

## Corrosion resistance of Mg-RE-Zr alloys

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### Properties

#### ABSTRACT

**Purpose:** Magnesium alloys are widely used in the automotive and aerospace industries. Data concerning corrosion of Mg alloys are numerous, but those concerning Mg-RE alloys are scarce. In this paper, the corrosion behavior of cast magnesium alloys containing rare earth elements (WE54, WE43 and Elektron21) were investigated by immersion test in 3.5% NaCl for times up to 7 days.

**Design/methodology/approach:** The study was conducted on WE54, WE43 and Elektron 21 alloys in the as-cast condition. Immersion test was performed using not deaerated 3.5% NaCl solution at room temperature. Several specimens were placed in 3.5% NaCl solution for periods of time between one and 7 days. The dissolution rates ( $\text{mg}/\text{cm}^2\text{day}^{-1}$ ) were determined by weight loss measurements.

**Findings:** Elektron 21 alloy exhibits the highest corrosion rate during the immersion test, while WE54 and WE43 alloys had a similar corrosion behavior. The corrosion rates of WE54 and Elektron 21 alloys increased linearly with increasing the exposure time in 3.5% NaCl, and that of WE43 was almost unchanged and finally reached maximum value  $0.26 \text{ mg}/\text{cm}^2\text{day}^{-1}$ .

**Research limitations/implications:** The knowledge about corrosion behavior of Mg-RE-Zr alloys is currently under evaluation on many speciality applications where lightweight connected with optimum corrosion resistance are required

**Practical implications:** The comparative results of corrosion behavior of new Mg-RE-Zr alloys leads to optimum choice of alloy for application in automotive, aircraft and aerospace industries.

**Originality/value:** This paper includes the comparative results of corrosion resistance investigations of new Mg-RE-Zr alloys.

**Keywords:** Metallic alloys; Methodology of research; Corrosion; Microstructure

### 1. Introduction

Magnesium is the lightest of all metals used as the basis for constructional alloys. Magnesium alloys offer of low density, high specific strength, good creep properties up to  $250^\circ\text{C}$ , machinability, and availability. The disadvantages are high reactivity and, in many cases, poor corrosion resistance [1-6]. The standard electrode potential of magnesium is  $-2.37 \text{ V}$ , but in 3% sodium chloride the electrode potential is  $-1.63 \text{ V}$  (vs SCE). Therefore magnesium is often used as a sacrificial anode. On the other hand, magnesium offers a high potential for use as a lightweight structural material in transport applications. Since these may be subjected to serious environments, their corrosion behavior is major concern. The reason for the poor corrosion

resistance of magnesium and its alloys lies on two aspects: 1) the oxide films forming on surface are not perfect and protective; 2) galvanic or bimetallic corrosion can be caused by impurities or secondary phases [7]. The effect of microstructure on the corrosion resistance magnesium alloys containing aluminum and manganese or zinc (e.g. AM50, AZ91) has been widely reported [8-16].

Data concerning corrosion and electrochemical behaviour of Mg-RE-Zr alloys are scarce. However, the latter data seem to indicate that, in addition to favourable high temperature properties, certain Mg-RE alloys present good corrosion resistance. Unsworth [17] showed that WE54 alloy had a corrosion resistance comparable to that of A356 and A347 Al alloys in 28 day tests in sea water. Geary [18] measured a corrosion rate of  $0.4 \text{ mm/y}$  on WE43 in NaCl solution and

reported that this alloy had the lowest maximum pit depth of all the Mg alloys tested. Nakatsugawa [19] compared the polarization curves of AZ91D and different Mg-RE alloys, WE54 included, recorded in 5% NaCl solution saturated with  $\text{Mg}(\text{OH})_2$ . The authors deduced from the electrochemical impedance spectra that Mg-RE alloys have a corrosion resistance about four times higher than that of AZ91D. WE43 alloy has a corrosion rate comparable to that of WE54 alloy and lower than Elektron 21 magnesium alloy in NaCl solution [20]. The aim of the present work was to study the corrosion resistance of three magnesium alloys containing yttrium, neodymium and gadolinium.

## 2. Experimental

The studied samples were obtained from commercial WE43, WE54 and Elektron 21 magnesium alloys after casting (Tab. 1).

Table 1.  
Chemical composition (wt-%) of experimental alloys

Alloy	Y	Gd	Nd	RE	Zn	Zr
WE54	5.0	-	1.7	3.1	<0.01	0.55
WE43	4.0	-	2.4	3.3	<0.01	0.48
Elektron 21	-	1.2	2.7	4.2	0.4	0.49

The specimens ( $S \sim 15 \text{ cm}^2$ ) were exposed 7 days to 3.5% NaCl solution maintained at room temperature, without stirring. Before the tests, the specimens were polished with SiC papers up to 1200 grit. After cleaning with acetone and drying, they were weighed to obtain their original weight ( $m_0$ ) before corrosion. After immersion test, the corroded specimens were taken out of the solution, cleaned with distilled water and dried. They were then immersed in chromate acid ( $200 \text{ g/dm}^3 \text{ CrO}_3 + 10 \text{ g/dm}^3 \text{ AgNO}_3$ ) to remove corrosion products. After that, the specimens were cleaned again with distilled water, rinsed with acetone and dried. The specimens were weighed on an analytical balance to an accuracy of  $\pm 0.1 \text{ mg}$ . The dried specimens were weighed ( $m_1$ ) after immersion. The difference between  $m_0$  and  $m_1$  is the corrosion weight loss ( $\Delta m$ ). According to the test results, the corrosion rate was calculated. To reveal more details of the corrosion morphology at a higher magnification, Hitachi S-3400N SEM microscopy was used.

With increasing the exposure time from 1 day to 7 days, the corrosion rates increased linearly in all cases. At exposure time of 7 days, the corrosion rates of investigated alloys attained the

maximum value. WE43 alloy exhibits the lowest corrosion rate. The corrosion rate of WE43 was almost constant, and finally reached  $0.26 \text{ mg/cm}^2\text{day}^{-1}$  at exposure time of 7 days. It can be found that WE54 and WE43 both alloys possess close corrosion rates, although the corrosion rate of WE54 is relatively higher than WE43. At exposure time of 1 day, WE54 and WE43 showed similar corrosion rate, which was about  $0.25 \text{ mg/cm}^2\text{day}^{-1}$ . With increasing exposure time to 7 days, the corrosion rate of WE54 gradually increased, while that of WE43 almost remains unchanged. At exposure time of 7 days, the corrosion rate of WE43 alloy attained value  $0.62 \text{ mg/cm}^2\text{day}^{-1}$ , which was about two times greater than that of WE54. The corrosion rate for Elektron 21 alloy was three times greater than that of WE43 after 1 day of exposure and about five times greater after the end of immersion test.

## 3. Results

### 3.1. Microstructure of investigated alloys

Fig. 1a shows the microstructure of Elektron 21 observed by scanning electron microscopy. A eutectic structure was evident at the grain boundaries. EDS analysis showed that the eutectic phase was richer in gadolinium and neodymium than the matrix (points 1,2, Table 2). This phase can be  $\text{Mg}_9(\text{Gd},\text{Nd})$ . Microstructure of WE43 alloy (Fig. 2b) is composed of  $\alpha$ -Mg matrix, irregular precipitations contain mainly magnesium and neodymium (point 3). In this alloy rectangular, particles which are composed of magnesium, yttrium and small amounts of neodymium (point 4, Table 2) were observed. TEM study indicate, that the precipitations can be  $\text{Mg}_{41}(\text{Nd},\text{Y})_5$  and  $\text{Mg}_{24}(\text{Y},\text{Nd})_5$  [21]. Microstructural investigations of WE54 alloy (Fig. 2c) showed that this alloy is characterized by matrix with particles of Y-rich phase at grain boundaries and the grain interiors (points 5,6, Table 2).

### 3.2. Immersion corrosion test

Fig. 2 shows the typical surface features of the corroded specimens after different periods of immersion test. From the appearance of the specimen surface, Elektron 21 was more severely corroded than WE series alloys and the difference in corrosion damage is more evident after long periods of immersion time. The corrosion damage of WE series alloys exhibit

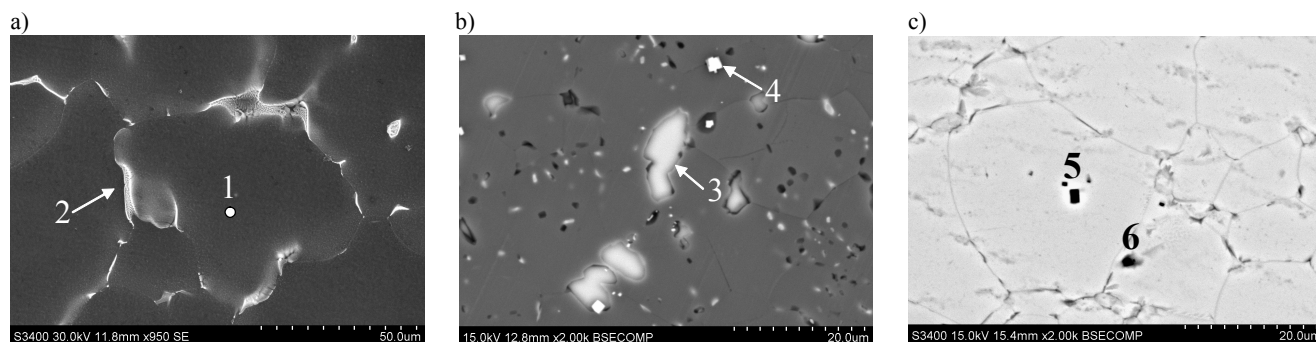


Fig. 1. Microstructure of investigated alloys; (a) Elektron 21, (b) WE43, (c) WE54

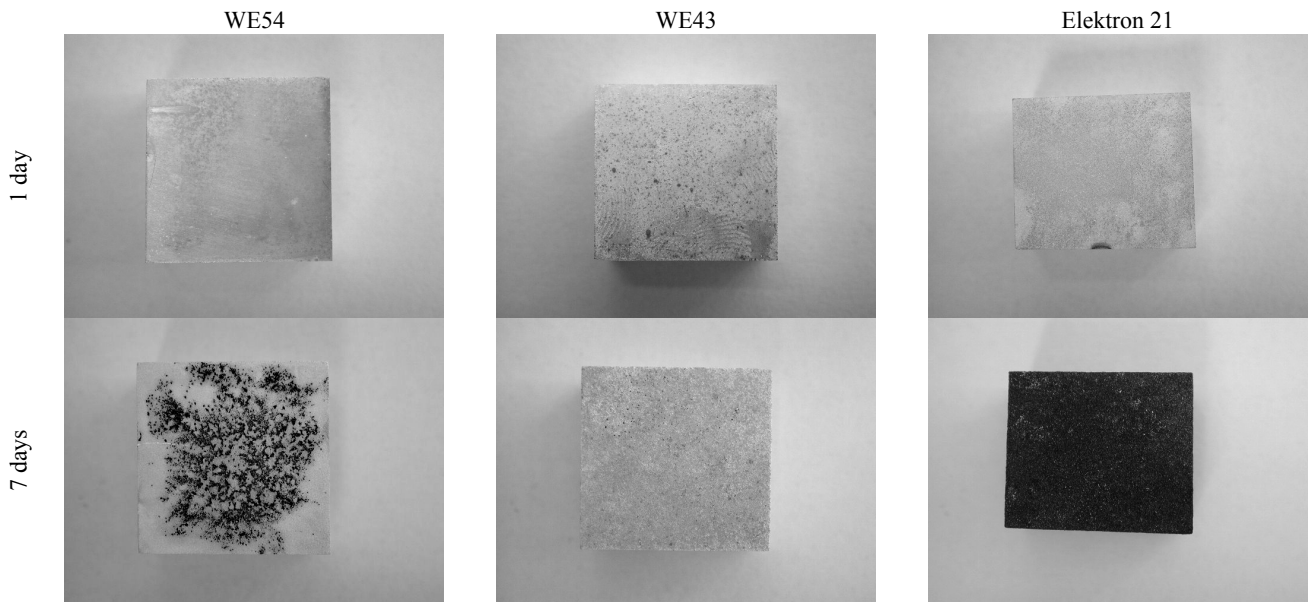


Fig. 2. Corrosion morphologies of WE54, WE43 and Elektron 21 alloys after 1-7 days of immersion test in 3.5% NaCl

similar behavior. The difference in macro-morphology of corroded specimens indicates different corrosion rates of investigated alloys. After one day of immersion in 3.5% NaCl, the corrosion damage only appeared on part of the surface of WE54 and Elektron 21 alloys. On the second day of immersion, clusters of deep pits on the surface of WE54 were observed. In case of Elektron 21 alloy, corrosion sources only appeared on some areas of the specimen. After seven days, serious corrosion damage occurred on WE54 and Elektron 21 alloys over all of its surface, whereas the corrosion of WE43 was only slight serious than after two days of immersion test. The comparison of the corrosion rates results obtained from immersion test in 3.5% NaCl are given in Fig. 3.

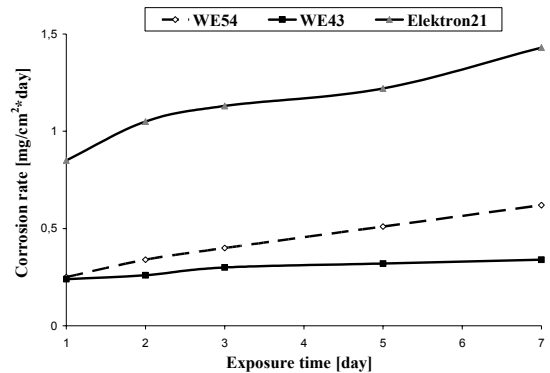


Fig. 3. Corrosion rates of WE54, WE43 and Elektron 21 alloys during immersion test in 3.5% NaCl

Table 2.

EDS results of points from Fig. 1 (% at.)

Point	Mg	Gd	Nd	Y
Point 1	99.0	0.2	0.8	-
Point 2	89.41	4.26	6.34	-
Point 3	92.77	-	6.22	1.02
Point 4	82.94	-	0.92	16.14
Point 5	37.10	-	-	62.90
Point 6	83.43	-	1.63	14.95

The micro-morphology of corroded specimen of Elektron 21 alloy is shown in Fig. 4, directly verifying the barrier effect of the eutectic phase. It can be seen that corrosion mainly occurred in the  $\alpha$ -Mg matrix. The precipitates of (Nd,Gd)-rich phase are stable in corrosion, and corrosion is confined by these precipitates. This is followed by the formation of an electrolytic cell in which the secondary phase particles are the cathode, and the surrounding Mg matrix is the anode. The corrosion products of this alloy are composed of magnesium, sodium and chlorine. [20]

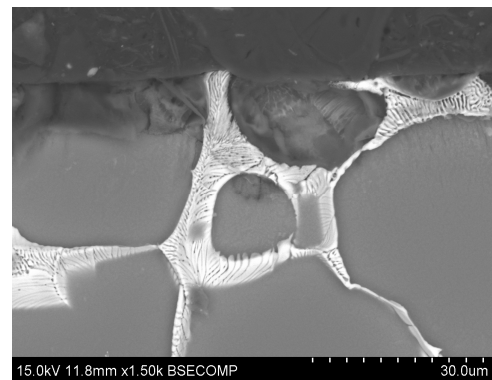


Fig. 4. Micro-morphologies of Elektron 21 specimen after immersion test in 3.5% NaCl

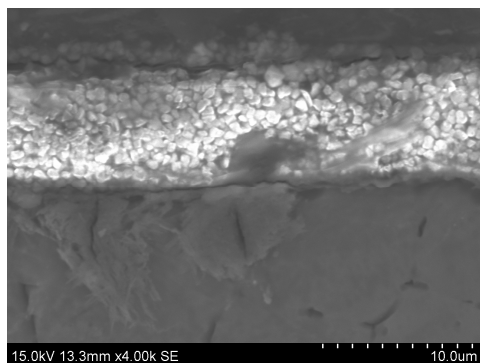


Fig. 5. Micro-morphologies of WE54 specimen after immersion test in 3.5% NaCl

In WE54 alloy corroded pits along grain boundaries were observed (Fig. 5). This suggested that grain boundaries of investigated alloy play special role in initiation of corrosion. These places are always the preferred sites at which precipitation and segregation in alloys occur. Corrosion film formed on the surface of specimen contains mainly sodium and chlorine [20]. Mechanism of corrosion in WE43 alloy was similar to that of WE54 alloy.

#### 4. Conclusions

Based on the research results obtained, it has been found that: 1) WE series alloys exhibit different corrosion behavior in 3.5% NaCl that Elektron 21 alloy., 2) The highest corrosion rate was observed for Elektron 21, which after 7 days of immersion achieve value  $1.43 \text{ mg/cm}^2\text{day}^{-1}$ , 3) WE54 and WE43 both alloys possess close corrosion rates, although the corrosion rate of WE54 is relatively higher than WE43, 4) The corrosion rate of WE43 alloy was almost constant, and finally reached value  $0.26 \text{ mg/cm}^2\text{day}^{-1}$ , 5) In Elektron 21 alloy pitting corrosion and anodic dissolution of  $\alpha$ -Mg matrix were observed. In WE54 and WE43 alloys intergranular corrosion was observed.

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