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The Influence of Casting Defects on Fatigue Resistance of Elektron 21 Magnesium Alloy

I. Pikos *, A. Kielbus, J. Adamiec

Faculty of Materials Engineering and Metallurgy, Silesian University of Technology,
Kraśińskiego 8, 40-019 Katowice, Poland

* Corresponding author. E-mail address: izabela.pikos@gmail.com

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Abstract

The Mg-RE alloys are attractive, constructional materials, especially for aircraft and automotive industry, thanks to combination of low density, good mechanical properties, also at elevated temperature, and good castability and machinability. Present paper contains results of fatigue resistance test carried out on Elektron 21 magnesium alloy, followed by microstructural and fractographical investigation of material after test. The as-cast material has been heat treated according to two different procedures. The fatigue resistance test has been conducted with 10^6 cycles of uniaxial, sine wave form stress between 9 MPa and 90 MPa. Fractures of specimens, which ruptured during the test, have been investigated with scanning electron microscope. The microstructure of specimens has been investigated with light microscopy. Detrimental effect of casting defects, as inclusions and porosity, on fatigue resistance has been proved. Also the influence of heat treatment's parameters has been described.

Keywords: Casting Defect, Mechanical Properties, Microstructure, Magnesium Alloy, Elektron 21

1. Introduction

The magnesium alloys are promising material for automotive and aircraft industry due to its satisfactory mechanical properties combined with low density. Good castability, machinability and possibility to recycling encouraged producers to develop new magnesium alloys with improved corrosion resistance and better properties at elevated temperature. Elektron 21 is a magnesium alloy containing Nd, Gd, Zn and Zr. Zn is responsible for improved hardness, tensile strength and elongation, Zr reduces microporosity of casts, provides good fatigue resistance also at elevated temperature and is responsible for grain refinement [1]. Nd and Gd are characterized by relatively high solid solubility in magnesium, which decreases exponentially with decreasing temperature, what provides suitable conditions for precipitation hardening. Therefore, addition of rare earth elements leads to

improved creep resistance and thermal stability of structure at elevated temperature [2, 3]. Microstructure of Elektron 21 magnesium alloy consists of α -Mg matrix with precipitations of $Mg_{12}(Nd, Gd)$ intermetallic phase on grain boundaries and fine precipitations of $Mg_3(Nd, Gd)$ phase [4]. Magnesium alloys are prone to oxidation during melting and pouring, what results in presence of impurities in material. The oxides, carbides and nitrides form by contact between atmosphere and melted metal and have been specified as α - Al_2O_3 , γ - Al_2O_3 , Al_4O_4C , Al_4C_3 . Furthermore, the magnesium alloys are prone to hydrogen adsorption and solution, what promotes porosity formation [5].

2. Material and methodology

Investigated material was sand casting Elektron 21 magnesium alloy containing 2.6-3.1% Nd, 1-1.7% Gd, 0.2-0.5% Zn and saturated Zr.

Table 1.

Heat treatment applied on investigated material

Sample	Solutioning	Ageing
E1	525°C+/-5°C/8h/water quenching	200°C/16h/air cooling
E2		250°C/16h/air cooling

Table 2.

Results of fatigue resistance test

Heat treatment	Sample	Amount of cycles before rupture
E1	1	1 000 000
	2	1 000 000
E2	1	60 000
	2	149 995

The casts have been heat treated, according to the table 1, by solutioning followed by water quenching and ageing followed by air cooling. Samples for fatigue resistance test have been prepared in shape of cylindrical rods according to PN-74/H-04327 norm.

Fatigue resistance test has been conducted according to PN-76/H-04325 and PN-74/H-04327 norm. Test was based on a uniaxial, cyclic tensile stress with a sine wave form, described by average stress $\sigma_m = 49,5$ MPa, the maximum stress $\sigma_{max} = 90$ MPa and the minimum stress $\sigma_{min} = 9$ MPa. Test consisted of 10^6 cycles.

Samples after fatigue resistance test have been investigated. Fractures of specimens, which ruptured during test, have been analyzed using stereoscope Olympus SZX9 and scanning electron microscope Hitachi S-3400N (SEM) with a Thermo Noran EDS spectrometer. Microstructure has been observed on microsections cut out perpendicularly to axis of applied stresses. Microsections have been prepared, according to standard procedure, by grinding with abrasive papers and polishing with diamond pasts. Final polishing has been done using $0,25 \mu\text{m}$ Alumina paste. Acetic glycol has been used as an etchant. The light microscope Olympus GX71 (LM) and SEM have been used for observations.

3. Results

3.1. Fatigue resistance test

In the case of samples E1 the test results have been satisfactory. Both investigated specimens did not rupture before accomplishing 10^6 cycles of fatigue resistance test. However, none of samples heat treated according to E2 heat treatment endured full amount of cycles. Both of them ruptured before the test was finished (table 2).

3.2. Fractures

Fractures arose during fatigue tests in samples E2 have been investigated. Fractographical observations revealed casting defects present in microstructure. Fig. 1. presents the examples of fracture with clearly visible inclusions and impurities. The casting defects are numerous and visible without magnification. In the fracture some small defects are present in the inner section of specimen and one bigger inclusion is present on the edge of specimen. The big inclusion is the area of fracture initiation, what

can be proved by fact that in the fractures of each studied specimens the big inclusion on the edge of specimen was present. The inclusions present in inner section of specimen are less prone to developing rupture due to the fact that crack growths mainly under vacuum conditions [6]. Furthermore, the porosity, revealed in fracture E2, can be also the fracture initiator (Fig. 2a). The pores can cause the notch effect with local stress concentrations and enable crack initiation at low applied stresses [6]. The presence of casting defects significantly contribute to decreased fatigue resistance.

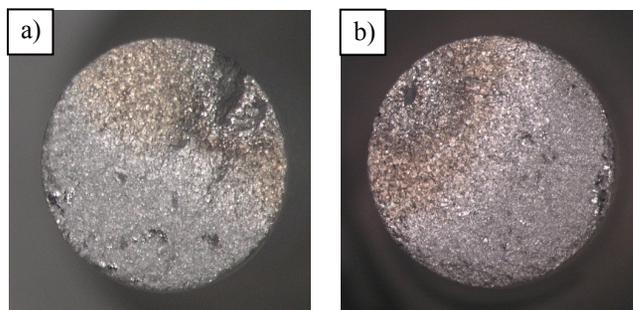


Fig. 1. Examples of fracture surfaces, sample E2-1 (a), sample E2-2 (b)

The fracture surfaces have mainly brittle, transcrystalline character. However intercrystalline areas and ductile areas are also present, mainly in the close vicinity to main inclusion, as a consequence of local overload (Fig. 2b). The twins, which are shown in Fig. 2c, have been also noticed. The striations, which are characteristic for fatigue fractures, have not been found in investigated material.

3.3. Microstructure

Microstructure revealed by etching in acetic glycol consists of homogenous grains, massive phase on grain boundaries (Fig. 3, pointed by black arrow) and Zn- and Zr-enriched areas in the centers of grains (Fig. 3, pointed by white arrow). Samples E1, observed by LM, exhibit monochromatic grains, whereas samples E2, etched in the same conditions, exhibit polychromatic grains (Fig. 4,5b). This phenomenon can be explained by precipitation of coherent β'' and semi-coherent β' phase in sample E1 during

ageing treatment conducted at 200°C, while the incoherent β phase precipitates in sample E2 aged at 250°C.

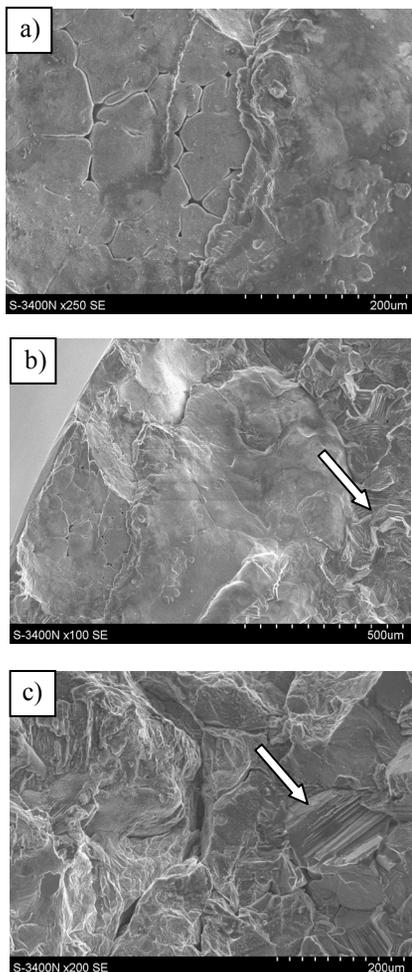


Fig. 2. SEM image of fracture surface, sample E2, porosity in area of fracture initiation (a), intercrystalline fracture in the close proximity to inclusion (pointed by arrow) (b), transcrystalline fracture surface with twins (pointed by arrow) (c)

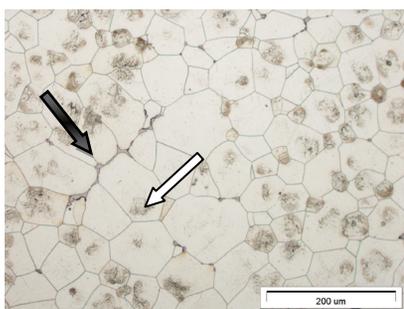


Fig. 3. Microstructure of sample E1, LM, black arrow points massive phase on grain boundaries, white arrow points Zn- and Zr- enriched zones

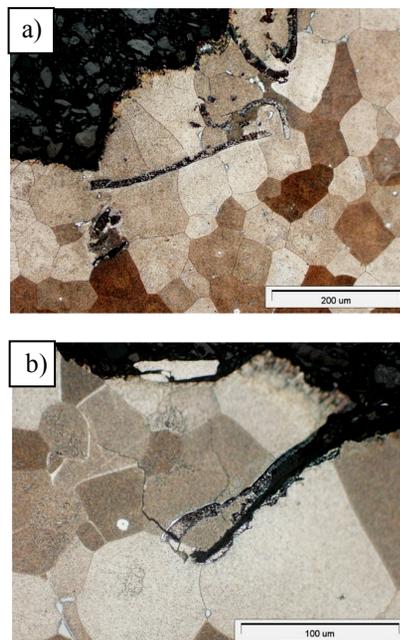


Fig. 4. Microstructure and inclusions near the fracture in sample E2, LM

Coexistence of coherent β'' and semi-coherent β' phase is responsible for peak hardness and properties of material, while the presence of β phase is responsible for deterioration of properties and hardness of material [7]. The microstructure of samples E1, which endure full amount of fatigue cycles, does not include any microcracks and pores. Also inclusions and metallurgical impurities have not been found (Fig. 3).

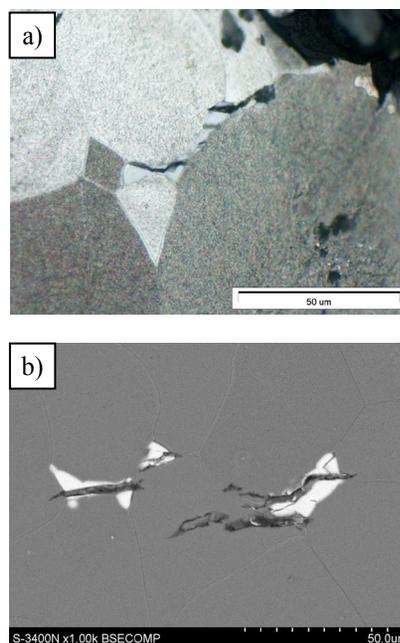


Fig. 5. Microcracks in massive phase on grain boundaries, sample E2, LM (a), SEM (b)

In the microstructure of samples E2 the numerous microcracks, mostly on massive phase, are present (Fig. 5). Microcracks are prone to merging, mainly across the grains and developing into major cracks.

In close proximity to the fracture the large impurities containing oxygen are present. According to EDS analysis the impurities can be specified as a magnesium and zirconium oxides. Some of them are also cracked (Fig. 4,6). Impurities, which contributed to material decohesion are mainly in the border area of specimen.

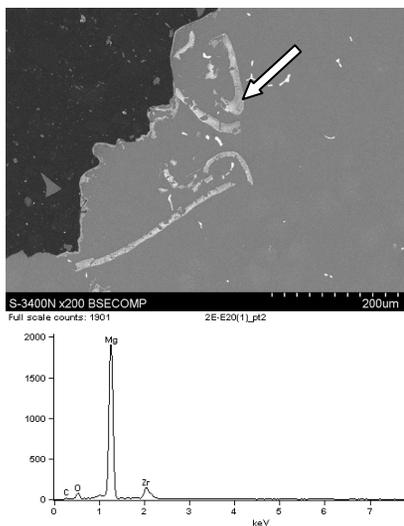


Fig. 6. EDS analysis of impurities, narrow points the area of analysis

4. Summary

1. Material E1 heat treated by solutioning (525°C/+/- 5°C/8h/water quenching) and ageing (200°C/16h/air cooling) exhibited satisfactory fatigue resistance. Samples endured 10^6 cycles of uniaxial stresses applied with amplitude 40,5 MPa.

2. Material E2 heat treated by solutioning (525°C/+/- 5°C/8h/water quenching) and ageing (250°C/16h/air cooling) did not exhibit proper fatigue resistance. Investigated samples ruptured after 60 000 cycles and ca. 150 000 cycles of fatigue test.

3. Microstructural observations revealed differences between E1 and E2 material. Monochromatic effect of etching in samples E1 could be evidence for precipitation of coherent β'' phase and semi-coherent β' phase, which are responsible for peak of hardness and mechanical properties of material. Microstructure of samples E2, etched with the same procedure, revealed polychromatic grains effect, what can be evidence for precipitation of incoherent β phase during ageing at 250°C. Presence of incoherent β phase causes deterioration of mechanical properties, so can also contribute to insufficient fatigue resistance.

4. Fractographical investigation revealed numerous casting defects in fractures arose during fatigue test in samples E2. Porosity and inclusions located near the edge of specimen are the areas of fracture initiation. The fracture is mostly transcrystalline with small areas of intercrystalline and ductile character. The twins have been found, while the striations have not been found. EDS analysis lead to magnesium and zirconium oxides identification. Microstructural observations revealed also numerous microcracks in samples E2, mostly in brittle, massive phase on grain boundary and in oxide inclusions. Microstructure of samples E1 did not include any microcracks, even on massive phase, and any inclusions of oxides.

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