MICROSTRUCTURE AND MECHANICAL PROPERTIES OF EXTRUDED Mg-2Y-1Zn MAGNESIUM ALLOY

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Abstract

Magnesium alloys are utilized in the aviation and automotive industry for their low density and good mechanical properties. Magnesium alloys are also interesting for use in the field of biodegradable implants because magnesium is biocompatible element essential for human body. There exist high demands on the mechanical and corrosion properties for both applications. Those properties can be strongly affected by alloying and production method. Alloying elements can improve mechanical properties by strengthening by intermetallic phases. Further improvement can be achieved by grain refinement, which can be obtained by alloying with Zr or by hot deformation associated with the recrystallization process. Present paper is focused on characterization of Mg-2Y-1Zn alloy, which has excellent mechanical and corrosion properties. The Mg-2Y-1Zn alloy is prepared by hot extrusion. Microstructure and mechanical properties are evaluated and compared with material prepared by conventional casting. High values of ultimate and yield strengths were measured, however at the cost of low ductility.

Keywords: Magnesium, extrusion, mechanical properties, grain size

1. INTRODUCTION

Good ratio between density and mechanical properties makes magnesium alloys valuable metal material for automotive and aviation industry [1]. Magnesium alloys are also considered as materials for biodegradable implants [2]. There are high demands on mechanical properties, which can be increased by alloying. Many magnesium alloying systems were investigated and most of them contains more than 3 wt.% of alloying elements [3]. There is tendency to reduce the amount of alloying elements in order to produce cheaper materials with better biocompatibility [4]. One of the magnesium alloys is WZ21, which consists of 2 wt. % of Y and 1 wt.% of Zn [5]. Zinc is also biocompatible material and its alloys are as well considered as materials for biodegradable implants [6]. Maximum zinc solubility in magnesium matrix is 6.2 wt.% at eutectic temperature. Zinc increases the modulus of elasticity and the mechanical properties by solid solution strengthening [7]. Yttrium also increases mechanical properties by solid solution strengthening, in addition to refining grain and increasing corrosion resistance by formation of more stable corrosion products [8]. The main contribution of yttrium is however in the formation of intermetallic phases with magnesium and zinc. There were observed four intermetallic phases in Mg-Y-Zn systems. $Mg_{24}Y_5$ binary cubic phase is heat stable and improves ductility so as induce nucleation of new grains [8]. Icosahedral I-phase (Mg_3Zn_6Y) is desirable for its high hardness and corrosion resistance. This phase is relatively thermally stable and its presence in the structure effectively suppresses the grain growth. It has also the ability to slow down the slip of dislocations at basal plains [9]. With increasing amount of this phase in the structure the overall mechanical properties improves [10]. On the other hand the W-phase ($Mg_3Zn_3Y_2$) is characterized with cubic structure and is incoherent with magnesium matrix. This diversity means weaker bonds between W-phase and magnesium matrix, which brings worse mechanical properties [11]. This undesirable phase can be eliminated by proper heat treatment [12]. The third phase is LPSO-phase ($Mg_{12}ZnY$), which is desirable as it increases plasticity and strength of the material. There are few kinds of LPSO phase (10H, 18R, 24R, 14H) depending on the structure of the phase (R means rhombohedral, H means hexagonal) [13]. Mechanical properties of alloy with

LPSO phase can be further improved by extrusion process as LPSO phase has positive effect on grain refinement during dynamic recrystallization [14]. Hot extrusion is common manufacturing process of magnesium alloys [15]. At high temperature new slipping plains of magnesium hexagons activates and the plasticity increases. This process is usually associated with recrystallization process. The final rod then consists of new equiaxed fine grains [16]. However magnesium alloys tends to form texture after extrusion [17]. Magnesium hexagons orient their basal planes parallel with the extrusion direction. This phenomenon leads to anisotropy of mechanical properties and is undesirable [18]. Alloying elements have the ability to change the preferred orientation or to change it randomly [19]. This paper is focused on characterization of the Mg-2Y-1Zn alloy prepared by extrusion and compared with sample prepared by conventional casting.

2. MATERIALS AND METHODS

Preparation of samples

WZ21 magnesium alloy was prepared by melting Mg, Y and Zn in induction furnace at 750 °C for 15 minutes under the argon atmosphere. As-cast ingot was then extruded at 350 °C with extrusion ratio 16 and extrusion speed 0.2 mm/s. Final extruded product was rod with 6 mm in diameter.

Samples were grinded on SiC grinding papers (P80-P4000) and subsequently polished on diamond paste. The final polishing was done on Topol 2 with fine particles of Al_2O_3. Subsequently samples were etched in solution containing 10 ml of acetic acid, 4.2 g picric acid, 10 ml distilled water and 70 ml ethanol. The microstructure was studied by scanning electron microscopy SEM (TescanVEGA3 equipped with energy dispersion spectrometry - EDS). Phase analyses were performed using X-ray diffraction (XRD, X'Pert Philips, 30 mA, 40 kV, Cu*Kα* X-ray radiation).

Compressive tests were performed on LabTest 5.250SP1-VM at room temperature on cylindrical samples with 6 mm in diameter and 9 mm high. Constant deformation speed of 0.001 s^{-1} was selected. Compressive yield strength (CYS), ultimate compressive strength (UCS) and total deformation were determined. Tensile properties were measured on the same machine at room temperature on samples with 3.5 mm in diameter in constricted area and 25 mm in length. Constant deformation speed of 0.001 s^{-1} was selected. Tensile yield strength (TYS), ultimate tensile strength (UTS) and elongation were determined.

3. RESULTS AND DISCUSION

Microstructure

Mg-2Y-1Zn alloy was successfully prepared by casting and extrusion. As-cast ingot (**Figure 1a**) was characterized with typical dendritic structure. Alloying elements segregated around dendrites, so there was higher concentration of them. Dendrites consist of α-Mg matrix and different intermetallic phases (**Figure 1b**). The intermetallic phases are characterized by round shape or narrow and elongated shape. Both phases contained Y and Zn in atomic ratio 1:1, which indicates the presence of LPSO phase ($Mg_{12}ZnY$), which was observed in alloys with the weight ratio of 2:1 [20]. The solid solution contained 0.4 wt.% of Y and 0.3 wt.% of Zn according to the EDS analysis.

Extrusion of the casted ingot was successfully performed. Intermetallic phases present in the structure were aligned in rows parallel with the extrusion direction (**Figure 1c**). However in this case the zinc was uniformly dispersed in α-Mg matrix and was no longer bound with yttrium in intermetallic phases. According to the EDS analysis cubic shaped phases (**Figure 1d**) contained primarily yttrium and were determined as $Mg_{24}Y_5$. Mg matrix contained 1.6 wt.% of Y and 1 wt.% of Zn, which was much more than in the case of as-cast ingot. This indicates that LPSO intermetallic phases dissolved or transformed into new intermetallic phases during hot extrusion process. Similar results were discussed by Zhang et al. [11]. One can see that very fine grained structure was obtained after extrusion thanks to newly formed heat stable intermetallic phases which works as a nuclei for new grains so as retarders of grain growth [10]. Grain size of extruded sample varied from 0.5 to 2.5 µm.

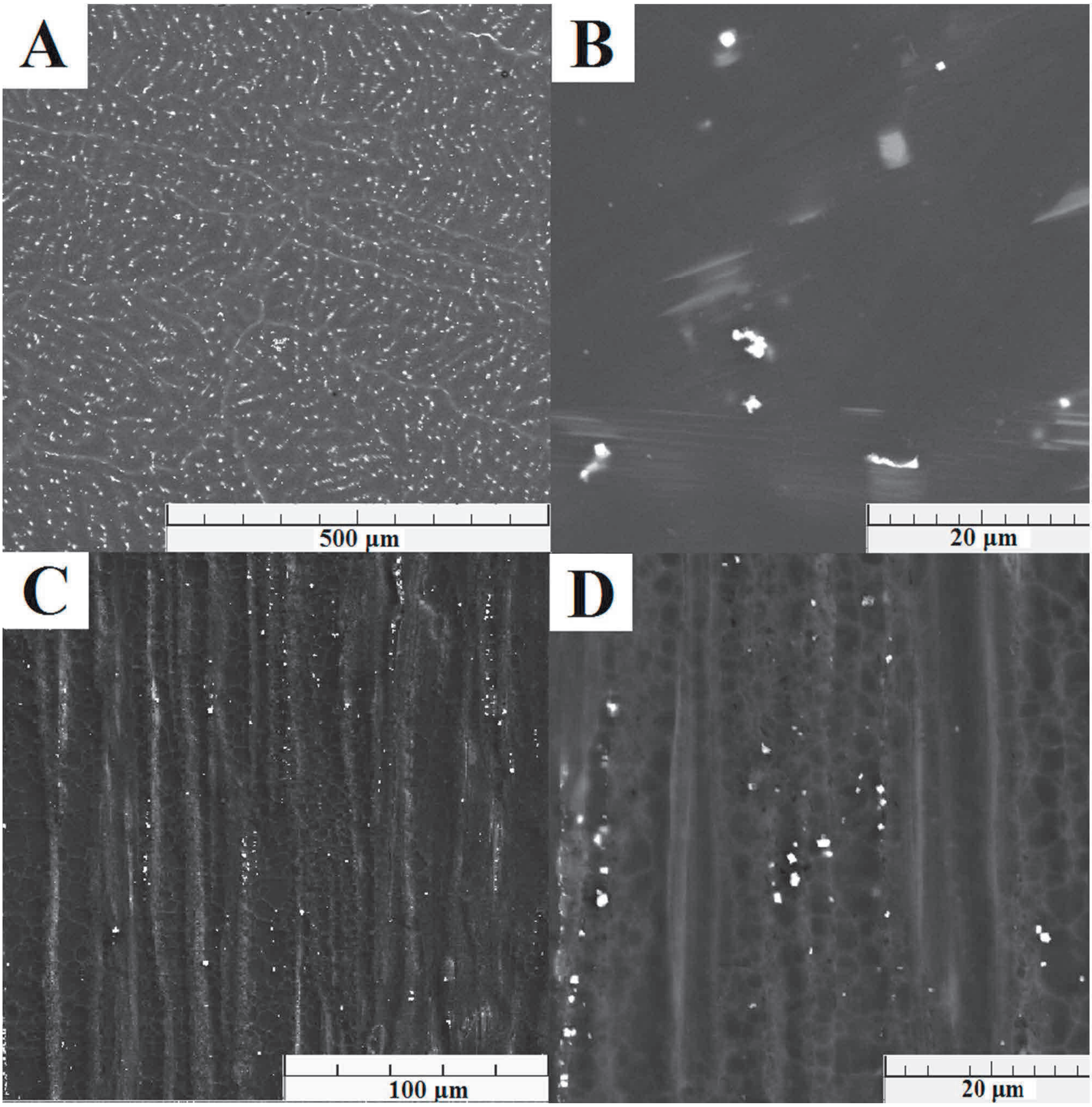

Figure 1 Microstructures of Mg-2Y-1Zn alloy: a) as-cast ingot, b) as-cast ingot - detail, c) extruded ingot, d) extruded ingot - detail

Mechanical properties

Hardness and compressive mechanical properties of extruded ingot were measured and compared with the as-cast ingot (**Figure 2**). Vickers hardness with 1 kg load was determined. Extruded ingot exerted higher value of hardness (**Table 1**) than as-cast ingot which is contributed primarily to the finer structure. Compressive yield strength and ultimate compressive strength of the extruded ingot was more than twice higher than in the case of casted ingot. This magnificent improvement is also contributed to the refined structure with average grain size of 1.6 µm. However, the solid solution of extruded sample contained three times higher amount of alloying elements compared to the as-cast ingot, therefore, the contribution of solid solution strengthening is considered as significant [21]. Also newly created intermetallic phases (**Figure 1d**) contributed to the improvement of mechanical properties. Tensile properties were also tested on the extruded sample. Tensile yield strength reached up to 267 MPa which is more than was achieved by Cabeza et al. [5] (211 MPa), who prepared samples by extrusion at the same temperature but with extrusion ratio of 32. However they were able to reach slightly higher value of ultimate tensile strength (322 MPa) and much higher ductility. There is noticeable difference between compressive yield strength (CYS) and tensile yield strength (TYS) of the extruded sample. This difference is probably associated with the texture after extrusion [17]. Deformation of magnesium alloys is associated with twinning mechanism besides slip mechanism, especially at room temperatures. Twinning mechanism requires much less energy than slip mechanism, but is dependent on the orientation of individual grains [22]. During extrusion process the new recrystallized grains preferably orient basal planes parallel with the extrusion direction. This orientation is favorable for twinning mechanism if the sample is compressed parallel with the basal planes. Contrary this orientation is unfavorable for twinning mechanism if the tensile force is applied parallel with the extrusion direction. Therefore extruded rods with texture are characterized with reduced plasticity and lower compressive yield strength than tensile yield strength [4].

Table 1 Mechanical properties: CYS = compressive yield strength, UCS = ultimate compressive strength, D = relative deformation, TYS = tensile yield strength, UTS = ultimate tensile strength, E = elongation

Sample	CYS (MPa)	UCS (MPa)	D (%)	TYS (MPa)	UTS (MPa)	E (%)	HV1
As-cast	86 ± 5	219 ± 13	17.5 ± 2.0	-	-	-	54.1 ± 3.1
Extruded	212 ± 2	455 ± 2	12.7 ± 0.4	267 ± 3	301 ± 2	2.4 ± 0.4	71.2 ± 4.3

4. CONCLUSION

Mg-2Y-1Zn magnesium alloy was prepared by extrusion and by conventional casting. Casted ingot was characterized with dendritic structure. LPSO phases were detected in the structure. Extrusion process provides fine structure with average grain size of 1.6 µm. LPSO phases disappeared after extrusion and new more heat stable $Mg_{24}Y_5$ phase was formed. Fine structure, solid solution enriched on alloying elements and new intermetallic phases contributed to the significant improvement of mechanical properties.

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REFERENCES

[1] WU, D., CHEN, R. S., KE, W. Microstructure and mechanical properties of a sand-cast Mg-Nd-Zn alloy. *Materials & Design*, 2014, vol. *58*, pp. 324-331.

[2] SMITH, P. Introduction to Magnesium Biomaterials. In *Magnesium Biomaterials: Design, Testing, and Best Practice*, Springer: New York, 2014, pp. 1-12.

[3] STAIGER, M. P., PIETAK, A. M., HUADMAI, J., DIAS, G. Magnesium and its alloys as orthopedic biomaterials: A review. *Biomaterials*, 2006, vol. *27,* no. 9, pp. 1728-1734.

[4] DVORSKÝ, D., KUBÁSEK, J., VOJTĚCH, D., VOŇAVKOVÁ, I., VESELÝ, M., ČAVOJSKÝ, M. Structure and mechanical characterization of Mg-Nd-Zn alloys prepared by different processes. In IOP Conference Series: *Materials Science and Engineering*, 2017, in print.

[5] CABEZA, S., GARCÉS, G., PÉREZ, P., ADEVA, P. Properties of WZ21 (%wt) alloy processed by a powder metallurgy route. *Journal of the Mechanical Behavior of Biomedical Materials*, 2015, vol. 46, pp. 115-126.

[6] KUBÁSEK, J., VOJTĚCH, D. Structural characteristics and corrosion behavior of biodegradable Mg-Zn, Mg-Zn-Gd alloys. *Journal of Materials Science: Materials in Medicine*, 2013, vol. *24,* no. 7, pp. 1615-1626.

[7] CHEN, Y., XU, Z., SMITH, C., SANKAR, J. Recent advances on the development of magnesium alloys for biodegradable implants. *Acta Biomaterialia*, 2014, vol. 10, no. 11, pp. 4561-4573.

[8] KUBÁSEK, J., DVORSKÝ, D., ČAVOJSKÝ, M., VOJTĚCH, D., BERONSKÁ, N., FOUSOVÁ, M. Superior properties of Mg-4Y-3RE-Zr alloy prepared by powder metallurgy. *Journal of Materials Science & Technology*, 2016. DOI: 10.1016/j.jmst.2016.09.019

[9] LEE, J. Y., KIM, D. H., LIM, H. K., KIM, D. H. Effects of Zn / Y ratio on microstructure and mechanical properties of Mg-Zn-Y alloys. *Materials Letters*, 2005, vol. 59, no. 29-30, pp. 3801-3805.

[10] XU, D. K., LIU, L., XU, Y. B., HAN, E. H. The influence of element Y on the mechanical properties of the as-extruded Mg-Zn-Y-Zr alloys. *Journal of Alloys and Compounds*, 2006, vol. 426, no. 1-2, pp. 155-161.

[11] ZHANG, E., HE, W., DU, H., YANG, K. Microstructure, mechanical properties and corrosion properties of Mg-Zn-Y alloys with low Zn content. *Materials Science and Engineering: A*, 2008, vol. 488, no. 1-2, pp. 102-111.

[12] CHEN, T. J., WANG, W., ZHANG, D. H., MA, Y., HAO, Y. Development of a new magnesium alloy ZW21. *Materials & Design*, 2013, vol. 44, pp. 555-565.

[13] ABE, E., ONO, A., ITOI, T., YAMASAKI, M., KAWAMURA, Y. Polytypes of long-period stacking structures synchronized with chemical order in a dilute Mg-Zn-Y alloy. *Philosophical Magazine Letters*, 2011, vol. 91, no. 10, pp. 690-696.

[14] YAMASAKI, M., HASHIMOTO, K., HAGIHARA, K., KAWAMURA, Y. Effect of multimodal microstructure evolution on mechanical properties of Mg-Zn-Y extruded alloy. *Acta Materialia*, 2011, vol. 59, no. 9, pp. 3646-3658.

[15] DVORSKY, D., KUBASEK, J., VOJTĚCH, D., PRUSA, F., NOVA, K. Preparation of WE43 using powder metallurgy route. *Manufacturing Technology*, 2016, vol. 16, no. 4, pp. 680-687.

[16] MACKENZIE, L. W. F., DAVIS, B., HUMPHREYS, F. J., LORIMER, G. W. The deformation, recrystallisation and texture of three magnesium alloy extrusions. *Materials Science and Technology* 2007**,** vol. 23, no. 10, pp. 1173-1180.

[17] BARNETT, M. R., SULLIVAN, A., STANFORD, N., ROSS, N., BEER, A. Texture selection mechanisms in uniaxially extruded magnesium alloys. *Scripta Materialia*, 2010, vol. 63, no. 7, pp. 721-724.

[18] KLEINER, S., UGGOWITZER, P. J. Mechanical anisotropy of extruded Mg-6% Al-1% Zn alloy. *Materials Science and Engineering: A,* 2004, vol. 379, no. 1-2, pp. 258-263.

[19] DVORSKY, D., KUBASEK, J., VOJTECH, D., CAVOJSKY, M. Structure and mechanical properties of WE43 prepared by powder metallurgy route. *Manufacturing Technology*, 2016, vol. 16, no. 5, pp. 896-902.

[20] HÄNZI, A. C., SOLOGUBENKO, A. S., UGGOWITZER, P. J. Design strategy for new biodegradable Mg-Y-Zn alloys for medical applications. *International Journal of Materials Research* 2009, vol. 100, no. 8, pp. 1127-1136.