J. PRZONDZIONO, W. WALKE, E. HADASIK, J. SZALA, J.WIECZOREK

ISSN 0543-5846
METABK 52(2) 243-246 (2013)
UDC – UDK 669.721:620.193=111

CORROSION RESISTANCE TESTS OF MAGNESIUM ALLOY WE43 AFTER EXTRUSION

Received – Prispjelo: 2012-06-04
Accepted – Prihvaćeno: 2012-10-11
Preliminary Note – Prethodno priopćenje

The purpose of the study was to evaluate resistance to electrochemical corrosion of magnesium alloy WE43 after plastic working. Potentiodynamic and immersion corrosion tests were performed in solutions with concentration of 0,01 – 2 M NaCl. The tests of microstructure of magnesium alloy after its exposure in NaCl solutions were performed with application of scanning microscope. The results of measurements of alloy surface topography were given, which were obtained by means of optical profile measurement gauge. The results of carried out tests prove explicitly that corrosion properties of extruded magnesium alloy WE43 deteriorate with the increase of molar concentration of NaCl solution. It was proved that irrespective of the concentration of the solution, WE43 alloy features pitting corrosion. It indicates the necessity to apply protective layers on the parts made of the tested alloy.

Key words: magnesium alloy WE43 after extrusion, electrochemical corrosion, potentiodynamic and immersion tests, SEM, surface topography

INTRODUCTION

Magnesium alloys, depending on chemical composition and formability, can undergo hot forming by means of the following methods: rolling, open die forging and stamping, extrusion forging and sheet press forming. Extrusion is one of basic methods of shaping magnesium alloys, which enables to produce long profiles with uniform cross-section. Concurrent extrusion and backward extrusion are both applied. Apart from matrix preparation and greasing, main parameters determining the process of extrusion include: temperature, degree of plastic forming and rate of strain. Extrusion forging 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 perform the process in lower temperatures and obtain better grain size reduction of magnesium alloys [1–4].

Application of magnesium alloys in aeronautic and automotive industries 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 aqueous solutions [5–11].

The purpose of this study was evaluation of resistance to electrochemical corrosion of magnesium alloy WE43 after extrusion. Corrosion tests were performed in NaCl solutions featuring various concentration of chloride ions from 0,01 – 2 M NaCl. Potentiodynamic tests enabled to register anodic polarisation curves. Immersion tests were performed that lasted 1 – 5 days. Hitachi scanning electron microscope with field emission FE SEM S-4 200 enabled to make analysis of chemical composition in micro-areas. Surface topography of alloy WE43 was measured by means of optical.

J. Przondziono, E. Hadasik, J.Szala, J. Wieczorek, Faculty of Materials Science and Metallurgy, The Silesian University of Technology, Katowice, Poland, W. Walke, Faculty of Biomedical Engineering, The Silesian University of Technology, Gliwice, Poland

MATERIAL AND METHODS

As stock material for the tests, samples of magnesium alloy WE43 after hot extrusion were used. Chemical composition of the alloy is presented in Table 1.

Table 1 **Chemical composition of magnesium alloy WE43 / % mass**

Y	Nd	RE	Zr	Mn	Cu	Ni	Zn	Mg
4,0	2,0	3,4	0,4	0,15	0,03	0,005	0,2	rest

Measurements were made in 0,01; 0,2; 0,6; 1 and 2 M NaCl solution. Solution temperature during the test amounted to 21 ± 1 °C.

Resistance to electrochemical corrosion was evaluated on the ground of registered anodic polarisation curves. System VoltaLab®PGP 201 by Radiometer was used for potentiodynamic test. 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 began with determination of opening potential E_{OCP}. Later, anodic polarisation curves were registered, beginning with measurement of potential with the value $E = E_{OCP} - 100$ mV. Potential changed in the anodic direction at the rate of 1 mV/s. When anodic current density reached 10 mA/cm^2, polarisation direction was reversed and return curve was registered. Opening potential E_{OCP} of tested samples stabilised after 30 min.

On the ground of registered anodic polarisation curves, typical values describing resistance to electrochemical corrosion were determined, i.e.: corrosion potential, corrosion current density and corrosion rate. Stern method was applied to determine polarisation resistance.

Immersion tests were performed in ambient temperature in 0,01 – 2 M NaCl solution during 1 – 5 days. After suitable preparation of samples surface, they were weighted and mass m_0 was determined. After immersion of the alloy in NaCl solutions during 1 – 5 days, the samples were taken out and corrosion products were removed in reagent containing 200 g/l CrO_3 and 10 g/l $AgNO_3$. Next, they were flushed with distilled water, degreased with acetone, dried and weighted again, which enabled to determine mass m_1. Performed tests enabled to determine corrosion rate. Qualitative and quantitative analysis of chemical composition in micro-areas was made by means of electron scanning microscope with field emission FE SEM S-4 200 Hitachi aided by spectrometer EDS Voyager 3 500 Noran Instruments. The study also presents measurement results of geometrical features of AZ31 alloy surface after corrosion tests. The tests were performed by means of optical profile measurement gauge Micro'prof. (CWL 3 000) made by FRT.

RESULTS

Potentiodynamic tests performed in NaCl solutions with various molar concentrations enabled to determine corrosion properties of magnesium alloy WE43 after hot extrusion. Corrosion resistance test results (mean values of measurements) have been compared in Table 2. Anodic polarisation curves are presented in Figure 1.

It was discovered that with the increase of chloride ion concentration, corrosion characteristics of magnesium alloy WE43 deteriorates. Decrease of polarisation resistance and increase of corrosion current density and corrosion rate can be seen. Polarisation resistance of the alloy tested in 0,01 M NaCl is R_p = 9,23 Ωcm^2, whereas in 2 M NaCl – R_p = 1,66 Ωcm^2. Corrosion current density increases from I_{coor} = 0,0028 A/cm^2 (0,01 M NaCl) to I_{coor} = 0,016 A/cm^2 (2 M NaCl). Corrosion rate determined in 0,01 M NaCl is *Corr.* = 0,64 mm/year and in 2 M NaCl – *Corr.* = 3,66 mm/year.

Table 2 **Results of electrochemical corrosion resistance tests of magnesium alloy WE43 (mean measurement values)**

NaCl concentration /M	E_{corr} /mV	I_{corr} /A/cm^2	R_p /Ωcm^2	*Corr.* /mm/year
0,01	-1 565	0,0028	9,23	0,64
0,20	-1 751	0,0071	3,64	1,63
0,60	-1 780	0,011	2,20	2,51
1,00	-1 792	0,013	1,98	2,97
2,00	-1 687	0,016	1,66	3,66

Corrosion rate in the immersion test was determined on the ground of the equation (1):

$$V = \frac{m_0 - m_1}{St} \quad (1)$$

where: V – corrosion rate, mg/(cm^{2}day); S – surface area (cm^2), t – exposure time (day).

Table 3 presents immersion test results.

Immersion test results for the tested alloy confirmed its greater predisposition for electrochemical corrosion with the increase of solution molar concentration.

Tests made by means of scanning microscope proved that after 1 day of immersion test in 0,01 M NaCl solution, WE43 alloy corrosion is of selective and non-uniform character. Oblong and round pits can be seen on the surface of the alloy (Figure 2). Corrosion progresses along with time of immersion in NaCl solution, and the number of pits increases (Figure 3). The analysis proved that WE43 alloy shows the structure of a solid solution with precipitation of phases containing neodymium and yttrium (e.g. $Mg_{41}Nd_5$, $Mg_{24}Y_5$, $Mg_{14}Nd_2Y$). It was proved that phases are placed both inside grains and on their boundaries.

With the increase of NaCl solution concentration, corrosion intensifies. Pits substantially enlarge their size (Figure 4).

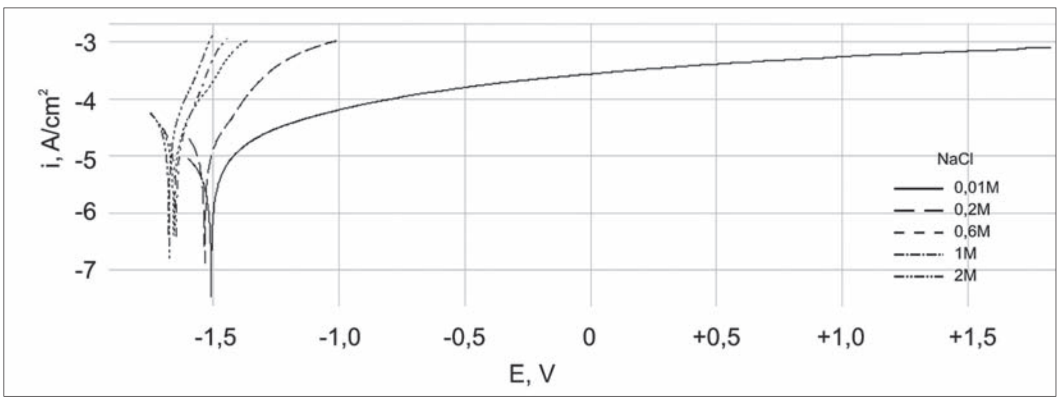

Figure 1 Anodic polarisation curves of WE43 alloy

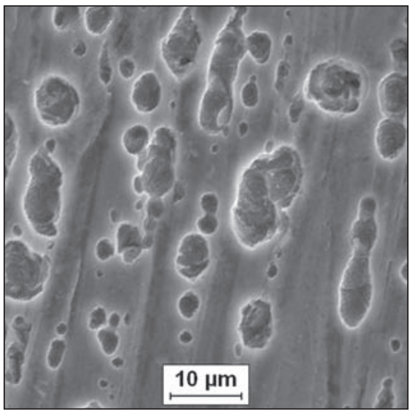

Figure 2 Pitting corrosion of WE43 (0,01 M NaCl, 1 day)

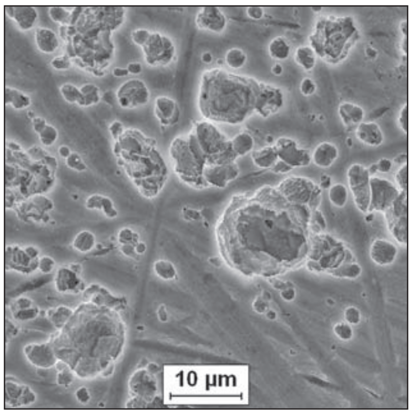

Figure 3 Pitting corrosion of WE43 (0,01 M NaCl, 3 days)

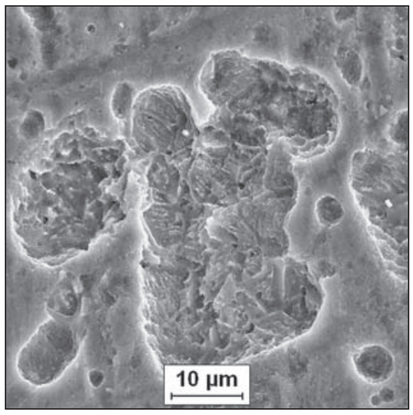

Figure 4 Pits on the surface of the alloy (1 M NaCl, 1 day)

Table 3 **Immersion test results**

NaCl concentration M	Corrosion rate / mg/(cm^{2}day)		
	1 day	3 day	5 day
0,01	0,29	0,39	0,76
0,2	0,41	1,27	1,43
0,6	0,94	1,87	2,01
1	1,42	2,48	2,69
2	1,61	2,66	2,94

Generally speaking, increase of exposure time is responsible for greater alloy surface subject to corrosion (Figure 5).

Tests in 2 M NaCl solution proved that few non-corroded spots can be observed on the surface of the alloy. Corrosion becomes more uniform. Intermetallic phases rich in Nd and Y, cube-shaped, are more and more visible deep in the pits. (Figure 6).

The tests enable to conclude that plastic working process is responsible for structure orientation, and thus - properties anisotropy. Depending on the direction of the orientation, corrosion of the respective grains proceeds more intensively in some crystallographic planes (Figure 7).

Tests performed with optical gauge proved that corrosion of WE43 alloy subject to exposure in 0,01 M NaCl is uniform. After 1-day test depth of pits does not exceed 6 μm (Figure 8), whereas after 5-day tests in 2 M NaCl solution, depth of pits can even exceed 15 μm (Figure 9).

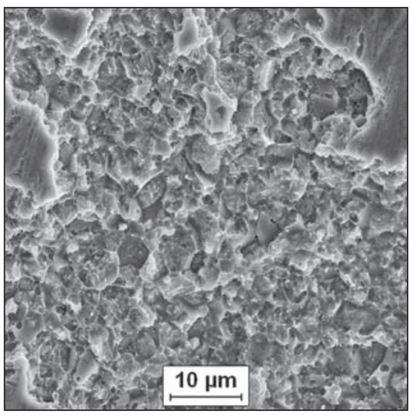

Figure 5 Alloy surface after exposure in 1 M NaCl for 3 days

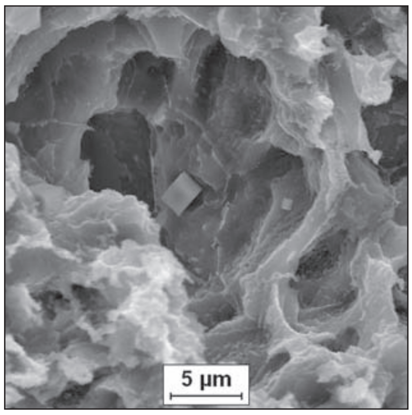

Figure 6 Deep pit with visible intermetallic phases (2 M NaCl, 3 days)

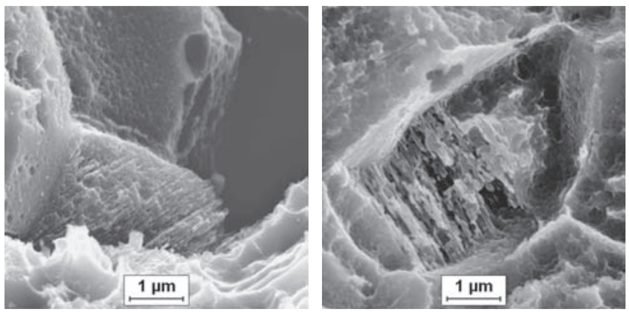

Figure 7 Crystallographic grains oriented corrosion (2 M NaCl, 5 days)

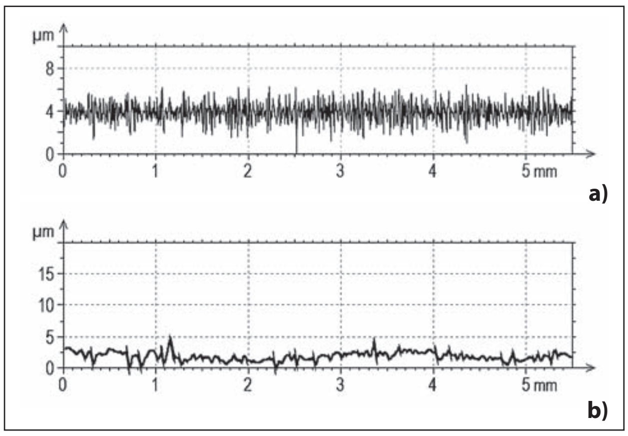

Figure 8 Roughness (a) and waviness (b) of WE43 alloy (0,01 M NaCl, 1 day)

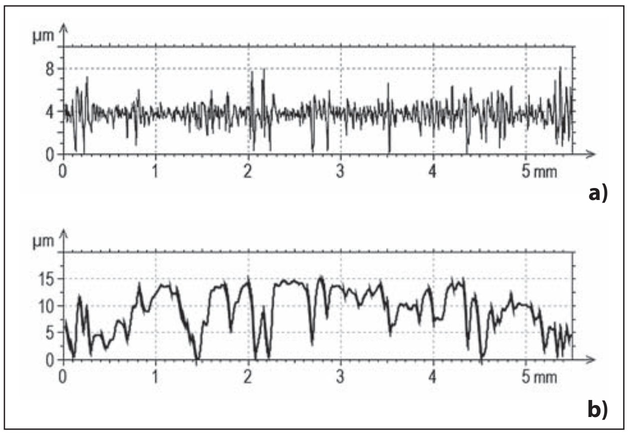

Figure 9 Roughness (a) and waviness (b) of WE43 alloy (2 M NaCl, 5 days)

CONCLUSIONS

Application of magnesium alloy WE43 after plastic working is to a great extent dependent on resistance to electrochemical corrosion, especially in chloride solutions. Results of performed tests explicitly prove deterioration of alloy corrosion properties with the increase of molar concentration of NaCl solution. Potentiodynamic tests performer in solution with concentration of 0,01 – 2 M NaCl proved that increase of chloride ion concentration is responsible for decrease of corrosion potential and polarisation resistance, as well as increase of corrosion current density and alloy corrosion rate. Deterioration of corrosion properties with the increase of NaCl concentration was also confirmed in immersion test as well as during surface topography test.

Anodic dissolution of the surface of the alloy and a large number of pits were observed. With the increase of solution concentration, the pits feature increasingly bigger surface and depth. The surface that was corroded to the greatest extent was the surface of WE43 alloy after corrosion tests in 2 M NaCl solution. WE43 alloy corrosion is of inter-crystallic character.

Following the tests in 2 M NaCl solution, areas with oriented microstructure, connected with plastic strain, can be seen. Due to anisotropy of features in the extruded alloy WE43, it can be expected that there is a crystallographic direction in which corrosion will proceed with greater intensity.

Potential for application of extruded magnesium alloy WE43 in aeronautic and automotive industries is related to the necessity of protective layers application.

Acknowledgements

Financial support of Structural Funds in the Operational Programme–Innovative Economy (IE OP) financed from the European Regional Development Fund - Project “Modern material technologies in aerospace industry”, No POIG.0101.02-00-015/08 is gratefully acknowledged.

REFERENCES

[1] A. Kiełbus, D. Kuc, T. Rzychoń: Magnesium alloys – microstructure, properties and application. Monograph. Modern metallic materials - presence and future. Department of Materials Engineering and Metallurgy, Katowice 2009.

[2] K. Bryła, J. Dutkiewicz, P. Malczewski: Grain refinement in AZ31 alloy processed by equal channel angular pressing. Archives of Materials Science and Engineering, 40 (2009) 17-22.

[3] Z. Cyganek, M. Tkocz: The effect of AZ31 alloy flow stress description on the accuracy of forward extrusion FE simulation results. Arch. Metal. Mater., 57 (2012) 199-204.

[4] H. Zhang, Q. Yan, L. Li: Microstructures and tensile properties of AZ31 magnesium alloy by continuous extrusion forming process. Materials Science and Engineering A, 486 (2008) 295–299.

[5] G.L. Maker, J. Kruger: Corrosion of Magnesium. International Material Review, 38 (1993) 138-153.

[6] X. Guo, J. Chang, S. He, W. Ding, X. Wang: Investigation of corrosion behaviors of Mg–6Gd–3Y–0.4Zr alloy in NaCl aqueous solutions. Elektrochimica Acta, 52 (2007) 2570–2579.

[7] S. Amira, D. Dubé, R. Tremblay, E. Ghali: Influence of the microstructure on the corrosion behavior of AXJ530 magnesium alloy in 3.5% NaCl solution. Materials Characterization, 59 (2008) 1508-1517.

[8] F. Zucchi, V. Grassi, A. Frignani, C. Monticelli, G. Trabanelli: Electrochemical behaviour of a magnesium alloy containing rare earth elements. Journal of Applied Electrochemistry, 36 (2006) 195-204.

[9] J. Przondziono, W. Walke, A. Szuła, E. Hadasik, J. Szala, J. Wieczorek: Resistance to corrosion of magnesium alloy AZ31 after plastic working. Metalurgija (Metallurgy), 50 (2011) 239-243.

[10] T. Zhang., G. Meng, Y. Shao, Z. Cui, F. Wang: Corrosion of hot extrusion AZ91 magnesium alloy. Corrosion Science, 53 (2011) 2934–2942.

[11] I. Nakatsugawa, S. Kamado, Y. Kojima, R. Ninomiya, K. Kubota: Corrosion of magnesium alloys containing rare earth elements. Corrosion Reviews, 16 (2011) 139-158.

Note: The responsible translator for English language is Mrs Agata Budziak, Siemianowice, Poland