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Plasticity and corrosion resistance of magnesium alloy WE43

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ABSTRACT

Purpose: The purpose of this study was to assess the extent to which magnesium alloy WE43 is susceptible to metal forming and to assess its structure after hot forming. Corrosion resistance evaluation of WE43 alloy in NaCl solutions, after casting and extrusion forging, was also made. Basic groups of magnesium alloys for plastic forming were characterised.

Design/methodology/approach: Formability of magnesium alloy WE43 was determined on the ground of uni-axial compression tests in the temperature from 200 to 450°C and with deformation rate within the range from 0.01 to 10 s^{-1}. The structure of the alloy after hot forming was presented. Corrosion tests of magnesium alloy WE43 were carried out in solutions with concentration of 0.01-2 M NaCl with application of electrochemical testing system VoltaLab®PGP201. Electrochemical corrosion resistance was evaluated on the ground of registered anodic polarisation curves by means of potentiodynamic method.

Findings: It was proved that resistance of magnesium alloy WE43 in temperature range from 200 to 300°C is limited. It was found that recrystallization begins during strain application at the temperature of 350°C. Strain at the temperature of 450°C guarantees full recrystallization of the alloy. The results of carried out corrosion tests explicitly show deterioration of corrosion characteristics of magnesium alloy WE43 together with increase of molar concentration of NaCl solution.

Practical implications: The tests results regarding the effect of strain parameters on magnesium alloy WE43 formability may be employed in preparation of metal forming technology for the alloy. In corrosion tests it was proved that irrespective of molar concentration of NaCl solution, pitting corrosion is present in the tested alloy. It proves it is necessary to apply protective layers on elements made of WE43 alloy, irrespective of its state of delivery.

Originality/value: Tests of technological plasticity enabled to determine the dependence of yield stress on temperature and rate of strain. Electrochemical corrosion tests showed that WE43 alloy obtained in extrusion features slightly higher corrosion characteristics.

Keywords: Metallic alloys; Magnesium alloy WE43; Plasticity; Corrosion

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MATERIALS

1. Introduction

Development that is taking place in the aircraft, automotive and machine industries is closely related to the development of construction materials featuring lower density, higher strength and resistance to high temperatures and influence of the environment in comparison with materials that have been used so far. This group of materials includes magnesium alloys that feature [1-3]:

- the lowest density among metallic construction materials (ca 1.74 g/cm^3),
- high specific strength,
- good castability, machinability, weldability in controlled atmospheres,
- high resistance to gas corrosion,
- good vibration dumping.

The applications range of magnesium alloys is limited by: small elastic modulus, limited formability and low creep resistance as well as high susceptibility to electrochemical corrosion.

Intensive development of magnesium alloys started in the twenties of the XXth century. In 1924 magnesium alloys containing aluminium and zinc were used for the first time for production of car engine cylinders, and in 1940 in the USA Northrop XP-56 plane was designed, in which practically all parts that were not subject to elevated temperatures, were made of magnesium and its alloys. Some difficulties in further development of magnesium alloys were caused by low corrosion resistance, small formability and inflammability of magnesium.

Main development of magnesium alloys falls on the 90-ties of the twentieth century and is closely related to the reduction of vehicle weight. The most popular application of magnesium is as a component of aluminium alloys, whereas magnesium alloys are used for production of pressure castings, the main consumer of which is automotive industry [4-19]. Alloys after metal forming can obtain higher mechanical properties in comparison with casting alloys, and their strength and formability may be shaped by means of hot working, mainly age hardening. Despite favourable mechanical characteristics, application of alloys for metal forming is modest and makes only 1% of annual world magnesium production. The main problem associated with metal forming of magnesium alloys is their limited formability.

Basic alloys for metal working contain up to 8% Al with additions of Mn (up to 2%), Zn (to 1.5%, although an alloy that contains 6% Zn was created), Si (ca. 0.1%) and minute quantities of Cu, Ni, Fe. The following groups of magnesium alloys can be distinguished [3]:

- Mg-Mn (M1, M2),
- Mg-Al-Zn (AZ21, AZ31, AZ 61 and AZ80),
- Mg-Zn - (Mn, Cu) (ZM21, ZC71).

The second group, similarly to casting alloys, includes alloys containing the following elements − Zn, RE, Y, Zr, Th:

- Mg-Zn-Zr (ZK30, ZK40 and ZK 60),
- Mg-Zn- RE (ZE10),
- Mg-Y-RE-Zr (WE43, WE54),
- Mg-Th (HK31, HM21, HZ11).

The third group, that is currently being under intensive tests, may be constituted by new ultralight alloys containing Li of the type:

- Mg-Li-Al (LA141).

Alloy components in magnesium alloys after plastic working can be divided into 3 categories [3]:

- additives that increase both strength and plasticity of magnesium, namely the following elements, in the order of decreasing strength – Al, Zn, Ca, Ag, Ce, Ni, Cu, Th, and increasing plasticity – Th, Zn, Ag, Ce, Ca, Al, Ni, Cu,
- elements that increase formability, without definite influence on magnesium strength, are Cd, Tl and Li,
- elements that increase strength, but decrease magnesium formability, are Sn, Pb, Bi and Sb.

Metal forming of magnesium and its alloys can be made, irrespective of the alloy elements content, only in restricted temperature range.

Magnesium alloys are mostly subject to extrusion process and hot forging. Extrusion of magnesium alloys is most often realised in temperature range 320-450°C at the rate from 1 to 25 m/min. Recently, intensive development of hydrostatic extrusion has been observed, which enables to carry out the process in lower temperatures and obtain better grain size reduction of magnesium alloys [20-32].

Methods of metal forming are also used to process a new generation alloy, WE43, that belongs to the group of magnesium alloys that contain rare earth elements, mainly RE, Y, Zr, Th. This alloy is mainly used as a casting alloy, but products obtained through extrusion are also used. After extrusion and heat treatment, the alloy obtains substantially better mechanical properties in comparison with its condition after casting: tensile strength is R_m=270 MPa, yield stress R_{pe}=195 MPa, and elongation A_5=15%. WE43 alloy, apart from good mechanical characteristics, also features good creeping resistance in elevated temperatures. It is a long-range material for applications in aircraft industry as its mechanical properties are stable up to the temperature of 200°C.

Application of magnesium alloys is to a great extent limited due to low corrosion resistance which results from insufficient protection of oxide layer that is created on the surface in oxidizing atmosphere or hydroxides layer in water solutions [33-41].

The purpose of this study was to determine formability of WE43 alloy to plastic forming. It was determined on the ground of uni-axial compression tests in the temperature from 200 to 450°C and at the rate of strain within the range from 0.01 to 10 s^{-1}. Moreover, evaluation of resistance to electrochemical corrosion of WE43 after casting and extrusion was made. The tests were carried out in NaCl solutions of various concentration (0.01-2 M NaCl). Potentiodynamic tests enabled to register anodic polarisation curves. Stern method was employed to determine parameters characterising corrosion resistance of the alloy.

2. Materials and methods

Initial material for the tests was samples of magnesium alloy WE43 after casting and hot extrusion. Chemical composition of the alloy is presented in Table 1.

Table 1.
Chemical composition of magnesium alloy WE43, % of mass

Y	RE	Zr	Mg
4.3	4.8	0.5	rest

Hot compression tests were carried out in a thermal-and-mechanical simulator Gleeble 3800 at the temperatures 200, 250, 300, 350, 400 and 450°C. Compression was made after heating the sample to the temperature of 450°C at the heating rate of 3°C/s, withstanding this temperature for 300 s and then cooling to strain temperature at the rate of 5 s^{-1}. The time of withstanding prior to strain was 30 s. The applied rates of strain were 0.01, 0.1, 1.0 and 10 s^{-1} and real reduction ε =1.0.

Structural tests were made on optical microscope OLYMPUS GX51.

Corrosion tests were realised in NaCl solutions featuring various concentration of chloride ions. Measurements were made in 0.01; 0.2; 0.6; 1 and 2 M NaCl solution. Solution temperature during the test was 21±1°C.

Resistance to electrochemical corrosion was evaluated on the ground of registered anodic polarisation curves. For potentiodynamic tests, measurement system VoltaLab®PGP201 made by Radiometer was used. Saturated calomel electrode (NEK) of KP-113 type served as reference electrode, whereas platinum electrode of PtP−201 type was used as auxiliary electrode. The tests started with determination of opening potential E_{OCP}. Then, anodic polarisation curves were registered, beginning with the measurement of potential with the value of $E=E_{OCP}-100$ mV. Potential changed in the anodic direction at the rate of 1 mV/s. When anodic current reached density of 10 mA/cm^2, polarisation direction was changed and thus return curve was registered. Opening potential E_{OCP} of tested samples steadied after 30 minutes. On the ground of registered curves, typical elements describing resistance to electrochemical corrosion were determined, i.e.: corrosion potential, corrosion current density and and corrosion rate. Stern method was used to determine polarisation resistance.

3. Results

Microstructure of the alloy in the initial condition after casting and after extrusion process is presented in Fig. 1 and Fig. 2. After casting the alloy has a coarse-grain structure and after hot extrusion from the initial diameter of 40 mm to the diameter of 12 mm, substantial grain size reduction was achieved.

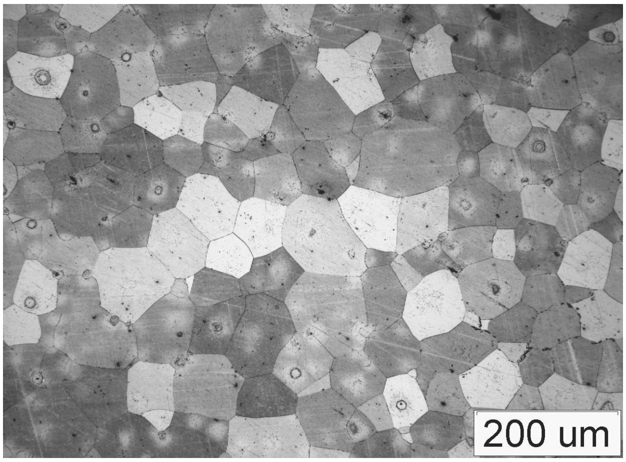

Fig. 1. Microstructure of WE43 in the initial state after casting

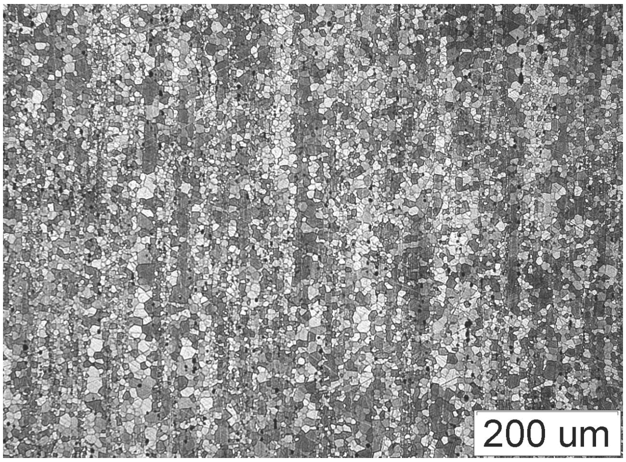

Fig. 2. Microstructure of WE43 after hot extrusion

Values of thrust and displacement as the function of time, registered in hot compression test, were calculated into the relation between stress and strain. These relations for tested temperatures and rates of strain are shown in Figs. 3-6. Typical values of maximum yield stress σ_{pp} and strain to reach maximum values of stress ε_p for the tested strain parameters, are presented in Table 2. Figs. 7 and 8 shows flow curves of WE43 alloy after extrusion at the temperature 400 and 450°C at the rate of strain 0.01÷10 s^{-1}.

Table 2.
Values of maximum yield stress σ_{pp} and strain ε_p correspondent to σ_{pp}

Temperature, °C	Strain rate, s^{-1}	Maximum yield stress σ_{pp}, MPa	Strain, ε_p
250	0.01	330	0.40
300	0.01	225	0.50
350	0.01	135	0.16
400	0.01	70	0.05
450	0.01	40	0.02
200	0.1	330	0.31
300	0.1	260	0.68
350	0.1	170	0.34
400	0.1	105	0.15
450	0.1	60	0.16
350	1	210	0.48
400	1	140	0.16
450	1	100	0.05
300	10	280	0.30
350	10	235	0.30
400	10	175	0.40
450	10	130	0.17

At the temperature of 200°C the alloy shows low formability, it cracks at the strain of ε=0.3 (Fig. 4). At the temperature of 250°C, the alloy also features limited formability (Fig. 3). Increase of plasticity was observed after compression at the temperature of 300°C at the strain rate of 0.01s^{-1} (Fig. 3), and substantial improvement of formability takes place in the temperature of 350°C (Figs. 3, 5). Similarly, at the higher temperatures − 400, 450°C − formability is good (Figs. 6-8). However, substantial decrease of yield stress can be seen at the rate of 10 s^{-1}, which can indicate the beginning of material cohesion loss or increase of temperature during compression test (Fig. 7).

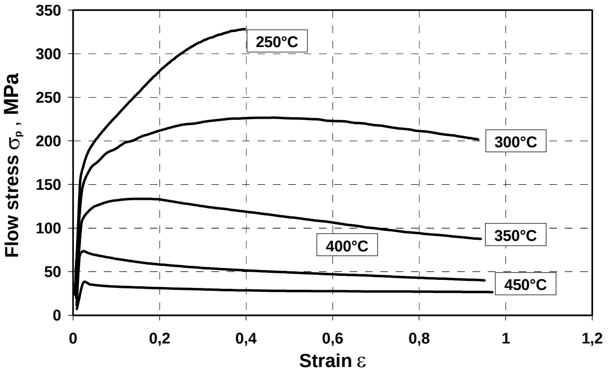

Fig. 3. Relation of yield stress and strain for WE43 alloy tested in temperatures 250°C to 450°C at the strain rate of 0.01s^{-1}

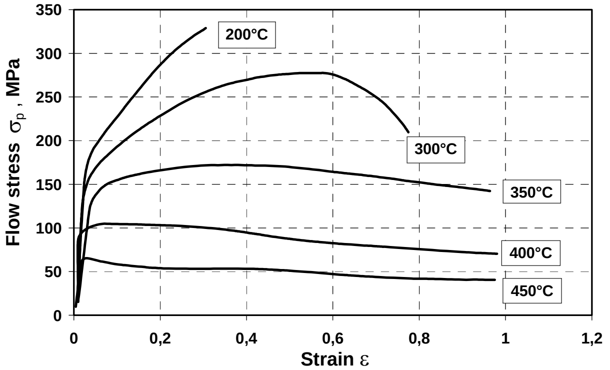

Fig. 4. Relation of yield stress and strain for WE43 alloy tested in temperatures 200°C to 450°C at the strain rate of 0.1s^{-1}

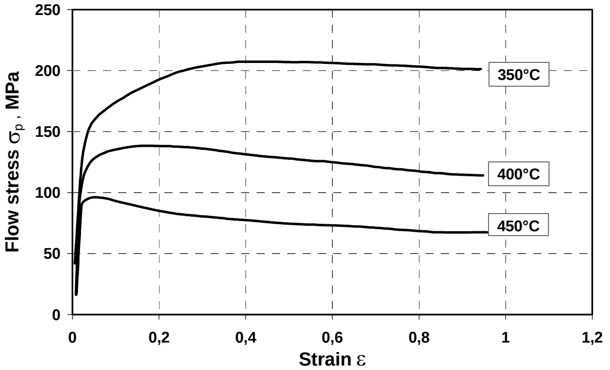

Fig. 5. Relation of yield stress and strain for WE43 alloy tested in temperatures 350°C to 450°C at the strain rate of 1s^{-1}

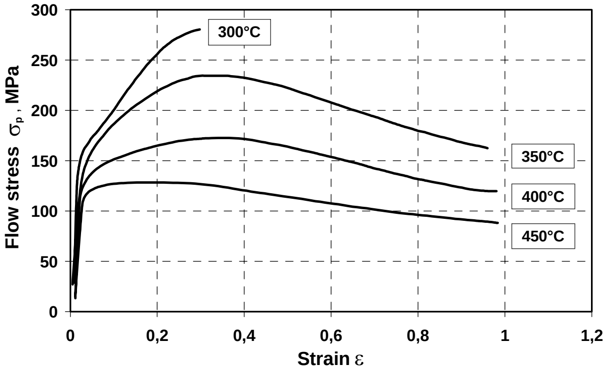

Fig. 6. Relation of yield stress and strain for WE43 alloy tested in temperatures 300°C to 450°C at the strain rate of 10 s^{-1}

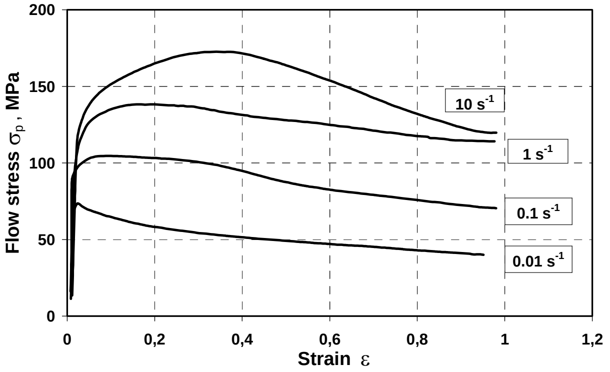

Fig. 7. Relation of yield stress and strain for WE43 alloy tested in temperature of 400°C at the strain rate of 0.01-10 s^{-1}

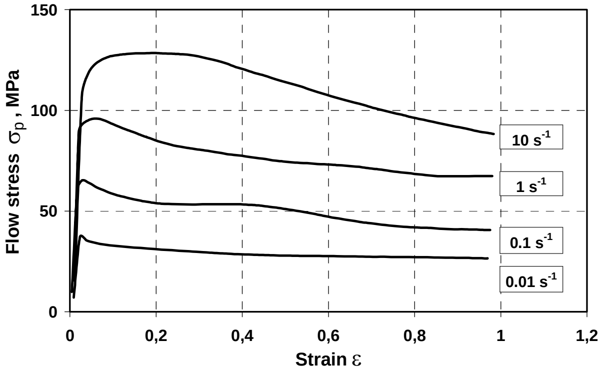

Fig. 8. Relation of yield stress and strain for WE43 alloy tested in temperature of 450°C at the strain rate of 0.01-10 s^{-1}

Exemplary results of WE43 structure evaluation after compression tests are shown in Figs. 9-14.

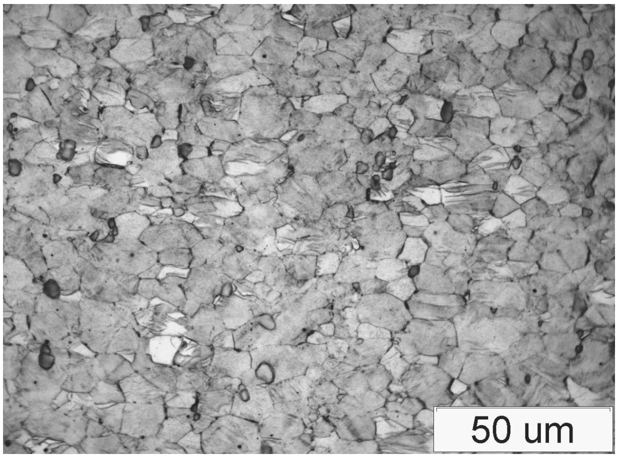

Fig. 9. Microstructure of WE43 after hot compression test at the temperature of 200°C at the strain rate of 0.1 s^{-1}

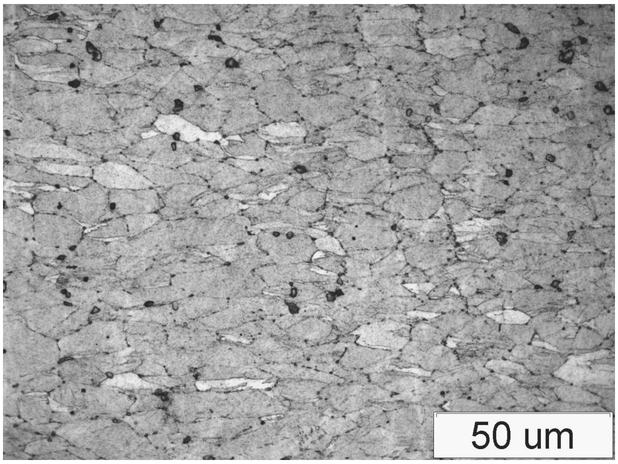

Fig. 10. Microstructure of WE43 after hot compression test at the temperature of 300°C at the strain rate of 0.1 s^{-1}

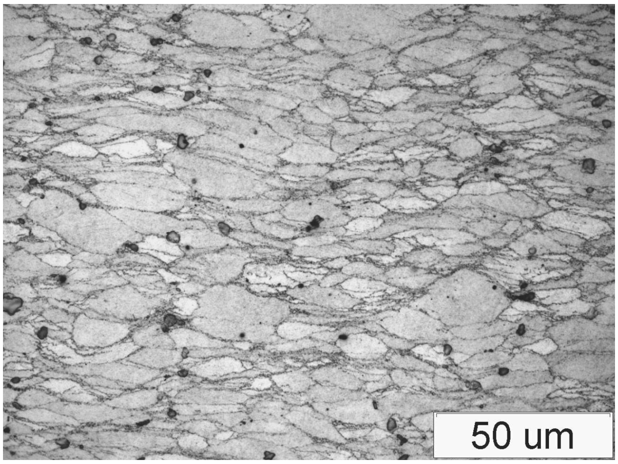

Fig. 11. Microstructure of WE43 after hot compression test at the temperature of 350°C at the strain rate of 0.1 s^{-1}

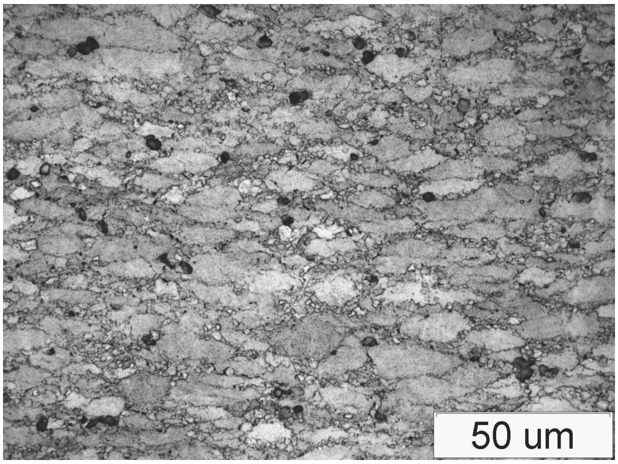

Fig. 12. Microstructure of WE43 after hot compression test at the temperature of 400°C at the strain rate of 0.1 s^{-1}

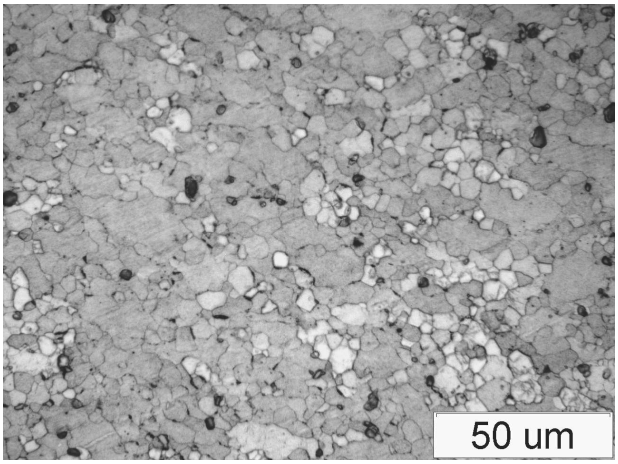

Fig. 13. Microstructure of WE43 after hot compression test at the temperature of 450°C at the strain rate of 0.1 s^{-1}

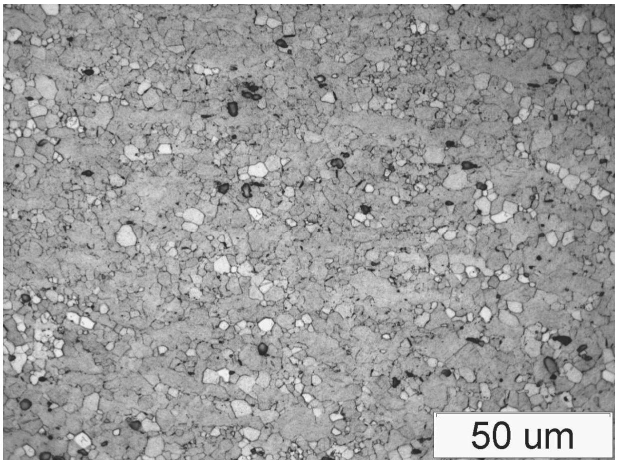

Fig. 14. Microstructure of WE43 after hot compression test at the temperature of 450°C at the strain rate of 10 s^{-1}.

At the temperature of 200°C (Fig. 9), elongation of original grains and creation of deformation twins was observed. At the temperature of 250 and 300°C (Fig. 10) the material behaves in a similar way, only grain elongation and creation of deformation twins can be seen. Within this range, as it was proved in compression tests, alloy formability is limited. Cracking takes place in the areas with the highest concentration of defects. The first signs of structure rebuilding processes, connected with dynamic recrystallisation, were observed at the temperature of 350°C (Fig. 11), where creation of ultra-small grains on the boundaries of elongated original grains was observed. Recrystallisation is more intensive at the temperature of 400°C (Fig. 12). The appearance of a typical necklace of recrystallised grains on the boundaries of original grains was observed at the same temperature. Recrystallised grains are extremely small. At the highest temperature of strain (450°C), microstructure is completely recrystallised and consists of small grains (Fig. 13 and Fig. 14). Potentiodynamic tests carried out in NaCl solutions of various molar concentrations enabled to determine corrosion properties of magnesium alloy WE43 after casting and after hot extrusion.

Table 3.
Results of electrochemical corrosion resistance tests of magnesium alloy WE43 (mean measurement values)

Molar concentration NaCl, M	E_{corr}, mV	$I_{corr.}$, A/cm^2	R_p, Ωcm^2	Corr., mm/year
WE43 alloy after casting				
0.01	-1536	0.0036	7.58	0.79
0.20	-1559	0.0131	2.14	2.91
0.60	-1658	0.0185	1.41	4.10
1.00	-1640	0.0264	1.07	5.84
2.00	-1658	0.0315	0.84	6.97
WE43 alloy after extrusion				
0.01	-1565	0.0028	9.23	0.64
0.20	-1751	0.0071	3.64	1.63
0.60	-1780	0.011	2.20	2.51
1.00	-1792	0.013	1.98	2.97
2.00	-1687	0.016	1.66	3.66

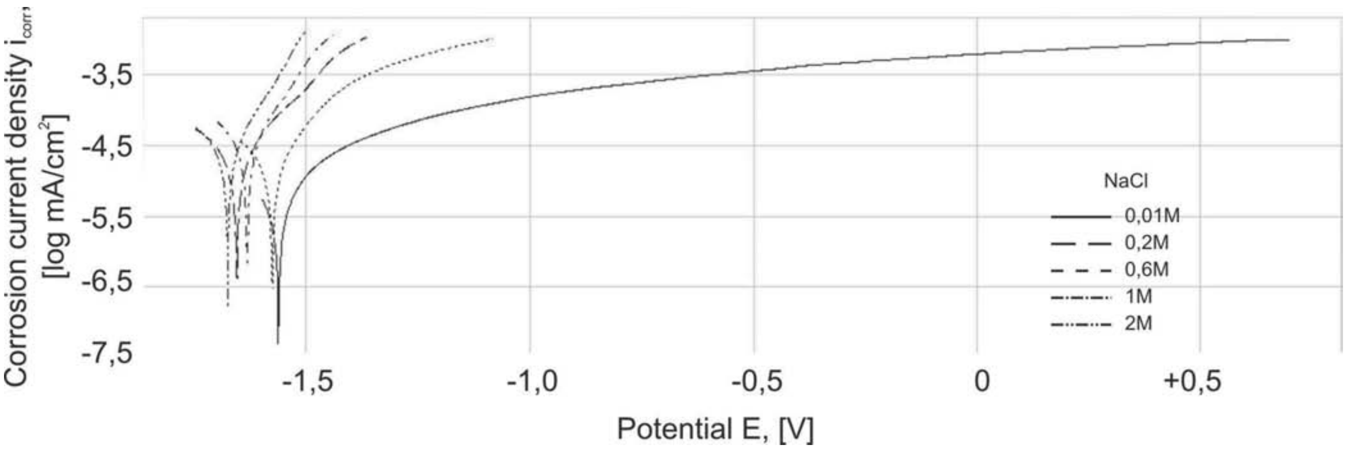

Fig. 15. Anodic polarisation curves of WE43 alloy after casting

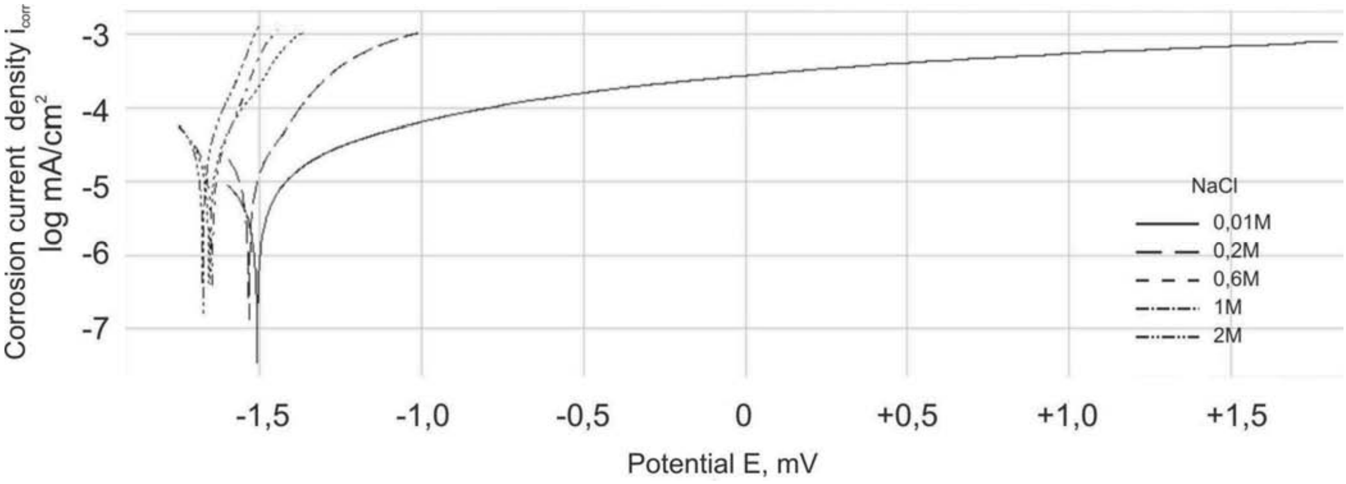

Fig. 16. Anodic polarisation curves of WE43 alloy after extrusion

The results of corrosion resistance tests (mean values of measurements) are presented in Table 3. Anodic polarisation curves of the selected samples are shown in Fig. 15 and Fig. 16.

It was determined that with the increase of chloride ions concentration, one can observe decrease of corrosion characteristics of magnesium alloy WE43 obtained both by means of pressure casting as well as extrusion. Decrease of polarisation resistance as well as increase of corrosion current density and corrosion rate of WE43 is observed, irrespective of the employed alloy production technology. Polarisation resistance of cast alloy tested in 0.01 M NaCl was R_p=7.58 Ωcm^2, whereas in 2 M NaCl – R_p=0.84 Ωcm^2. For extruded alloy, polarisation resistance decreases with the increase of NaCl concentration from R_p=9.23 Ωcm^2 to R_p=1.66 Ωcm^2. Corrosion current density of cast alloy increases from I_{coor}=0.0036 A/cm^2 (0.01 M NaCl) to I_{coor}=0.0315 A/cm^2 (2 M NaCl), and extruded alloy from I_{coor}=0.0028 A/cm^2 (0.01 M NaCl) to I_{coor}=0.016 A/cm^2 (2 M NaCl).

Slightly higher corrosion properties can be attributed to WE43 alloy, obtained by means of extrusion. It features higher polarisation resistance and lower corrosion current density and corrosion rate. For example, corrosion rate determined in 0.01 M NaCl of cast alloy is Corr=0.79 mm/year, and for extruded alloy Corr=0.64 mm/year. Potentiodynamic tests carried out in 2 M NaCl solution proved that corrosion rate for cast alloy is Corr=6.97 mm/year, whereas for extruded alloy Corr=3.66 mm/year.

4. Conclusions

Magnesium alloys, depending on their chemical composition and formability, can be formed by means of hot rolling, open die forging and matrix forging, extrusion and sheet pressing in warmed matrix after rolling. Extrusion is one of the basic methods of shaping magnesium alloys, that enables to produce long profiles with uniform cross-section. Forward extrusion as well as backward extrusion are both applied. Apart from preparation and greasing of the matrix, main parameters determining the process of extrusion, are: temperature, degree of plastic forming and rate of strain. Therefore, it is necessary to determine technological plasticity of the alloy each time.

In this study characteristics of magnesium alloy WE43 formability was determined. Moreover, tests of alloy microstructure after hot forming were made. Obtained results show low formability of the alloy at the temperatures of 200, 250, 300°C. In these conditions, the alloy cracks prior to strain ε=1.0. In microstructure of the alloy formed in lower temperatures, elongated grains and numerous deformation twins were observed. Cracking may be the consequence of dislocation concentration and deformation twins that are created intensively at those temperatures. At the temperature of 350°C correct flow of material was observed. Increase of temperature brings about decrease of flow resistance. Recrystallisation begins in the alloy subject to compression at the temperature of 350°C. Strain at this temperature and higher temperatures (400°C) leads to creation of structure that consists of elongated original grains ultra-small recrystallised grains that form a typical necklace structure. Strain at the temperature of 450°C guarantees complete recrystallisation, whereas strain at a higher rate leads to obtaining smaller grain size.

The results of this study can be used to design metal forming technology of WE43 alloy.

It has already been mentioned that application of magnesium alloys is substantially limited due to low resistance to electrochemical corrosion, especially in chloride solutions. Therefore, it was purposeful to carry out corrosion tests in solutions featuring a wide range of NaCl solution concentration.

The results of carried out tests prove explicitly deterioration of corrosion characteristics of magnesium alloy WE43 together with increase of NaCl solution molar concentration. Potentiodynamic tests carried out in solutions with concentration of 0.01-2 M NaCl proved that with the increase of chloride ions concentration, decrease of corrosion potential and polarisation resistance is observed, as well as increase of corrosion current density and corrosion rate of WE43 alloy.

To sum up, it must be highlighted that irrespective of molar concentration of NaCl solution, pitting corrosion is present in the tested alloy. It proves the lack of resistance of magnesium alloy WE43 after plastic forming to this type of corrosion. Test results indicate the need for application of protective layers on elements made of the tested alloy.

Acknowledgements

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