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WE43 magnesium alloy – material for challenging applications

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Abstract

WE43 magnesium alloy is a commercial light-weight material developed for application at temperatures up to 250 °C. This alloy is also considered for applications in medicine as a biodegradable material. The present study provides microstructure characterization and related mechanical properties of the WE43 alloy prepared by different processing techniques including casting, extrusion, rotary swaging and heat treatment. Results indicate huge differences in observed microstructures, such as precipitation of secondary phases, grain coarsening, texture formation and also concomitant changes of mechanical properties, such as tensile yield strength, ultimate tensile strength, compressive yield strength, ultimate compressive strength and elongation to fracture. Although this material is well-known, WE43 prepared in this study by a combination of extrusion and rotary swaging offered highly improved mechanical properties, including a tensile yield strength of 370 MPa and elongation of 15 %. Such a combination of values is rarely seen in literature and is not generally offered for commercially produced materials although both preparation methods are easily commercially available.

Key words: magnesium, WE43 alloy, thermomechanical treatment, microstructure, mechanical properties

1. Introduction

Magnesium alloy designated as WE43 according to ASTM is a high-strength casting alloy that can be used in temperatures of up to 250 °C. The alloy contains mainly 3.7–4.3 wt.% of yttrium and 2.3–3.5 wt.% of rare earth elements; among them, neodymium is the most abundant. Also, zirconium is included in the alloy in about 0.2–0.4 wt.%. Its main effect is the refinement of the as-cast microstructure. This alloy is characterized by good mechanical properties at both ambient and elevated temperatures and by good corrosion resistance. The huge advantage of this alloy is its low density ($1.82\,\mathrm{g\,cm^{-3}}$) owing to which it can be used in applications where weight reduction without compromising performance is required. Therefore, the presented alloy is used for specific applications such as parts of helicopter transmissions, power systems, aero-engines, gearboxes of military aircraft, sports cars and missiles. Currently, WE43 is also considered for applications in medicine as degradable screws, plates or even stents [1–5]. Such implanted materials are expected to be slowly dissolved in the organism and gradually replaced by newly healed tissue. The main benefit of the presented alloy is its superior corrosion resistance compared to other magnesium-based alloys which are degraded in the organism too quickly and lose their load capacity for the damaged tissue too soon.

WE43 magnesium alloy can be prepared in various final conditions. First of all, it is an alloy originally developed for casting. Cast ingots are generally heat-treated at 525 °C for 8 h with subsequent air cooling or quenching into hot water/polymer and aged at temperatures close to 200 °C [6–9]. Ageing at 250 °C for 16 h [6, 9] is the most widespread. The final product in this condition is characterized by a tensile yield strength (TYS) of about 180 MPa and ultimate tensile strength (UTS) of about 260 MPa (Table 1).

Due to the increasing demands on mechanical

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Table 1. Rough values of mechanical properties of WE43 alloy in different conditions at 25 ℃. All designated values for wrought materials are considered for tensile loading in the longitudinal direction

	TYS (MPa) (0.2 % of proof stress)	UTS (MPa)	E (%)	References
WE43, as-cast + T6	180	260	7	[17]
WE43, forged (plate)	260	360	9	[18]
WE43, forged + aged (180 ℃/60 h)	340	390	23	[19]
WE43, 525 ℃/5 h + extrusion (300 ℃)	–	320	20	[19]
WE43, hot rolled plate	185	260	31	[19]
WE43, hot rolled plate + T5	270	350	15	[19]
WE43, extrusion + T5	240	350	12	[20]

properties of magnesium-based alloys, various thermomechanical treatments such as extrusion, hot rolling or forging are used to process WE43. Resulting mechanical properties are roughly summarized in Table 1.

Proper processing, often including both thermomechanical treatment and subsequent ageing, can lead to values of TYS and UTS as high as 280–300 and 340–360 MPa, respectively. Such values are achievable with commercial products (Table 1). Considering research area, values of UTS about 400 MPa have been reached, however, non-standard conditions of processing, such as experiments with hydrostatic extrusion performed at laboratory temperatures [10], submerged friction stir processing [11, 12] or long ageing times at lower temperatures (150–200 ℃) after sufficient thermomechanical treatment [7], are necessary. However, such processing conditions are not economically advantageous for commercial producers of magnesium-based alloys or are feasible only in the laboratory.

It is worth mentioning that the mechanical properties of wrought WE43 alloy differ based on the direction of loading. Also, the asymmetry of tensile yield strength (TYS) and compressive yield strength (CYS) values is generally observed if loading in the same direction for both kinds of tests is selected. These phenomena are associated with specific material texture and differences in activation energies for the slip in different slip systems and twinning processes based on the direction of loading [13–16].

The present paper is focused on the general characterization of WE43 magnesium alloy in different states prepared in laboratory conditions; however, with the use of basic industrially available forming techniques. Microstructure, mechanical properties and their relationships are described.

2. Materials and methods

As-cast ingots of commercial WE43 magnesium alloy were obtained from Magnesium Elektron. Cylindrical billets with 30 mm in diameter were produced from this ingot and processed by the combination of heat treatment and extrusion. Applied heat treatments were performed under a protective argon atmosphere and include solution annealing – T4 (525 ℃/8 h) and the combination of solution annealing and artificial ageing – T6 (525 ℃/8 h + 250 ℃/16 h). The extrusion of samples was performed at 400 ℃, extrusion ratio of 16 : 1 and at 0.3 mm s^{-1}. Rotary swaging (RS) was performed on the extruded rods with 11 mm in diameter at 400 ℃ to a final diameter of 8 mm. Bars were kept at 400 ℃ for 15 min before processing. The feed rate of 100 mm s^{-1} and the rotational speed of dies of 24.2 rps were selected.

The designation and processing routes of the studied material are shown in Table 2. Microstructure studies were performed using light microscopy and scanning electron microscopy (Tescan Vega 3 LMU). The preparation of metallographic samples consisted of mechanical grinding, polishing and final etching in a solution containing 10 ml of acetic acid, 4.2 g of picric acid, 10 ml of distilled water and 70 ml of ethanol. Phase and chemical compositions were characterized by energy dispersion spectrometry (Oxford Instruments Inca 350) and X-ray diffraction (X'Pert Philips, 30 mA, 40 kV, X-ray radiation Cu Kα), respectively. Tensile tests were performed according to the ČSN EN ISO 6892-1 standard on dog-bone-shaped cylindrical samples with 4 mm in diameter. Compressive tests were carried out on samples in the shape of cylinders of 6 mm in diameter and 10 mm in height. All mechanical tests were carried out at a strain rate of 0.001 s^{-1} using a mechanical testing machine (Lab Test 5.250SP1-VM). Three specimens were measured for each kind of sample for both tensile and compressive tests.

3. Results and discussion

3.1. Structure

The structure of WE43 alloy is generally composed of α-Mg solid solution (dark areas in Fig. 1a–h) and intermetallic phases distributed at interdendritic or

Table 2. Designation of samples processed in various ways

Material designation		Heat treatment	Extrusion	Post-extrusion heat treatment
As-cast	Cast to the non-preheated brass mould	–	–	–
Ex	Cast to the non-preheated brass mould	–	400 °C, ER = 16	–
T4 + Ex	Cast to the non-preheated brass mould	525 °C/8 h	400 °C, ER = 16	–
T6 + Ex	Cast to the non-preheated brass mould	525 °C/8 h + 250 °C/16 h	400 °C, ER = 16	–
Ex + T6	Cast to the non-preheated brass mould	–	400 °C, ER = 16	525 °C/8 h + 250 °C/16 h
Ex + RS*	Cast to the non-preheated brass mould	–	400 °C, ER = 10	–

*Extruded rods were rotary swaged at 400 °C from 11 mm in diameter to 8 mm in diameter

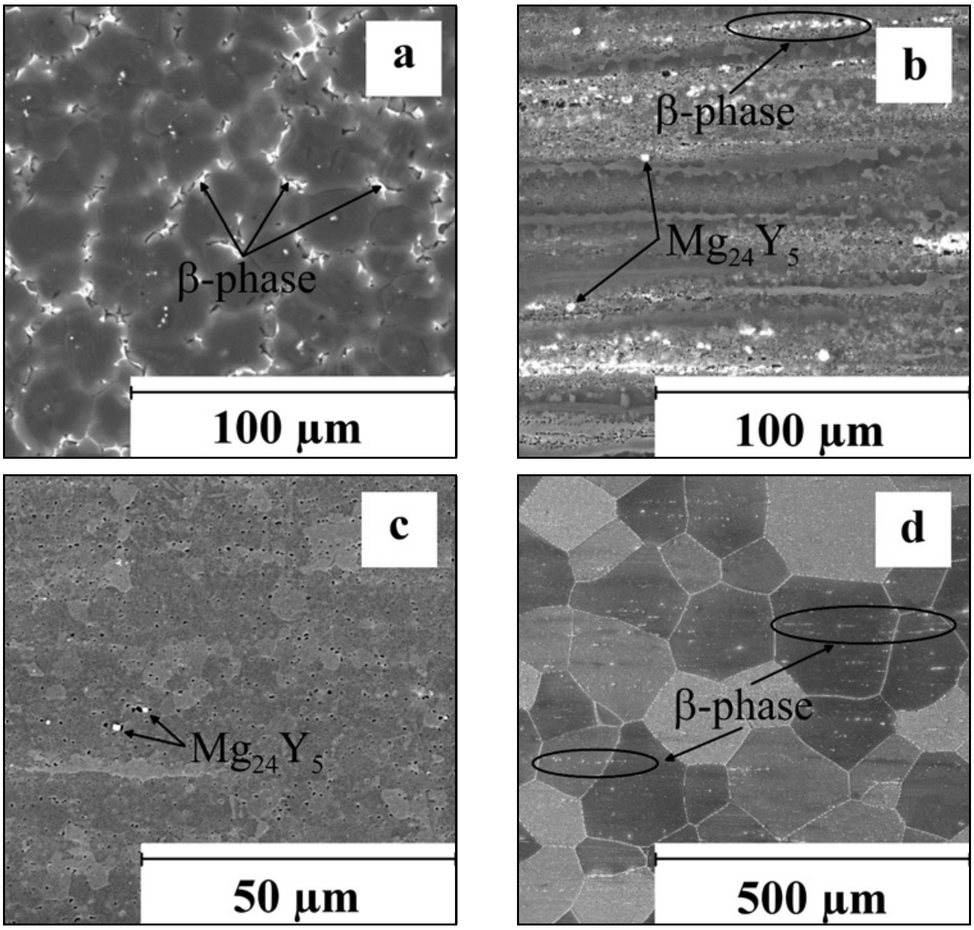

Fig. 1a–d. Microstructure of WE43 magnesium alloy after various processing: (a) WE43 – as-cast, (b) WE43 – Ex, (c) WE43 – T4 + Ex, and (d) WE43 – Ex + T6. (Ex = extrusion, RS = rotary swaging, T4, T5 and T6 correspond to specific heat treatment).

grain boundaries regions. These phases are enriched by Y and Nd. Except for eutectic β-phase ($Mg_{14}Nd_2Y$), also $Mg_{41}Nd_5$ and $Mg_{24}Y_5$ phases are distributed in the microstructure of WE43 alloys [21–24]. However,

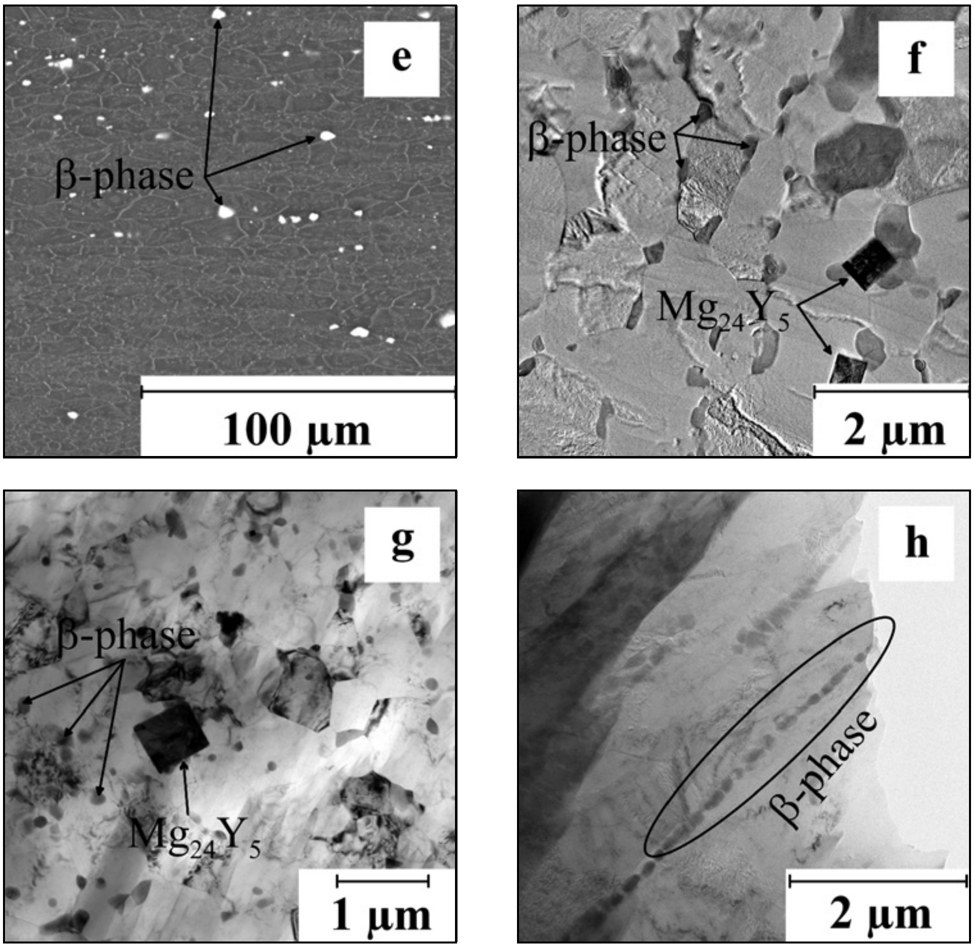

Fig. 1e–h. Microstructure of WE43 magnesium alloy after various processing: (e) WE43 – Ex + RS, (f) detail of microstructure of WE43 – Ex (TEM), (g) detail of microstructure of WE43 – T4 + Ex (TEM), and (h) detail of microstructure of WE43 – Ex + RS (TEM). (Ex = extrusion, RS = rotary swaging, T4, T5 and T6 correspond to specific heat treatment).

Table 3. Grain size determined in selected materials

Material designation	Grain size (µm)
As-cast	equiaxed grains (30 ± 9 µm)
Ex	equiaxed grains (2.7 ± 1.5 µm)
T4 + Ex	elongated grains (150–250 µm in length and 50–80 µm in thickness), fine grains (2.5 ± 0.8 µm)
Ex + T6	equiaxed grains (196 ± 34 µm)
Ex + RS*	slightly elongated grains (10–22 µm in length and 3–11 µm in thickness)

*Extruded rods were rotary swaged at 400 ℃ from 11 mm in diameter to 8 mm in diameter

strong differences in microstructure conditions are observed based on the processing technique applied.

The as-cast state was characterized by strong dendritic microsegregation with differences in Y and Nd concentrations between dendrite cores and dendrite edges (Fig. 1a). The concentration of Y and Nd in dendrite cores reached about 1.5–2.2 and 0.5–1.1 wt.%, respectively. The average grain size reached 30 ± 9 µm.

The extrusion of the as-cast state caused significant grain refinement as a consequence of dynamic recrystallization. The grain size was between 2 and 12 µm. The as-cast microstructure was broken, and original intermetallic phases were arranged in the rows parallel to the extrusion direction.

If solution annealing (525 ℃/8 h) is performed for the material in the as-cast state, the majority of secondary phases is dissolved. Due to the thermal stability, $Mg_{24}Y_5$ phases remain in the microstructure. After the extrusion of WE43 in the solution annealed state, the microstructure was composed of elongated deformed areas with about 150–250 µm in length and 50–80 µm in thickness. Along the circumference, these areas contained recrystallized grains, but interiors remained still non-recrystallized (Fig. 1c). Due to the solution annealing (525 ℃/8 h), the structure contained a lower amount of coarse intermetallic phases, and the concentration of alloying elements in solid solution reached 3.7 wt.% Y, 1.3 wt.% Nd and 0.3 wt.% of both Gd and Dy. After extrusion, the structure also contained a high amount of fine precipitates which were formed during the process (Fig. 1g). Since extrusion was performed at a relatively high temperature (400 ℃), these precipitates were stable β-phases, and their size ranged from 50 to 500 nm. Metastable precipitates such as β' or β_1, which are considered as the main strengtheners, are generally presented in the thermally treated WE43 alloy. However, these precipitates are formed at lower temperatures. At higher temperatures of processing, these phases coarsen or are replaced by stable β-phase [21, 25].

The microstructure of the WE43 alloy processed by T6 after the extrusion process is displayed in Fig. 1. It is evident that such material is characterized by relatively coarse equiaxed grains with 196 ± 34 µm in diameter. Except for coarse intermetallic phases like $Mg_{41}Nd_5$ and $Mg_{24}Y_5$, small precipitates β' and β were present after this processing.

As an example of unconventional processing, the WE43 alloy was processed by extrusion and subsequently rotary swaged at 400 ℃ from billet with 11.0 mm in diameter to the final diameter of 8 mm. Obtained microstructure contained some residues of coarse intermetallic phases $Mg_{41}Nd_5$ and slightly deformed grains prolonged in the direction of extrusion. Only β-phases were observed in the microstructure as a consequence of processing at high temperatures (Fig. 1e).

3.2. Mechanical properties

Mechanical properties of studied materials varied based on the processing methods. The lowest values of TYS (140–170 MPa) and UTS (210–230 MPa) were obtained in the case of the as-cast material and WE43 alloy processed by extrusion and subsequent T6 treatment (Fig. 2). However, other processing conditions led to significantly improved mechanical properties. Such behaviour is associated with various strengthening mechanisms. Strengthening by grain boundaries (Hall-Petch relation), strengthening by secondary phases or precipitates, solid solution strengthening and plastic deformation strengthening are considered generally. Low mechanical properties of both mentioned conditions of WE43 (WE43 – as-cast, WE43 – Ex + T6) are attributed especially to coarse-grained structures (Figs. 1a,d). Other materials were characterized by at least partially recrystallized fine-grained structures. This is especially evident in Fig. 1b for the extruded alloy, where the grain size ranged between 2–8 µm, and therefore, TYS and UTS values reached 250 and 300 MPa, respectively. However, the WE43 alloy prepared by the combination of extrusion and T4 pre-treatment or extrusion in combination with rotary swaging was characterized by even higher values of TYS and UTS. These materials were not completely recrystallized, and some work hardening and residual stresses remained in the structures in non-recrystallized regions which are prolonged in the direction of processing (Figs. 1c,e). This means a significant contribution to the mechanical properties.

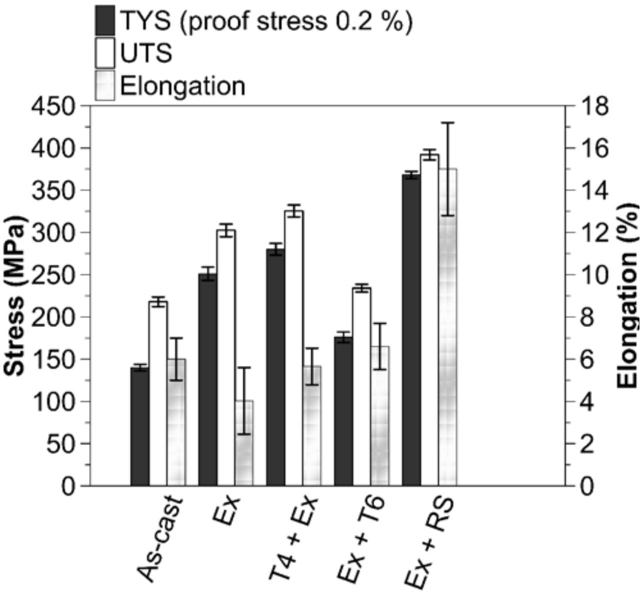

Fig. 2. Tensile properties of the WE43 alloy prepared by various processing.

Also, precipitation strengthening has to be considered for the studied materials. However, all materials with improved mechanical properties were processed by extrusion at 400 ℃, which is a quite high temperature at which stable β-phases are preferentially formed (Figs. 1f–h). These phases have an only minor strengthening effect [26]; therefore the general contribution to the mechanical properties of the studied materials is expected to be low. The only exception is the extruded WE43 alloy subsequently processed by T6. In such case, β' metastable phase with strong strengthening effect is expected in the material [27, 28]. Unfortunately, this positive effect is balanced by a very coarse-grained microstructure (Fig. 1a).

Another important contribution is strengthening by alloying elements dissolved in the solid solution. In the first approximation, such strengthening is associated with the difference in the atomic radii of the elements dissolved in the solid solution and magnesium. Atoms of Y and Nd reach a comparable radius of 0.18 nm. Compared to the atomic radius of magnesium (0.16 nm), this is a 12 % difference. Therefore, it can be assumed that the presence of a higher concentration of these elements in the solid solution has a direct effect on mechanical properties. Another important factor for the solid solution strengthening is the difference in the shear modulus associated with the bond strength of the dissolved substance and the magnesium matrix. The shear modulus for Y, Nd and Mg corresponds to $G_{\mathrm{Nd}} = 16.3\,\mathrm{GPa}$, $G_{\mathrm{Y}} = 25.6\,\mathrm{GPa}$, $G_{\mathrm{Mg}} = 17\,\mathrm{GPa}$ [29]. From this point of view, only the size of the atom plays a role in the strengthening effect by Nd, and, in general, the dominant strengthening effect of Y in the solid solution can be assumed for the WE43 alloy. Strengthening by solid solution can be considered especially in the case of WE43 processed by T4 and subsequent extrusion because during heat pretreatment majority of secondary phases is dissolved in the solid solution. Although part of these elements is precipitated during extrusion in the form of already mentioned β-phase (Fig. 1g), the concentration of Y and Nd in solid solution reaches values about 3 and 2 wt.%, respectively.

Also, the texture of the material has a significant effect on mechanical properties in the case of magnesium-based alloys. The presence of a specific texture with the orientation of the HCP basal planes parallel to the direction of extrusion affects the tensile yield strength and compressive yield strength measured in the direction parallel to the extrusion direction [13–16]. For a fibre textured extruded material, a large number of grains is oriented inappropriately for the slip in the basal planes and twinning during the tensile test. As a result, higher yield stresses are needed to activate more complex slip systems. Conversely, during compression performed in the extrusion direction twinning is easily activated. This mechanism causes reorientation of the crystal lattice, and plastic deformation is then realized in reoriented basal planes [30, 31]. The values of the compressive yield strength of the material thus fall to lower values (Fig. 3). This effect was documented especially in the case of WE43 prepared by T4 pre-treatment and subsequent extrusion, where TYS and CYS values reached approximately 280 and 235 MPa, respectively.

Excellent mechanical properties were observed in the alloy prepared by the combination of extrusion and subsequent rotary swaging. In this case, TYS of almost 370 MPa and UTS of 385 MPa were measured. This material was characterized by a partially recrystallized microstructure with deformed grains, and therefore, residual stress is considered to affect mechanical properties highly. Interestingly, the alloy in this condition was characterized by a high value of elongation to fracture (about 15 %) compared to other states of the material with elongation reaching from 4 to 8 %. Also, compressive mechanical properties were close to those observed in tension so that low mechanical asymmetry is expected. Therefore, WE43 in the presented state represents an interesting constructional material with superior mechanical properties. In addition, it is prepared by well-available industrial methods without the need for specific long and uneconomical heat treatment or mechanical processing [19].

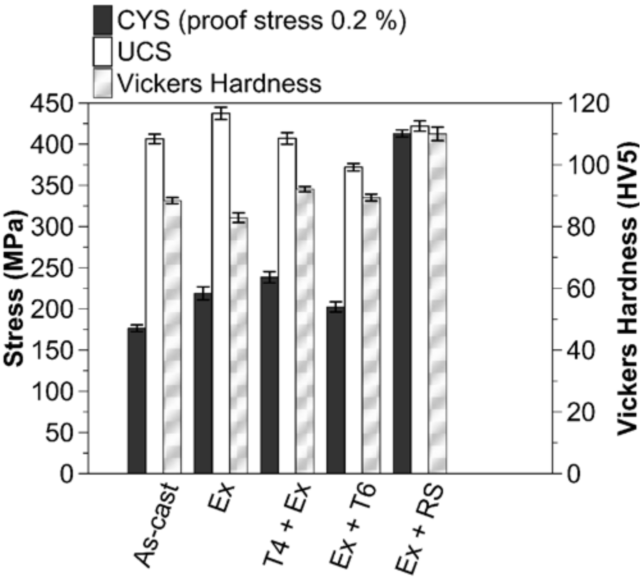

Fig. 3. Compressive properties of the WE43 alloy prepared by various processing.

4. Conclusions

In the present work, microstructure and mechanical properties of the WE43 magnesium alloy were studied. Obtained results have indicated a huge effect of processing conditions on the observed characteristics of the material. After heat treatment (T6), coarse grains are present in the material, which cause a decrease in strength; however, precipitation strengthening by metastable β'-phase may partially compensate this decrease. Thermomechanical processing, such as extrusion or rotary swaging, at 400 ℃ caused significant grain refinement and the precipitation of stable β-phase, resulting in superior mechanical properties. As a consequence, TYS ranged from 140 MPa in the as-cast state up to 370 MPa for material processed by the combination of extrusion and rotary swaging. Although prepared alloys were generally characterized by lower elongation of about 4–8 %, when prepared by the combination of extrusion and rotary swaging, the material reached an elongation to failure of about 15 %. Such a combination of TYS, UTS and elongation values are interesting for possible applications in both automotive industries and medicine.

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References

[1] Peeters, P., Bosiers, M., Verbist, J., Deloose, K., Heublein, B.: J. Endovasc. Ther., *12*, 2005, p. 1. doi:10.1583%2F04-1349R.1

[2] Castellani, C., Lindtner, R. A., Hausbrandt, P., Tschegg, E., Stanzl-Tschegg, S. E., Zanoni, G., Beck, S, Weinberg, A. M.: Acta Biomater., *7*, 2011, p. 432. doi:10.1016/j.actbio.2010.08.020

[3] Waizy, H., Diekmann, J., Weizbauer, A., Reifenrath, J., Bartsch, I., Neubert, V., Schavan, R., Windhagen, H.: J. Biomater. Appl., *28*, 2014, p. 667. doi:10.1177/0885328212472215

[4] Windhagen, H., Radtke, K., Weizbauer, A., Diekmann, J., Noll, Y., Kreimeyer, U., Schavan, R., Stukenborg-Colsman Christina, Waizy, H.: Biomed. Eng. Online, *12*, 2013, p. 62. doi:10.1186/1475-925x-12-62

[5] Ezechieli, M., Ettinger, M., König, C., Weizbauer, A., Helmecke, P., Schavan, R., Lucas, A., Windhagen, H., Becher, Ch.: Knee Surgery, Sports Traumatology, Arthroscopy, *24*, 2016, p. 3976. doi:10.1007/s00167-014-3325-6

[6] Mengucci, P., Barucca, G., Riontino, G., Lussana, D., Massazza, M., Ferragut, R., Hassan, A. E.: Mat. Sci. Eng. A-Struct., *479*, 2008, p. 37. doi:10.1016/j.msea.2007.06.016

[7] Riontino, G., Massazza, M., Lussana, D., Mengucci, P., Barucca, G., Ferragut, R.: Mat. Sci. Eng. A-Struct., *494*, 2008, p. 445. doi:10.1016/j.msea.2008.04.043

[8] Xu, L., Liu, C. M., Wan, Y. C., Wang, X., Xiao, H. C.: Mat. Sci. Eng. A-Struct., *558*, 2012, p. 1. doi:10.1016/j.msea.2012.06.085

[9] Yu, K., Li, W. X., Wang, R. C., Wang, B., Li, C.: Mater. Trans., *49*, 2008, p. 1818. doi:10.2320/matertrans.MRA2008602

[10] Pachla, W., Mazur, A., Skiba, J., Kulczyk, M., Przybysz, S.: Arch. Metall. Mater., *57*, 2012, p. 485. doi:10.2478/v10172-012-0050-3

[11] Cao, G. H., Zhang, D. T., Chai, F., Zhang, W.W., Qiu, C.: Mat. Sci. Eng. A-Struct., *642*, 2015, p. 157. doi:10.1016/j.msea.2015.06.086

[12] Kumar, N., Choudhuri, D., Banerjee, R., Mishra, R. S.: Int. J. Plast., *68*, 2015, p. 77. doi:10.1016/j.ijplas.2014.11.003

[13] Stanford, N., Barnett, M.: Scripta Mater., *58*, 2008, p. 179. doi:10.1016/j.scriptamat.2007.09.054

[14] Laser, T., Hartig, C., Nürnberg, M. R., Letzig, D., Bormann, R.: Acta Mater., *56*, 2008, p. 2791. doi:10.1016/j.actamat.2008.02.010

[15] Kleiner, S., Uggowitzer, P. J.: Mat. Sci. Eng. A-Struct., *379*, 2004, p. 258. doi:10.1016/j.msea.2004.02.020

[16] Mackenzie, L. W. F., Davis, B., Humphreys, F. J., Lorimer, G. W.: Mater. Sci. Technol., *23*, 2007, p. 1173. doi:10.1179/174328407X226509

[17] Elektron, M. Elektron WE43. https://www.magnesium-elektron.com/wp-content/uploads/2016/10/Elektron-WE43B_0.pdf (accessed 9.2.2018)

[18] Elektron M. ELEKTRON 43 PLATE PRODUCTS. https://www.magnesium-elektron.com/wp-content/uploads/2016/10/Elektron-43-Plate_0.pdf (accessed 9.2.2018)

[19] Tekumalla, S., Seetharaman, S., Almajid, A., Gupta, M.: Metals, *5*, 2015, p. 1. doi:10.3390/met5010001

[20] Elektron M. ELEKTRON 43 EXTRUDED PRODUCTS. https://www.magnesium-elektron.com/wp-content/uploads/2016/10/Elektron-43-Extruded-Products_0.pdf (accessed 9.2.2018)

[21] Nie, J. F., Muddle, B. C.: Acta Mater., *48*, 2000, p. 1691.

[22] Antion, C., Donnadieu, P., Perrard F., Deschamps, A., Tassin, C., Pisch, A.: Acta Mater., *51*, 2003, p. 5335. doi:10.1016/s1359-6454(03)00391-4

[23] Apps, P. J., Karimzadeh, H., King, J. F., Lorimer, G. L.: Scripta Mater., *48*, 2003, p. 475. doi:10.1016/S1359-6462(02)00509-2

[24] Smola, B., Stulíková, I.: J. Alloys Compd., *381*, 2004, p. L1. doi:10.1016/j.jallcom.2004.02.049

[25] Liang, S., Guan, D., Tan, X., Chen, L., Tang, Y.: Mat. Sci. Eng. A-Struct., *528*, 2011, p. 1589. doi:10.1016/j.msea.2010.10.082

[26] Apps, P. J., Lorimer, G. W., Karimzadeh, H., King, J. F.: Scripta Mater., *48*, 2003, p. 1023. doi:10.1016/s1359-6462(02)00596-1

[27] Liu, K., Zhang, J., Su, G., Tang, D., Rokhlin, L. L., Elkin, F. M., Meng, J.: J. Alloys Compd., *481*, 2009, p. 811. doi:10.1016/j.jallcom.2009.03.119

[28] He, S. M., Zeng, X. Q., Peng, L. M., Gao, X., Nie, J. F., Ding, W. J.: J. Alloys Compd., *427*, 2007, p. 316. doi:10.1016/j.jallcom.2006.03.015

[29] Lukáč, P.: Phys. Status Solidi A, *131*, 1992, p. 377. doi:10.1002/pssa.2211310212

[30] Sarker, D., Chen, D. L.: Mat. Sci. Eng. A-Struct., *596*, 2014, p. 134. doi:10.1016/j.msea.2013.12.038

[31] Mirza, F. A., Chen, D. L., Li, D. J., Zeng, X. Q.: Mat. Sci. Eng. A-Struct., *575*, 2013, p. 65. doi:10.1016/j.msea.2013.03.041