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STRENGTH, DUCTILITY AND IMPACT TOUGHNESS OF THE MAGNESIUM ALLOY AZ31B AFTER EQUAL-CHANNEL ANGULAR PRESSING

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ABSTRACT: The room temperature strength, ductility and impact toughness of the commercial Mg wrought alloy AZ31B was investigated after equal-channel angular pressing (ECAP). It is shown, that the introduction of a beneficial texture allows a tremendous increase of ductility. An equivalent strain of ~4.4 at 260°C processing temperature increases the elongation to failure for example from ~12 % to ~35 % (strain rate 10^{-3} s^{-1}). Simultaneously, the yield stress drops from 225 MPa to 80 MPa. Since the strain hardening capability is increased, an ultimate tensile stress close to that of the commercial material is reached. Instrumented Charpy impact toughness tests reveal also an increase of toughness, whereas crack initiation contributes in particular. Additionally it is shown, that the decrease of the processing temperature necessitates the reduction of the feeding rates to ensure homogenous plastic deformation without shear localisations on the one hand, but gains a higher strength, ductility and toughness on the other hand.

KEYWORDS: Mechanical properties, Extrusion, Texture, Room temperature, ECAP, ECAE

1 INTRODUCTION

Equal-channel angular pressing (ECAP) is a forming technique that introduces large amounts of simple shear into a bulk metallic billet, maintaining its cross section [1]. The boundary conditions ensure a perfect homogeneous deformation and enable the repetition of the process to accumulate the strain. In addition, the billet may also be rotated along the extrusion axis between successive passes in order to change the orientation of the shear plane.

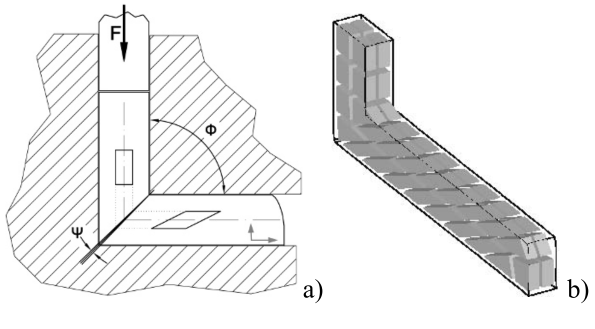

Figure 1: Schematic illustration of the ECAP-process (a) and the corresponding deformation of brick-shaped volume elements (b)

In this way, an effective refinement of the microstructure into the submicrocrystalline or ultrafine-grained regime and a changed crystallographic texture can be achieved for different materials [2]. Since basal slip acts as the primary deformation mechanism for hexagonal close packed (HCP) materials [3-6] the application of ECAP for Mg-alloys is of special interest. It was shown that the basal planes become aligned parallel to the shear plane of the ECAP-deformation, enabling remarkable room temperature (RT) properties [7-9] that are retained even after full recrystallization [10, 11].
In this study the influence of different processing parameters on room temperature strength, ductility and impact toughness of a commercial magnesium wrought alloy after ECAP is investigated. So far there is no information available on the toughness of strongly textured Mg-alloys, yet.

2 MATERIAL AND EXPERIMENTAL PROCEDURES

An extruded AZ31B-F (Mg-2.91Al-0.94Zn-0.33Mn – wt.%) rod with a diameter of 62 mm was supplied by Otto-Fuchs KG, Germany. Repetitive ECA-pressings (N – number of pressings) were performed after machining the rod into the initial billet geometry of 15 x 15 x 130 mm³.
The extrusions were performed in a die with an internal angle of Φ=90° and an outer angle of Ψ=4°. According to [12], the equivalent plastic strain by a single pressing is ~1.1. To increase the pressure in the shear zone, the

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exit-channel provides a circular diminution of 0.2 mm. The extrusions were performed at temperatures between 200°C and 260°C with a feeding rate below 7.5 mm/min following the so-called route C [2]. Therefore the billet gets rotated 180° after each pass around the channel axis whereas the orientation of the shear plane remains identical with respect to the billet. Simultaneously the direction of shear gets reversed, causing a periodic shear-reversal that restores the initial shape of the volume elements or grains after an even number of passes. The billets were lubricated with MoS_2 grease, inserted into the channel and held for 15 min inside the preheated die to reach temperature equilibrium. The temperature was measured by integrated thermocouples mounted close to the channel.

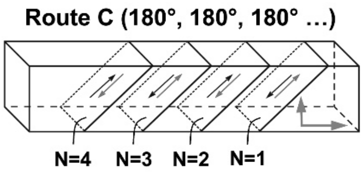

Figure 2: *Orientations of the shear planes within the billet by Route C processing after 1, 2, 3 and 4 passes respectively*

For the characterisation of strength and ductility tensile samples with an aspect ratio of the gauge length of three were machined from the billets in the direction of extrusion. Quasi-static tensile tests were operated according DIN EN 10002 in a conventional screw-driven testing machine Zwick-Roell at a constant crosshead speed with an initial strain rate of 10^{-3} s^{-1}.
For impact toughness testing, samples with a geometry of 4 x 4 x 44 mm³ were extracted along the direction of extrusion according to DIN 50115. The V-shaped notch (depth of 1 mm, 45° opening angle, 0.25 mm notch-radius) was machined according to Figure 3, so that the direction of crack propagation is parallel to the transverse plane. An instrumented Charpy impact tester with a nominal energy of 15 J was used to measure the absorbed energy.

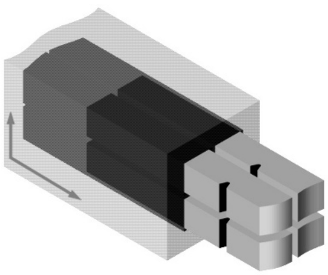

Figure 3: *Schematic illustration for the notch orientation in the samples for impact toughness testing with respect to the ECA-processed billets*

3 RESULTS AND DISCUSSION

3.1 PROCESSING

In contrast to some reports in the literature [5, 10, 11, 13] where the AZ31B was successfully processed at ~200°C with feeding rates of ~25 mm/min or higher, sound billets could be produced in the actual study only at temperatures of 250°C or above. Beside the required increase in temperature, the feeding rate had to be reduced to 2.5 mm/min. With these parameters, N=2 extrusions at 250°C or N=4 at 260°C were performed. A higher feeding rate of 7.5 mm/min at 260°C for example caused the initiation of cracks from the top surface of the billets. The determined values are similar to those reported by *Kim et al.* and *Lapovok et al.* [9, 14].
It is assumed that the differences in reported parameters for successful extrusions are due to different locations of the thermocouples used for temperature measurement within the dies. Slightly different channel geometries and friction conditions may also contribute.

3.2 TENSILE TESTING

The influence of ECAP on strength and ductility is presented in Figure 4.

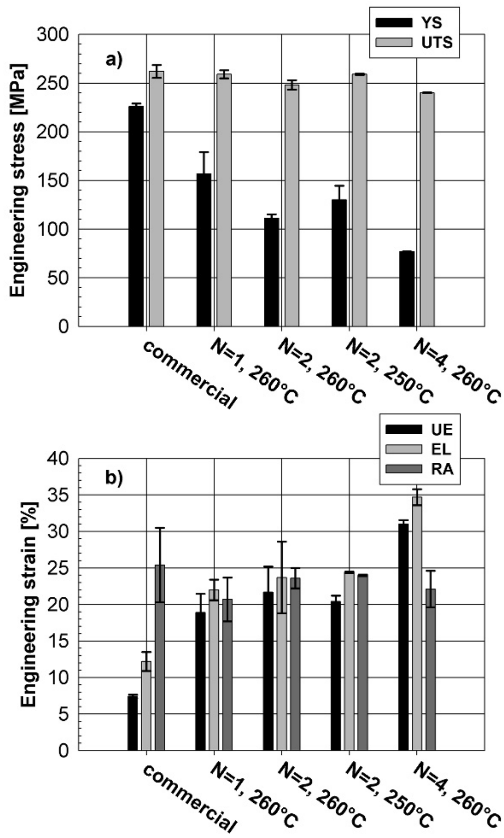

Figure 4: *Influence of ECAP on strength (a) and ductility (b) from quasi-static tensile tests at RT*

The yield stress (YS) decreases significantly with increasing shear strain. It is reduced from 225 MPa for ~65% to 80 MPa after N=4 at 260°C. The ultimate

tensile stress (UTS) is less affected, but is also lowered for ~10% from 260 MPa to 240 MPa.
Simultaneously, the uniform elongation (UE) and the elongation to failure (EL) are improved for more than fourfold and for almost threefold the values of the commercial material. That corresponds to increases from 7.4% to 31.0% and 12.2% to 34.7% respectively. If one considers the variations, there does no clear effect of ECAP on the reduction of area (RA) exist. A comparison to ECAP at 250°C after N=2 shows that a lower temperature results in higher strength and better ductility.
These results are in agreement with the literature and can primarily be attributed to the change in texture [5, 7, 10, 11, 13] and less influenced by the grain refinement [7, 9]. The application of route C effectively enforces the texturing since the same shear plane orientation is used several times. Thus, the number of optimal aligned grains with their basal planes in ~45° with respect to the extrusion axis increases continuously. Therewith the *Schmid factor* for basal slip approaches the maximum of 0.5 at tensile loading [10].

3.3 CHARPY IMPACT TESTING

The force-deflection response obtained from the instrumented Charpy impact test allows to split the total energy consumption into a first portion up to the maximum (corresponding to the crack initiation) and a second portion for crack propagation until total fracture of the sample. The actual toughness is represented by the second portion, as it covers the amount of absorbed energy during crack propagation.

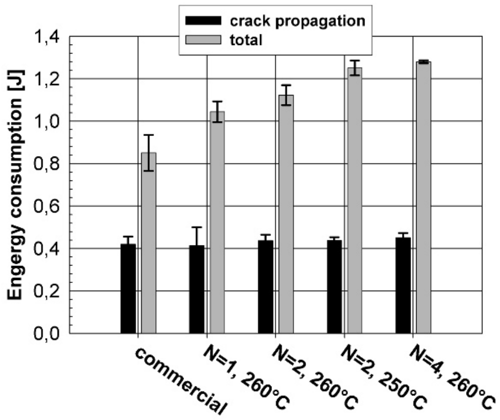

Figure 5: *Influence of ECAP on the energy consumption in Charpy impact testing*

The results in Figure 5 show, that ECA-processing significantly improves the total energy consumption. After N=4 at 260°C the Charpy impact toughness is increased from 0.85 J (7.1 J/cm²) for ~50 % to 1.3 J (10.7 J/cm²). This can be ascribed almost fully to crack initiation which is a result of the low YS in conjunction with the improved ductility. In contrast, the energy consumed during crack propagation remains almost unchanged. As a result it is assumed that ECA-processing might not affect the toughness significantly. In analogy to the tensile testing the toughness also benefits from a lower pressing temperature.
It is assumed that the positive effect of a lower processing temperature is twofold. On the one hand it can be expected, that the texturing is most beneficial when basal slip is effectively promoted during processing and prismatic or pyramidal slip is suppressed. This is the case at lower temperatures [3-6]. Another contribution results from the lower propensity for recrystallization and recovery producing a smaller grain size on the other hand.

4 CONCLUSIONS

HCP-materials like Magnesium and it alloys have a low symmetry of slip systems contributing to a high anisotropy of the mechanical properties. This was used for the present study to "tailor" the texture of AZ31B for consecutive tensile and Charpy impact testing. For this purpose the material was processed by ECAP following route C, providing the most effective deformation pattern for an optimal and homogeneous texturing. In the strict sense a ~45°-orientation of the basal planes with respect to the direction of the tensile loading is obtained. Since the basal planes represent the predominant slip plane at room temperature the mechanical properties can be changed remarkably if compared to conventional extrusions.
The processing was performed at 250°C and 260°C with a feeding rate of 2.5 mm/min up to equivalent strains of 2.2 and 4.4 respectively. Due to the limited ductility cracks occurred at higher feeding rates as well as at lower temperatures. The elongation to failure was tripled to ~35 % (strain rate 10^{-3} s^{-1}) while uniform elongation was quadrupled to 31%. Simultaneously, the yield stress drops from 225 MPa to 80 MPa. The increase of the strain hardening capability enables an ultimate tensile tress that is only reduced for ~10% to 240 MPa.
Instrumented Charpy impact toughness tests reveal an increase of total energy consumption, whereas crack initiation contributes in particular. The actual toughness is represented by the amount of absorbed energy during crack propagation is expected to be influenced insignificant. To further investigate the fracture toughness the process needs to be scaled-up in order to enlarge the size of the samples. It is important to note that the deviations caused by heterogeneities in the commercial materials are reduced.

The low yield stress, good strain hardening response, remarkable ductility and improved Charpy impact toughness represents a promising combination of properties for several light-weight applications. However, the behaviour is highly anisotropic and some directions actually exhibit lower ductilities [10]. Consequently, the direction of the external loads needs to be considered.

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REFERENCES

[1] V. M. Segal, A. E. Reznikov, A. E. Drobyshevskiy, and V. I. Kopylov, "Plastic Working of Metals by Simple Shear," *Russ. Metall. (english translation),* p. 7, 1981.

[2] R. Z. Valiev and T. G. Langdon, "Principles of equal-channel angular pressing as a processing tool for grain refinement," *Progress in Materials Science,* vol. 51, pp. 881-981, 2006.

[3] G. G. Yapici and I. Karaman, "Common trends in texture evolution of ultra-fine-grained hcp materials during equal channel angular extrusion," *Materials Science and Engineering: A,* vol. In Press, Corrected Proof.

[4] R. E. Reed-Hill and W. D. Robertson, "The crystallographic characteristics of fracture in magnesium single crystals," *Acta Metallurgica,* vol. 5, pp. 728-737, 1957.

[5] J. Koike, T. Kobayashi, T. Mukai, H. Watanabe, M. Suzuki, K. Maruyama, and K. Higashi, "The activity of non-basal slip systems and dynamic recovery at room temperature in fine-grained AZ31B magnesium alloys," *Acta Materialia,* vol. 51, pp. 2055-2065, 2003.

[6] F. E. Hauser, P. R. Landon, and J. E. Dorn, "Fracture of Magnesium Alloys at Low Temperature," *Transactions of the American Institute of Mining and Metallurgical Engineers,* vol. 206, pp. 589-593, 1956.

[7] W. J. Kim, S. I. Hong, Y. S. Kim, S. H. Min, H. T. Jeong, and J. D. Lee, "Texture development and its effect on mechanical properties of an AZ61 Mg alloy fabricated by equal channel angular pressing," *Acta Materialia,* vol. 51, pp. 3293-3307, 2003.

[8] H. K. Lin, J. C. Huang, and T. G. Langdon, "Relationship between texture and low temperature superplasticity in an extruded AZ31 Mg alloy processed by ECAP," *Materials Science and Engineering: A,* vol. 402, pp. 250-257, 2005.

[9] H. K. Kim and W. J. Kim, "Microstructural instability and strength of an AZ31 Mg alloy after severe plastic deformation," *Materials Science and Engineering A,* vol. 385, pp. 300-308, 2004.

[10] S. R. Agnew, J. A. Horton, T. M. Lillo, and D. W. Brown, "Enhanced ductility in strongly textured magnesium produced by equal channel angular processing," *Scripta Materialia,* vol. 50, pp. 377-381, 2004.

[11] T. Mukai, M. Yamanoi, H. Watanabe, and K. Higashi, "Ductility enhancement in AZ31 magnesium alloy by controlling its grain structure," *Scripta Materialia,* vol. 45, pp. 89-94, 2001.

[12] Y. Iwahashi, J. Wang, Z. Horita, M. Nemoto, and T. G. Langdon, "Principle of equal-channel angular pressing for the processing of ultra-fine grained materials," *Scripta Materialia,* vol. 35, pp. 143-146, 1996.

[13] D. R. Fang, Z. F. Zhang, S. D. Wu, C. X. Huang, H. Zhang, N. Q. Zhao, and J. J. Li, "Effect of equal channel angular pressing on tensile properties and fracture modes of casting Al-Cu alloys," *Materials Science and Engineering: A,* vol. 426, pp. 305-313, 2006.

[14] R. Lapovok, L. S. Tóth, A. Molinari, and Y. Estrin, "Strain localisation patterns under equal-channel angular pressing," *Journal of the Mechanics and Physics of Solids,* vol. 57, pp. 122-136, 2009.