The influence of magnesium alloy AE42 test specimens deformation magnitude on their microstructure

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Abstract. It is known that the properties of metals and their alloys depend on their microstructure. An important aspect of microstructure study is the ability to predict the properties and the behavior of the material in the process of its exploitation taking into account determined structural changes and their relationship with the material properties. The goal of this work is to study the effect of the magnitude of the plastic deformation on the microstructure of magnesium alloy AE42 test specimens. This paper describes the actions to get test specimens with various magnitude of residual deformation. The microstructure of those test specimens is studied. The gathered results are discussed.

1. Introduction
The magnesium alloys find increasingly wider application in automotive industry, aircraft building industry, production of electronic devices, etc. [1].

The magnesium is the lightest structural metal, much lighter than steel, which is the most used material with industrial application. Unfortunately the magnesium alloys, available to the industry, are expensive. To produce automotive structural components, forming operations at high temperatures are required due to ductility problems of the magnesium alloys. This is the reason for the high cost of magnesium automotive parts. After a lot of resources were invested in research in the last twenty years, it has been discovered that the addition of rare-earth elements in small quantities can be a potential solution to achieve better ductility of magnesium alloys [2]. The most commonly used magnesium alloys which contain rare-earth elements are AE42 and AE44 [3].

The use of magnesium alloys is often limited by their high electrochemical activity and low corrosion resistance. The corrosion behavior of the metallic materials is highly dependent on their microstructure. The change of this microstructure under the influence of various factors may lead to changes in the corrosion behavior of a given alloy due to a change in the dimensions of metal grains, the borders of the grains, change in the distribution of intermetallic particles and others. The effect of the change of the microstructure of magnesium alloys on their corrosion behavior hasn’t been systemically studied [1].

The microstructure of metal alloys can be affected by the influence of mechanical deformations, especially during the processes of forming metal parts using plastic deformation and in the cases when the material is subjected to stress higher than the elastic limit stress during its service life at ambient temperature. In the case of ductile materials, the yield stress $R_{0.2}$ can be accepted for allowed stress. That is why it is interesting to study the influence of the magnitude of plastic deformation on the microstructure of AE42 magnesium alloy test specimens as a part of wider study of corrosion resistance of magnesium alloys.
2. Experimental

AE42 is the representative of Mg-Al-RE system, which is in the group of high-pressure die casting (HPDC) alloys and are particularly attractive for mass production [4]. The chemical composition of the studied alloy is given in table 1.

Table 1. Chemical composition of the studied AE42 magnesium alloy, (wt %).

|     |  Al  |  Ce  |  Mn  |  Zn  |  Cu  |  Ni  |  Fe  |  other |
|-----|------|------|------|------|------|------|------|--------|
|     | 3.6 – 4.4 | max. 2.5 | min. 0.1 | max. 0.02 | max 0.04 | max 0.001 | max 0.004 | 0.01   |

2.1 Preparing of test specimens with various magnitude of residual deformation

In order to determine the mechanical properties of the studied magnesium alloy, tensile tests have been carried out at ambient temperature using modernized testing machine ZD10 with lead screw loading mechanism and numeric control [5], which assures precise loading in accordance with EN ISO 6892-1:2016.

Four test specimens were subjected to pure tension until their fracture, while continuously the values of the applied force and longitudinal deformation were recorded. The fracture of the test specimens occurs outside their gauge length – figure 1a. In table 2 the gathered results for the following parameters are given:

- Tensile strength \( R_m \) – the stress corresponding to the maximum force, which the test specimen can bear during testing;
- Proof strength, plastic extension \( R_{p,0.1} \) – the stress, under which the relative percentage extension is equal to 0.1%;
- Proof strength, plastic extension \( R_{p,0.2} \) – the stress, under which the relative percentage extension is equal to 0.2%.

Figure 1. Test specimens.
Table 2. Mechanical properties of the studied AE42 magnesium alloy.

| Test specimen No | $R_m$, MPa | $R_{p0.1}$, MPa | $R_{p0.2}$, MPa |
|------------------|------------|----------------|----------------|
| 1                | 203        | 98             | 121            |
| 2                | 209        | 94             | 118            |
| 3                | 205        | 97             | 119            |
| 4                | 210        | 99             | 123            |
| Average          | 207        | 97             | 120            |

Four test specimens are loaded until $R_{p0.1}$ is reached, after that the load is removed. Four test specimens are loaded until $R_{p0.2}$ is reached, then the load is removed. Four test specimens are not subjected to any load.

Four sets of 4 test specimens each are produced. The first set contains 4 non-loaded test specimens, the second set contains 4 test specimens loaded up to $R_{p0.1}$, the third set contains 4 test specimens loaded up to $R_{p0.2}$ and the fourth set contains 4 test specimens loaded up to $R_m$.

From the gauge length of each test specimen 4 smaller test specimens are cut (figure 1b). Thus from each set 16 test specimens are collected (15 test specimens for corrosion tests and one for microstructure study).

Each test specimen, intended for microstructure study is split in 2 smaller test specimens – figure 1c.

2.2 Microstructure study

Test specimens with various magnitude of deformation are packed in acrylic resin. The studied cross-sections have been cleaned up with a series of sand papers followed by mechanical polishing. The microstructure is developed for 5s at room temperature using an etching solution with the following composition: 20ml CH$_3$COOH, 1ml HNO$_3$, 60 ml ethylene glycol and 20 ml H$_2$O.

The microstructure was studied by optical observations using inverted metallographic microscope Optika XDS-3MET with built-in camera for digital photography.

3. Results and discussion

Figs. 2-4 show the typical etched microstructure of unloaded and loaded to various magnitude of deformation test specimens. It can be concluded, that a serious difference exist in the microstructure in the core of the specimen and in the vicinity of the surface of the test specimen, even in the case of unloaded specimens (figure 2). A narrow band that follows a contour parallel approximately to the surface divides the specimen into two different regions.

3.1. Regions in the vicinity of the edges of the test specimens

In the vicinity of edge A (close to the surface) of the cross-sections (figure 1) of the test specimens, the size of the grains decreases. Areas with different microstructure are seen (figure 2). Bands with dendritic structure can be found as well as segregations of intermetallic phase.

The occurrence of areas with different microstructure is a feature of high-pressure die castings of Mg alloys and is called skin effect [6, 7]. Due to the very high rate of heat extraction (rapid cooling), the surface layer (skin) of Mg die-castings has a very fine microstructure with very small (<0.5 μm) α-Mg grains and a higher volume fraction of the intergranular eutectic β-Mg$_{17}$Al$_{12}$ phase. This results in a hard surface layer, which can have a significant effect on the mechanical properties of the casting [6].

Changes due to the various degree of loading are apparent mainly in the areas near the edges B of the cross-sections of the test specimen (figure 3). In the test specimen loaded up to $R_{p0.1}$ elongation of the α-phase grains can be seen. In the test specimen loaded up to $R_{p0.2}$ this elongation is greater, while in the test specimen loaded up to $R_m$ micro-fractures are seen. The fracture is trans-crystal and probably starts from the line between α and β phases.
Figure 2. Microstructure along edge A of the cross-section of the test specimen:
(a) non-loaded; (b) loaded up to $R_{p0.1}$; (c) loaded up to $R_{p0.2}$; (d) loaded up to $R_m$.

Figure 3. Microstructure along edge B of the cross-section of the test specimen:
(a) non-loaded; (b) loaded up to $R_{p0.1}$; (c) loaded up to $R_{p0.2}$; (d) loaded up to $R_m$.

3.2. Areas of the core of the studied specimens

The microstructure of non-loaded specimen consists of two phases: $\alpha$-Mg matrix and eutectoid (intermetallic) phase [3, 8 - 11]. In the core of the cross section the structure is homogenous in respect to the grain size. The grains of the $\alpha$-phase are equiaxial and 5 to 10 $\mu$m in diameter. The eutectic distribution along the $\alpha$-phase grain boundary is uniform, but separate aggregations (about 5 $\mu$m in diameter, figure 4a) are present.

According to the literature, in the presence of rare-earth (RE) elements in the alloy, even though the $\text{Al}_{11}\text{RE}_3$ phase, mainly located at the grain boundaries of the (Mg) matrix, potentially, there are many different phases that may form, such as the $\text{Mg}_{17}\text{RE}_2$, $\text{Mg}_2\text{RE}$ or $\text{Mg}_3\text{RE}$ phases. However, it is not clear which one, or in which form, these phases will nucleate under given solidification conditions [12]. The intermetallic phase could content not only $\text{Mg}_{17}\text{Al}_{12}$, but also $\text{Mg}-\text{Ce}$ [3, 10], or $\text{Al}_{11}\text{Ce}_3$ [3], or $\text{Al}_2\text{Ce}$ and $\text{Al}_{11}\text{Ce}_3$ [11]. The eutectic has mostly lamellar structure. The lamellas consist of $\alpha$ and $\beta$-phases, but there are also areas with prevailing $\beta$-phase in which $\alpha$-phase grains are enclosed.

In the core of the test specimen loaded up to $R_{p0.1}$, the microstructure consists of $\alpha$ and $\beta$-phases. Most of the $\alpha$-phase grains are equiaxial, but bigger grains with irregular shape are also present (figure 4b). The intermetallic phase is formed along the $\alpha$-phase grain boundary forming separate bigger clusters compared to the non-loaded test specimen.
In the test specimen loaded up to $R_{p0.2}$ the structure is not significantly changed due to the loading and consists of $\alpha$ and $\beta$-phases. Here, formation of clusters of the $\alpha$-phase with irregular shape also can be seen. They are larger when compared with the test specimen loaded up to $R_{p0.1}$ (figure 4c).

Generally, the microstructure of the loaded to $R_m$ specimen is similar, the formation of larger grains (clusters, about 20 $\mu$m in diameter) is apparent. The intermetallic phase grains also recombine in a bigger clusters.

4. Conclusion

With the increase of the magnitude of deformation changes in the microstructure of the alloy occur. Next to the surface, the skin effect is clearly seen. In the core of the studied cross-sections of the test specimen segregation of the metallic grains of $\alpha$-phase occurs and formation of larger clusters with the increase of the deformation magnitude. Full explanation of the observed effects could be obtained with more detailed study and using of other methods of examinations.

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