the centre of the TD-ND plane (see Figure 1), where TD and ND mean the transversal and normal directions respectively. Metallographic preparation consisted of mechanical grinding and electropolishing with 5:3 of ethanol and phosphoric acid for 30 min and then etching for 3 s in a 5% HNO₃, 15% CH₃COOH, 60% C₂H₅OH, and 20% H₂O. At least six metallographs were used for an accurate mean grain size measurement. The mean grain size of the samples was measured by the line intercept method.

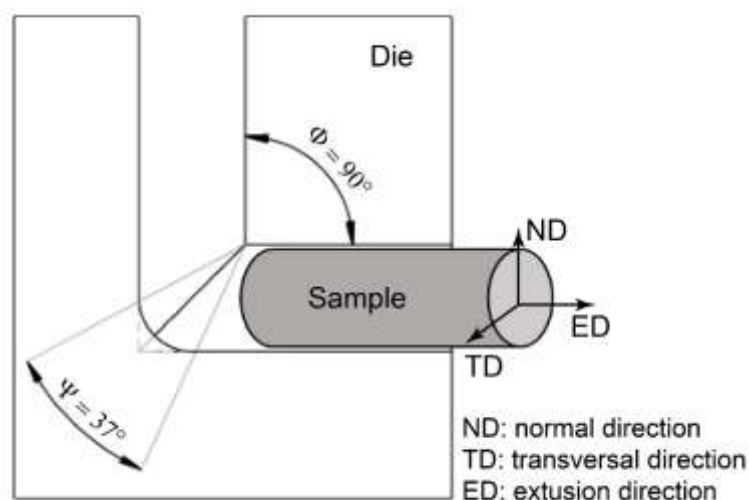


Figure 1: Sketch showing details of the ECAP die and sample reference axes.

Scanning Electron Microscopy (SEM) and Electron BackScatter Diffraction (EBSD) areas of $100 \times 100 \mu\text{m}^2$ with a step size of $0.1 \mu\text{m}$ of the ECAP-processed samples were used to identify the presence of the second phase and the distribution of strain. More details on the EBSD preparation and microstructural evolution of ECAP-processed Mg-0.3Ce alloy can be found in the reference [14].

A SHIMADZU type HMV-2 tester was used to measure the Vickers microhardness of the annealed samples with a load of 100 g and a dwell time of 10 s. At least 10 indentations were recorded on one sample to obtain the average microhardness value.

3. Results and discussion

Figure 2 reveals the microstructure evolution of ECAP-processed Mg-0.3Ce alloy at 300 and 350 °C with annealing temperature. The progress of mean grain size as a function of annealing temperatures is shown in Figure 3a. It is worth noting that the mean grain size under the deformation condition was found equal to 1.6 and $4.3 \mu\text{m}$ for ECAP-processed samples at 300 and 350 °C, respectively [14].

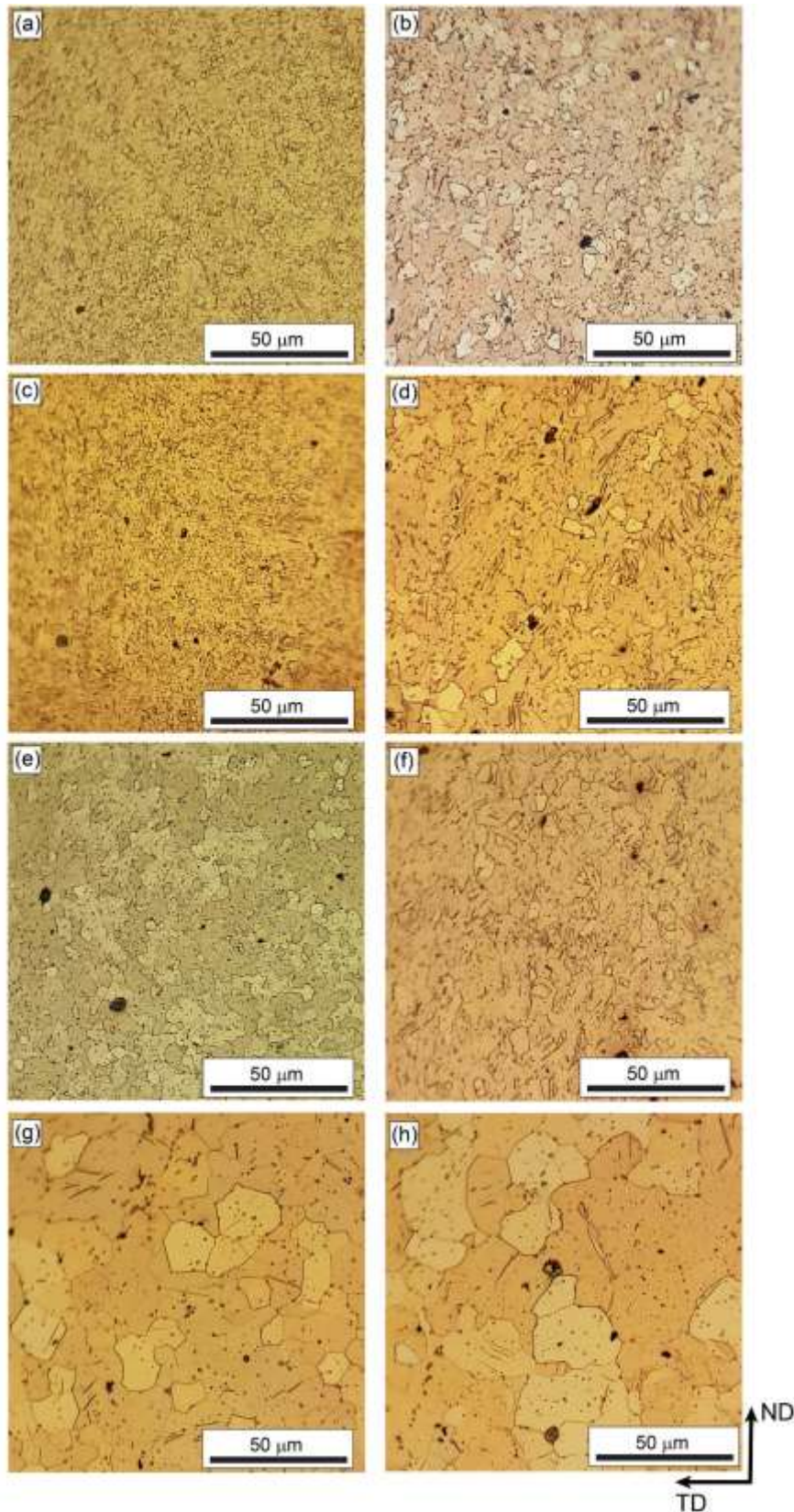


Figure 2: Microstructure of ECAP-processed Mg-0.3Ce alloy at 300 °C after annealing temperature at: (a) 150, (c) 250, (e) 350, and (g) 450 °C and microstructure of ECAP-processed sample at 350 °C after annealing temperature at: (b) 150, (d) 250, (f) 350, and (h) 450 °C.

Obviously, the microstructure of both samples is heterogenous at low annealing temperature (150–350 °C). It is mainly formed by a mixture of deformed grains and small recrystallized grains. It became more homogenous with equiaxed grains at 450 °C due to the occurrence of static recrystallization and grain growth. It is visible that the recrystallized grains fraction is higher in the ECAP-processed sample at 350 °C. It can be observed that all the annealed samples contain globular second particles distributed randomly through the microstructures. Figure 3a displays that the mean grain size raises at increasing annealing temperatures. As well, the mean grain sizes of the ECAP-processed sample at 300 °C are lower than those for the ECAP-processed sample at 350 °C. The mean grain size of the ECAP-processed sample at 300 °C increases from $2.1 \pm 0.7 \mu\text{m}$ at 150 °C to $9.5 \pm 1.1 \mu\text{m}$ at 450 °C. While the mean grain size of the ECAP-processed sample at 350 °C increases from $6.7 \pm 1 \mu\text{m}$ at 150 °C to $13.7 \pm 0.8 \mu\text{m}$ at 450 °C.

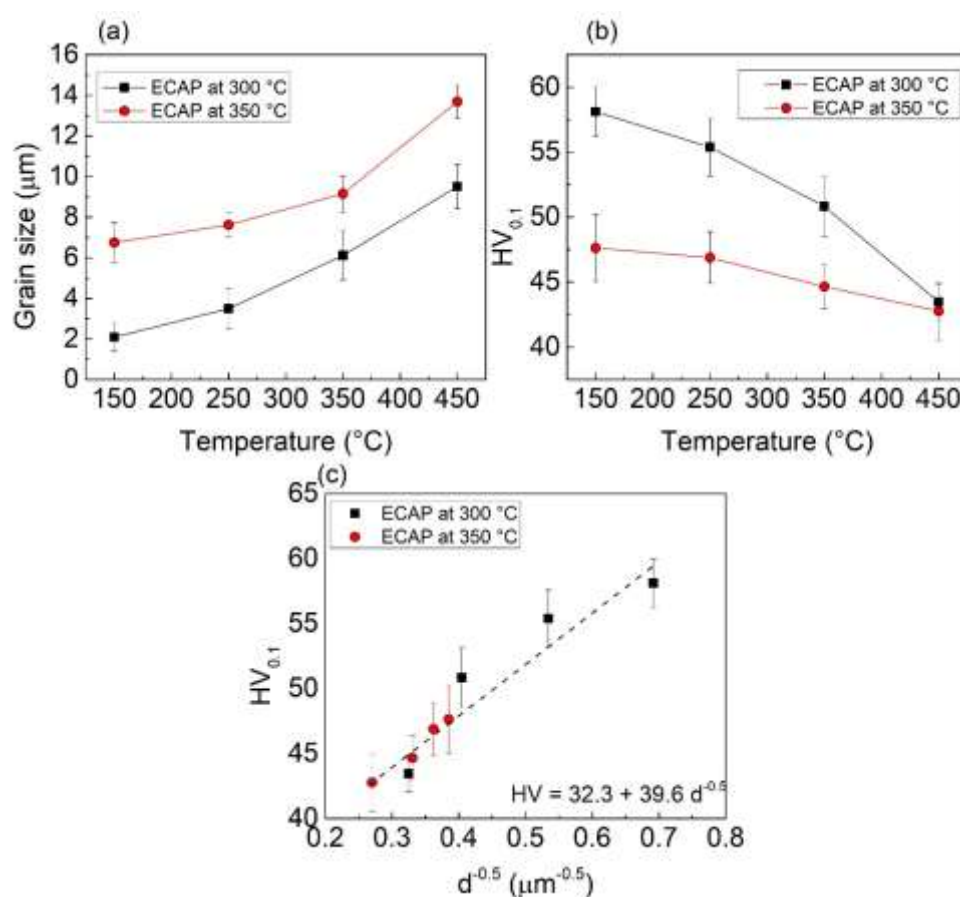


Figure 3: (a) Evolution of mean grain size as a function of annealing temperature, (b) evolution of microhardness as a function of annealing temperature and (c) Hall-Petch relationship of ECAP-processed Mg-0.3Ce alloy at 300 and 350 °C, respectively.

As a consequence of the occurrence of static recrystallization and grain growth phenomena, the microhardness of both samples decreases with increasing annealing temperature as shown in Figure 3b. It was reported earlier that the microhardness of the Mg-0.3Ce alloy increased from 37 ± 1.2 HV in the as-cast state to 64.3 ± 2.4 HV and 54.7 ± 2.1 HV after the ECAP processing at 300 and 350 °C, respectively [14]. The microhardness values of the ECAP-processed sample at 300 °C are higher than those for the ECAP-processed sample at 350 °C in the temperature range of 150–350 °C. For example, the microhardness at 150 °C was found equal to 58.1 ± 1.9 HV for the ECAP-processed sample at 300 °C versus 47.6 ± 2.6 HV for the ECAP-processed sample at 350 °C. However, the microhardness of both samples reached an almost similar value at 450 °C, 43.4 ± 1.4 HV vs. 42.7 ± 2.2 HV for the ECAP-processed sample at 300 and 350 °C respectively, probably due to the grain growth process.

The microhardness values were replotted versus the grain size values in Figure 3c following the Hall-Petch equation [22]:

$$H_v = H_{v0} + \frac{K_H}{\sqrt{d}} \quad (1)$$

where H_{v0} is the friction microhardness that characterizes the lattice resistance to the motion of dislocations and K_H a parameter that reflects the role of the grain boundaries on the hardening.

Accordingly, Figure 3c shows that the Hall–Petch relationship more or less holds over the different annealing conditions with the fitting parameters: $H_{v0} = 32.3$ and $K_H = 39.6$ HV $\mu\text{m}^{-1/2}$. The present results indicated that the variation of mechanical properties during static recrystallization and grain growth phenomena of the ECAP-processed Mg-0.3Ce alloy are more related to the grain size than the precipitation or dislocations effects.

Similar fitting values were reported for a AZ31 alloy ($H_{v0} = 38$ and $K_H = 42$ HV $\mu\text{m}^{-1/2}$) after ECAP processing [6] and for a Mg-1.44Nd (wt.%) alloy ($H_{v0} = 39$ and $K_H = 43$ HV $\mu\text{m}^{-1/2}$) processed by high-pressure torsion [23].

The grain growth kinetics of ECAP-processed samples at 300 and 350 °C are investigated following the general equation [24]:

$$d^n - d_0^n = A \exp\left(-\frac{Q}{RT}\right) \quad (2)$$

where d is the mean grain size, d_0 is the initial mean grain size (taken as 1.6 and 4.3 μm for ECAP-processed samples at 300 and 350 °C, respectively [14]), n is the grain growth exponent, A is a pre-exponential constant, Q is the activation energy, R is the gas constant and T is the annealing temperature.

Theoretically, $n = 2$ for metals without defects and therefore a parabolic growth law is assumed [24]. Practically, the n value has been reported in a range from 2 to 15 in Mg-based alloys under various deformation and recrystallization conditions [19, 25-29]. For example, it was found previously that $n = 8$ for hot-rolled and annealed AZ31 alloy and it was attributed to the effect of microstructure heterogeneities such as presence of second phases, dislocation network and crystallographic texture on the static recrystallization and grain growth. Based on the previous study [19], the n for the present investigation is chosen equal to 8.

Figure 4 shows the plot of $\ln(d^8 - d_0^8)$ versus $1000/RT$ of ECAP-processed Mg-0.3Ce alloy at 300 and 350 °C, respectively. As can be evidenced, the sample ECAP-processed at 300 °C exhibits only one temperature range with one activation energy. While two temperature ranges with different activation energy can be distinguished in the sample ECAP-processed at 350 °C. The activation energy value (111.4 ± 5.7 kJ/mol) of the sample ECAP-processed at 300 °C is slightly higher than the activation energy for grain boundary diffusion in pure Mg (92 kJ/mol) [30]. A similar activation energy, $Q = 109.2$ kJ/mol, was found for a hot-rolled AZ31 alloy at the temperature range of 150–350 °C [19]. It is well known that the activation energy for grain boundary diffusion is higher in alloys containing stable second particles than in pure metals [7].

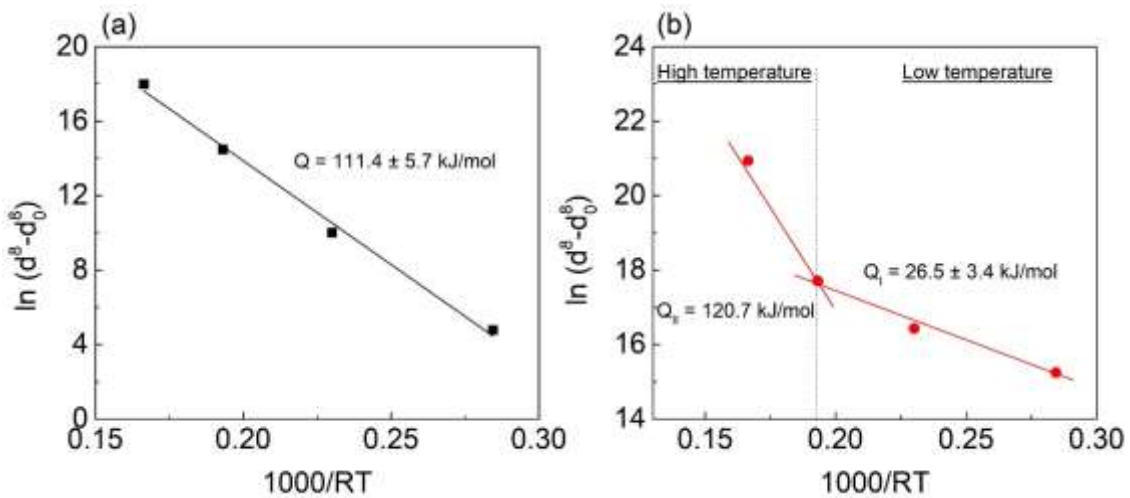


Figure 4: Activation energy estimation by plotting $\ln(d^8 - d_0^8)$ as a function of $1000/RT$ of ECAP processed Mg-0.3Ce sample at: (a) 300 °C, and (b) 350 °C.

Indeed, the SEM images shown in Figures 5a and 5b indicate that both ECAP-processed samples exhibit the presence of low amount of a second phase (see the arrows) containing 2.8% (at. %) of Ce element. These particles are randomly distributed in both deformed samples and they are characterized by a circular form with a diameter range of 2-2.5 μm . It is believed that

these particles are the same as those observed during the isochronal annealing of both ECAP-processed samples, as shown in Figure 2. In addition, similar particles were found stable in ECAP-processed sample at 300 °C through the isothermal annealing treatment at 450 °C for a time ranging from 5–180 min [16].

The activation energy (26.5 ± 3.4 kJ/mol) in the low-temperature range (150–350 °C) of the sample ECAP-processed at 350 °C is lower than the grain boundary diffusion one (92 kJ/mol). Such low value was already reported in severely deformed Mg-based alloys [5, 23, 31]. In the high-temperature range (350–450 °C), the activation energy (120.7 kJ/mol) is close to the bulk diffusion in pure Mg (135 kJ/mol) [30]. This value is in good agreement with the supposition that the grain growth occurs by lattice self-diffusion process when the microstructure is characterized by large grain size (Figure 2). Two activation energies of 26 and 147 kJ/mol were found for HPT-processed Mg-1.4Nd alloy at temperature ranges of 150–250 °C and 250–450 °C, respectively [23]. The difference in the activation energy at a high-temperature range in comparison with the present work could be explained by the occurrence of precipitation in the Mg-1.4Nd alloy [23]. Two activation energies of 31.3 kJ/mol in the temperature range 200–400 °C, and 109.2 kJ/mol in the temperature range 400–500 °C were obtained for ECAP-processed AZ31 alloy for 4 passes [5]. Interesting to note that only one activation value of 33.7 kJ/mol in the entire temperature range (200–500 °C) was reported for the same ECAP-processed AZ31 alloy after 1, 2 and 3 passes [5]. Two main explanations were proposed to elucidate the low grain growth activation energy. The first reason is that the grain growth occurs in deformed microstructure with very high dislocation density and non-equilibrium grain boundaries (un-recrystallized conditions) [32]. The second reason is that the grain growth occurs in dynamically recrystallized microstructure having already low dislocation density due to the enhancement of the recovery process (recrystallized conditions) [5]. It was reported earlier that the precipitation during annealing treatment could be also a factor in decreasing the activation energy of grain growth [23]. The second explanation is more adapted in the present case since the microstructure of the Mg-0.3Ce alloy was dynamically recrystallized after ECAP processing for 4 passes [14]. However, it must be mentioned that the dynamic recrystallization fraction was identical ($\sim 55\%$) in samples ECAP-processed at 300 and 350 °C for 4 passes [14] and both sample show completely different grain growth activation energy behavior. The transition of the activation energy from one temperature range to two temperature ranges with increasing deformation processing from 300 to 350 °C can be attributed to the resulting deformation microstructure [14]. The effect of the distribution of second particles can be excluded since both

samples in the deformation state were characterized by similar second particle distribution and identical particle composition as demonstrated in Figures 5a and 5b.

To calculate the stored energy in the ECAP-processed samples, the Kernel Average Misorientation (KAM) method was used following the equation [33]:

$$E = \frac{\mu b \theta_{KAM}}{2d} \quad (2)$$

where μ is the shear modulus, b is the Burgers vector, d is the scan step size and θ_{KAM} is the misorientation angle and it was calculated from the mean misorientation angle between a given point and its 3rd neighbors and by excluding misorientations of $\theta > 15^\circ$.

Figures 5c and 5d present the KAM maps of the ECAP-processed Mg-0.3Ce alloy at 300 and 350 °C, respectively. The KAM maps indicate that the distribution of dislocation and strain is denser in the sample ECAP-processed at 300 °C (see green color) than in the processed at 350 °C.

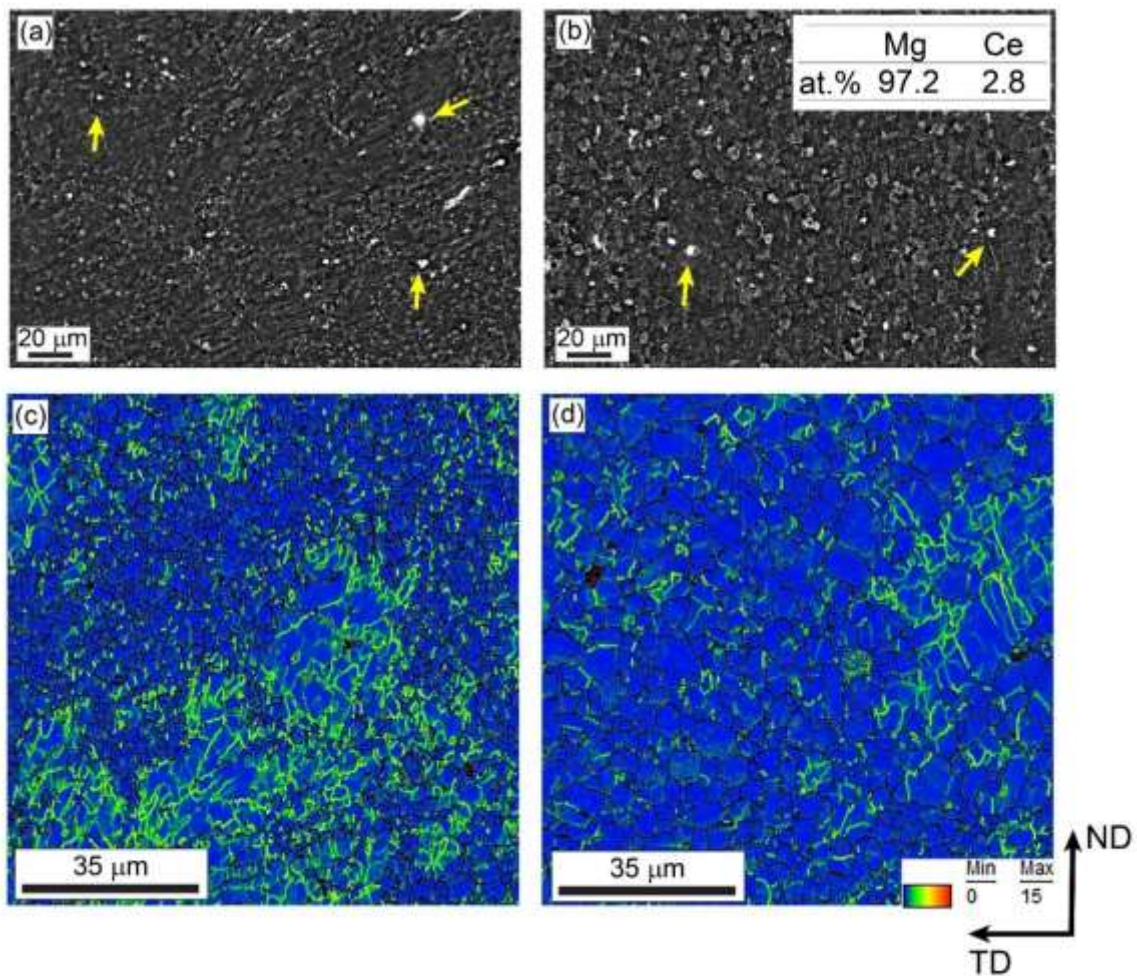


Figure 5: SEM photo and KAM map of ECAP-processed Mg-0.3Ce alloy at: (a, c) 300 °C and (b, d) 350 °C, respectively.

It can be noticed that the dislocation density is lower inside the small equiaxed grains which are dynamically recrystallized. The θ_{KAM} is found slightly higher for ECAP-processed Mg-0.3Ce alloy at 300 °C ($\theta_{KAM} = 1.5^\circ$) than 350 °C ($\theta_{KAM} = 1^\circ$). Consequently, the stored energy was found equal to 5 J/mol for ECAP-processed Mg-0.3Ce alloy at 300 °C and equal to 3.3 J/mol for ECAP-processed Mg-0.3Ce alloy at 350 °C. Since both ECAP-processed samples exhibit similar DRX fractions, the difference in the stored energy (1.7 J/mol) is related to the dynamic grain growth observed in the dynamically recrystallized grains of the sample ECAP-processed at 350 °C. Indeed, ECAP processing at 350 °C led to a larger grain size (4.3 μm) than for the sample ECAP-processed at 300 °C (1.6 μm) [14] which is noticeable in the KAM maps (Figures 5c and 5d). It can be concluded that the deformed grain size resulting from dynamic recrystallization and dynamic grain growth could be the origin of the transition of activation energy from one to two regimes.

4. Conclusion

- The activation energy of grain growth of the ECAP-processed Mg-0.3Ce alloy was found equal to 111.4 ± 5.7 KJ/mol for the sample processed at 300 °C. While the sample processed at 350 °C shows the presence of two different values depending on the annealing temperature, $Q_I = 26.5 \pm 3.4$ kJ/mol in the low-temperature range (150–350 °C) and $Q_{II} = 120.7$ kJ/mol in the high-temperature range (350–450 °C).
- The transition of activation energy from one to two regimes with increasing ECAP deformation temperature is attributed to the grain growth of the dynamically recrystallized grains during ECAP processing at 350 °C.
- The evolution of microhardness against the mean grain size follows the Hall-Petch relationship with the fitting parameters $H_{v0} = 32.3$ and $K_H = 39.6 \text{ H}_v \mu\text{m}^{-1/2}$.

Acknowledgments

The authors thank Dr. T. Al-Samman from RWTH Aachen University, Germany for supplying the Mg-0.3Ce alloy.

Conflict of Interest: The authors declare that they have no conflict of interest.

Data Availability: The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

References

- [1] R.B. Figueiredo, T.G. Langdon, Factors influencing superplastic behavior in a magnesium ZK60 alloy processed by equal-channel angular pressing, *Materials Science and Engineering: A* 503(1) (2009) 141-144.
- [2] F. Nazeer, J. Long, Z. Yang, C. Li, Superplastic deformation behavior of Mg alloys: A-review, *Journal of Magnesium and Alloys* 10(1) (2022) 97-109.
- [3] R.Z. Valiev, T.G. Langdon, Principles of equal-channel angular pressing as a processing tool for grain refinement, *Progress in Materials Science* 51(7) (2006) 881-981.
- [4] T. Sakai, A. Belyakov, R. Kaibyshev, H. Miura, J.J. Jonas, Dynamic and post-dynamic recrystallization under hot, cold and severe plastic deformation conditions, *Progress in Materials Science* 60 (2014) 130-207.
- [5] H.-K. Kim, Activation energies for the grain growth of an AZ31 Mg alloy after equal channel angular pressing, *Journal of Materials Science* 39(23) (2004) 7107-7109.
- [6] H.K. Kim, W.J. Kim, Microstructural instability and strength of an AZ31 Mg alloy after severe plastic deformation, *Materials Science and Engineering: A* 385(1) (2004) 300-308.
- [7] Y. Radi, R. Mahmudi, Effect of Al₂O₃ nano-particles on the microstructural stability of AZ31 Mg alloy after equal channel angular pressing, *Materials Science and Engineering: A* 527(10) (2010) 2764-2771.
- [8] J. Suh, J. Victoria-Hernández, D. Letzig, R. Golle, W. Volk, Enhanced mechanical behavior and reduced mechanical anisotropy of AZ31 Mg alloy sheet processed by ECAP, *Materials Science and Engineering: A* 650 (2016) 523-529.
- [9] Z. Yang, A. Ma, H. Liu, D. Song, Y. Wu, Y. Yuan, J. Jiang, J. Sun, Managing strength and ductility in AZ91 magnesium alloy through ECAP combined with prior and post aging treatment, *Materials Characterization* 152 (2019) 213-222.
- [10] Z. Shan, J. Yang, J. Fan, H. Zhang, Q. Zhang, Y. Wu, W. Li, H. Dong, B. Xu, Extraordinary mechanical properties of AZ61 alloy processed by ECAP with 160° channel angle and EPT, *Journal of Magnesium and Alloys* 9(2) (2021) 548-559.
- [11] P. Minárik, J. Veselý, R. Král, J. Bohlen, J. Kubásek, M. Janeček, J. Stráská, Exceptional mechanical properties of ultra-fine grain Mg-4Y-3RE alloy processed by ECAP, *Materials Science and Engineering: A* 708 (2017) 193-198.
- [12] J. Sun, B. Xu, Z. Yang, H. Zhou, J. Han, Y. Wu, D. Song, Y. Yuan, X. Zhuo, H. Liu, A. Ma, Achieving excellent ductility in high-strength Mg-10.6Gd-2 Ag alloy via equal channel angular pressing, *Journal of Alloys and Compounds* 817 (2020) 152688.

- [13] Y. Zhang, M. Gao, I.P. Etim, L. Tan, K. Yang, Optimising the torsional properties and corrosion resistance of biodegradable WE43 Mg alloy by ECAP and subsequent ageing, *Materials Technology* 35(7) (2020) 402-410.
- [14] S. Sadi, A. Hanna, H. Azzeddine, C. Casas, T. Baudin, A.-L. Helbert, F. Brisset, J.M. Cabrera, Characterization of microstructure and texture of binary Mg-Ce alloy processed by equal channel angular pressing, *Materials Characterization* 181 (2021) 111454.
- [15] Y. Yuan, A. Ma, Z. Gao, H. Wu, Y. Gu, J. Wang, J. Chen, C. Ji, J. Jiang, Improving microstructure and corrosion resistance of LPSO-containing Mg-Y-Zn-Mn alloy through ECAP integrated with prior solution treatment, *Journal of Materials Research and Technology* 19 (2022) 2275-2286.
- [16] S. Sadi, A. Hanna, T. Baudin, F. Brisset, J.M. Cabrera, H. Azzeddine, Microstructure and texture evolution of ECAP-processed Mg-Ce alloy during isothermal annealing, *Materials Today Communications* 32 (2022) 103920.
- [17] W. Yang, G.F. Quan, B. Ji, Y.F. Wan, H. Zhou, J. Zheng, D.D. Yin, Effect of Y content and equal channel angular pressing on the microstructure, texture and mechanical property of extruded Mg-Y alloys, *Journal of Magnesium and Alloys* 10(1) (2022) 195-208.
- [18] W. Sun, Y. He, X. Qiao, X. Zhao, H. Chen, N. Gao, M.J. Starink, M. Zheng, Exceptional thermal stability and enhanced hardness in a nanostructured Mg-Gd-Y-Zn-Zr alloy processed by high pressure torsion, *Journal of Magnesium and Alloys* (2022).
- [19] S. Sadi, A. Hanna, T. Baudin, A.-L. Helbert, F. Brisset, D. Bradai, H. Azzeddine, Evaluation of static recrystallization and grain growth kinetics of hot-rolled AZ31 alloy, *Journal of Metals, Materials and Minerals* 32(1) (2022) 12-26.
- [20] J. Wei, G. Huang, D. Yin, K. Li, Q. Wang, H. Zhou, Effects of ECAP and Annealing Treatment on the Microstructure and Mechanical Properties of Mg-1Y (wt. %) Binary Alloy, *Metals* 7(4) (2017) 119.
- [21] L.L. Rokhlin, *Magnesium alloys containing rare earth metals: structure and properties*, 1st ed., Crc Press, London, 2003.
- [22] M. Furukawa, Z. Horita, M. Nemoto, R.Z. Valiev, T.G. Langdon, Factors influencing the flow and hardness of materials with ultrafine grain sizes, *Philosophical Magazine A* 78(1) (1998) 203-216.
- [23] S. Tighiouaret, R. Lachhab, A. Hanna, H. Azzeddine, Y. Huang, T. Baudin, A.-L. Helbert, F. Brisset, D. Bradai, T.G. Langdon, Thermal Stability of an Mg-Nd Alloy Processed by High-Pressure Torsion, *Advanced Engineering Materials* 21(12) (2019) 1900801.

- [24] J.E. Burke, D. Turnbull, Recrystallization and grain growth, *Progress in Metal Physics* 3 (1952) 220-292.
- [25] M.A. Thein, L. Lu, M.O. Lai, Kinetics of grain growth in nanocrystalline magnesium-based metal-metal composite synthesized by mechanical alloying, *Composites Science and Technology* 66(3) (2006) 531-537.
- [26] S. Abdessameud, H. Azzeddine, B. Alili, D. Bradai, Grain growth in AZ31 alloy after uniaxial compression, *Transactions of Nonferrous Metals Society of China* 20(12) (2010) 2215-2222.
- [27] M. Roostaei, M. Shirdel, M.H. Parsa, R. Mahmudi, H. Mirzadeh, Microstructural evolution and grain growth kinetics of GZ31 magnesium alloy, *Materials Characterization* 118 (2016) 584-592.
- [28] D. Panda, R.K. Sabat, S. Suwas, V.D. Hiwarkar, S.K. Sahoo, Texture weakening in pure magnesium during grain growth, *Philosophical Magazine* 99(11) (2019) 1362-1385.
- [29] Q. Wang, B. Jiang, A. Tang, J. Fu, Z. Jiang, H. Sheng, D. Zhang, G. Huang, F. Pan, Unveiling annealing texture formation and static recrystallization kinetics of hot-rolled Mg-Al-Zn-Mn-Ca alloy, *Journal of Materials Science & Technology* 43 (2020) 104-118.
- [30] H.J. Frost, M.F. Ashby, *Deformation-mechanism maps : the plasticity and creep of metals and ceramics*, Pergamon Press, Oxford 1982.
- [31] A. Hanna, H. Azzeddine, Y. Huang, D. Bradai, J.M. Cabrera, T.G. Langdon, An investigation of the thermal stability of an MgDy alloy after processing by high-pressure torsion, *Materials Characterization* 151 (2019) 519-529.
- [32] J. Wang, Y. Iwahashi, Z. Horita, M. Furukawa, M. Nemoto, R.Z. Valiev, T.G. Langdon, An investigation of microstructural stability in an AlMg alloy with submicrometer grain size, *Acta Materialia* 44(7) (1996) 2973-2982.
- [33] H. Azzeddine, T. Baudin, A.-L. Helbert, F. Brisset, Y. Huang, M. Kawasaki, D. Bradai, T.G. Langdon, A stored energy analysis of grains with shear texture orientations in Cu-Ni-Si and Fe-Ni alloys processed by high-pressure torsion, *Journal of Alloys and Compounds* 864 (2021) 158142.