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THERMOPHYSICAL PROPERTIES AND MICROSTRUCTURE OF MAGNESIUM ALLOYS OF THE Mg-Al TYPE

TERMOFIZIKALNE LASTNOSTI IN MIKROSTRUKTURA MAGNEZIJEVIH ZLITIN TIPA Mg-Al

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Generally speaking, magnesium alloys of the Mg-Al type are used as structural materials, but their disadvantage lies in their low heat resistance. The addition of suitable alloying elements can be positive, as it makes it possible to achieve good thermo-mechanical properties. For the application of a specific material for thermally stressed cast parts it is necessary to consider the extent of their linear and volumetric changes at elevated and high temperatures. The aim of this paper is to study the behaviour of selected magnesium alloys based on Mg-Al during heat stress conditions in order to simulate real conditions using dilatometric analyses. These properties were evaluated on samples of alloys prepared by gravity casting in metallic moulds. The effect of the metallurgical processing of the alloys on the studied parameters was also investigated.

Keywords: castings, magnesium alloys, thermophysical properties, microstructure

V splošnem se zlitine Mg-Al uporabljajo kot konstrukcijski materiali, toda njihova pomanjkljivost je, da imajo majhno toplotno odpornost. Dodatek ustreznih zlitinskih elementov pozitivno vpliva na izboljšanje njihove toplotne stabilnosti oz. odpornosti. Pri uporabi nekega materiala, ki bo toplotno obremenjen, moramo upoštevati njegove linearne in volumenske spremembe pri povišanih in visokih temperaturah. Namen tega prispevka je študij vedenja izbranih Mg-zlitin tipa Mg-Al med toplotnimi obremenitvami, da bi tako simulirali njihovo vedenje v realnih razmerah. Njihovo vedenje smo analizirali z dilatometričnimi analizami na vzorcih zlitin, ki so bili izdelani z gravitacijskim litjem v kovinskih modelih. Raziskovali smo tudi vpliv metalurških procesov na izbrane zlitine.

Ključne besede: ulitki, magnezijeve zlitine, termofizikalne lastnosti, mikrostruktura

1 INTRODUCTION

Aluminium is the main alloying element in magnesium alloys. Mg-Al based alloys belong to the most widely used group for the foundry industry and they are the oldest of the foundry magnesium alloys. Aluminium is one of the few metals that easily dissolves in magnesium. These alloys may also contain additional alloying elements (e.g., Si, Mn, Zr, Th, Ag, Ce). Their properties are the result of a relatively large area of the solid solution δ in the equilibrium diagram of a Mg-Al alloy and by the possibility of their alloying also with other elements. The most common alloys contain 7–10 % of Al.[1]

Alloys containing more than 7 % Al are hardenable, and during their hardening a discontinuous precipitate of the $Mg_{17}Al_{12}$ phase is formed, the alloys are usually alloyed with small quantities of zinc and manganese. An increasing aluminium content significantly increases the solidification interval and thus also the width of the two-phase zone. Such alloys have during gravity casting a strong tendency to form micro-shrinkages and shrinkage porosities. For this reason the content of Al in the alloys for gravity casting does not exceed 5 %. A brittle intermetallic $Mg_{17}Al_{12}$ phase is formed above the solubility limit. The limit of solubility of aluminium at the eutectic temperature is at the amount fraction $x = 11.5$ % (mass fraction, $w = 12$ %), and approximately 1 % at room temperature. As a result of this, the $Mg_{17}Al_{12}$ phase plays a dominant role and it decides what the properties will be.[2,3]

2 PROPERTIES OF MAGNESIUM ALLOYS AT ELEVATED TEMPERATURES

The use of magnesium alloys in the automotive industry is currently limited to several chosen applications (such as car dashboard, steering wheel, structure of seats, etc.).[4] The alloys used in these applications are based on the Mg-Al system, for example the series AM and AZ. The alloys based on the Mg-Al system are on an industrial scale the most acceptable from the perspective of economics. These alloys offer a good combination of strength and ductility at room temperature. Another advantage is their good corrosion resistance and excellent pourability. The main areas of the increasing use of Mg alloys for car manufacturers are such components as gear boxes and engine blocks. These applica-

Table 1: Chemical composition of the used magnesium alloys
Tabela 1: Kemijska sestava uporabljenih magnezijevih zlitin

alloy	Element, *w*/%									
	Zn	Al	Si	Cu	Mn	Fe	Ni	Ca	Be	Sr
AZ91	0.56	8.80	0.06	0.004	0.20	0.004	0.001	0.000	0.001	0.00
AM60	0.07	5.78	0.03	0.001	0.33	0.003	0.001	0.000	0.001	0.00
AMZ40	0.14	3.76	0.02	0.001	0.34	0.003	0.000	0.000	0.001	0.00
AJ62	0.01	5.78	0.04	0.001	0.35	0.003	0.001	0.008	0.001	2.92

tions require exploitation in operating conditions at a temperature of 150–200 °C. Commercial magnesium alloys of the type AM and AZ do not have these properties, this is related to their poor mechanical properties at elevated temperatures,[5] and the cause is the low structural stability, and thus the creep resistance. Developments in this area brought about the introduction of new alloys, i.e., Mg-Al-Sr (AJ) and Mg-Al-RE (AE). Magnesium alloys alloyed with rare-earth metals, which do not contain aluminium, are in the long term recognised as one of the most resistant to creep. From the viewpoint of the use of castings made from Mg-alloys at elevated temperatures the volumetric and linear changes of the material are also critical. Their magnitude is determined, among other things, by the chemical composition and by the microstructure of the material (e.g., by presence and share of individual phases, by grain size).

3 DESCRIPTION OF USED ALLOYS

For the experimental evaluation both commonly used alloys AZ91, AM60, AMZ40 and the AJ62 alloy were used. All the compared materials were supplied by a Czech manufacturer and **Table 1** shows their chemical composition according to the supplier's certificate.

4 PREPARATION OF THE TEST SAMPLES

Magnesium alloys were melted in an electric resistance furnace in a metal crucible made from low-alloyed steel. Magnesium alloys are highly reactive thanks to the high affinity of magnesium for oxygen. For this reason the material was treated during melting with an agent having the trade mark EMGESAL. This material in a form of covering and refining flux served for limiting the alloy oxidation and for cleaning the melt of possible inclusions. The castings were produced by gravity casting into the ingot mould made of cast iron, which was prior to pouring pre-heated to a temperature of 450 °C ± 30 °C in order to extend its service life and to achieve sufficient fluidity of the metal. Casting temperatures and operating temperatures were kept in a narrow range in order to achieve as high as possible limitation of the influence of different cooling effects. Part of the melt was treated metallurgically by an agent with the commercial designation MIKROSAL MG T 200, which was based on hexachloretane, and which introduced into the melt the nuclei for crystallisation to achieve the fine-grained structure. This was followed by the manufacture of samples from the castings for an evaluation of the microstructure, as well as samples for a determination of the thermo-physical properties, and test samples for the metallographic analyses.

5 MICROSTRUCTURE OF THE CAST SAMPLES

The microstructure of the AZ91 alloy is shown in **Figure 1**. It is a structure with a share of eutectics and with a significant share of the $Mg_{17}Al_{12}$ phase. The addition of the forced crystallisation nuclei did not have any significant effect on this material (**Figure 2**). A large share of plate-type precipitates is also evident. **Figure 3**

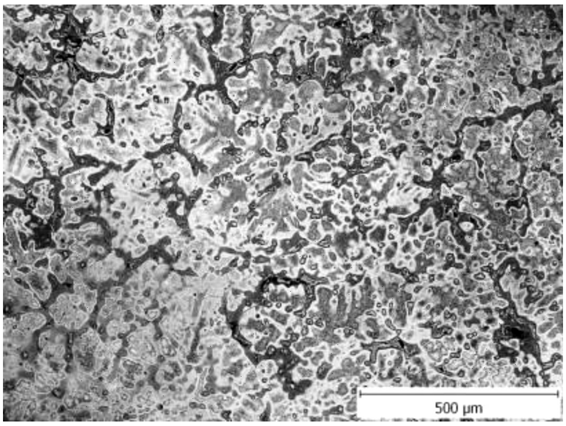

Figure 1: Non-inoculated material AZ91
Slika 1: Necepljena zlitina AZ91

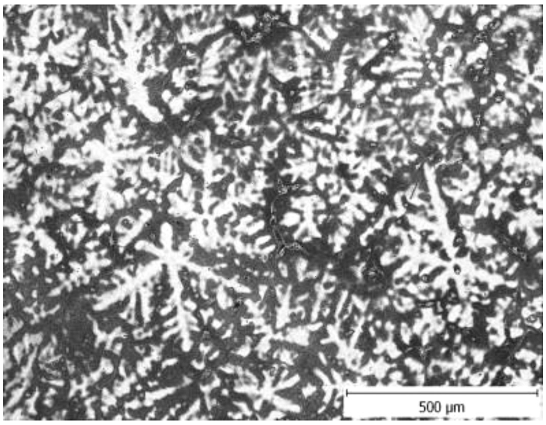

Figure 2: Inoculated material AZ91
Slika 2: Cepljena zlitina AZ91

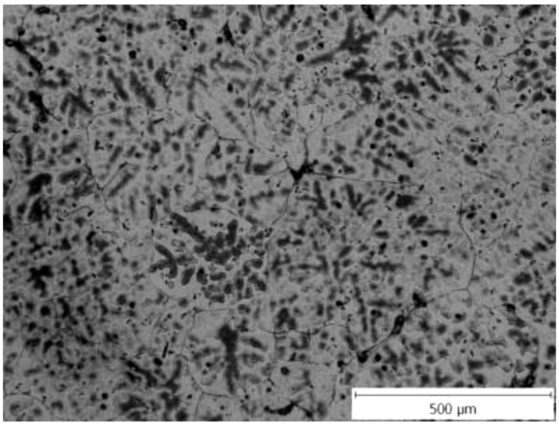

Figure 3: Non-inoculated material AM60
Slika 3: Necepljena zlitina AM60

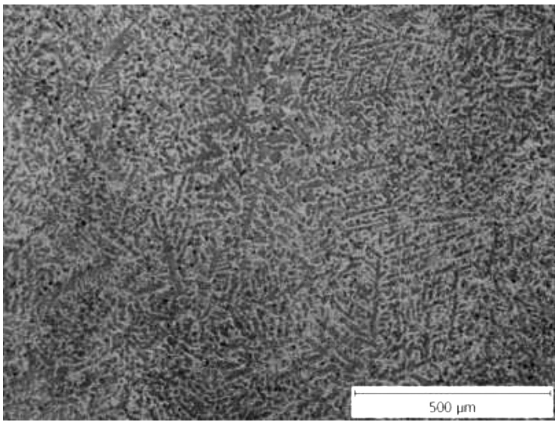

Figure 4: Inoculated material AM60
Slika 4: Cepljena zlitina AM60

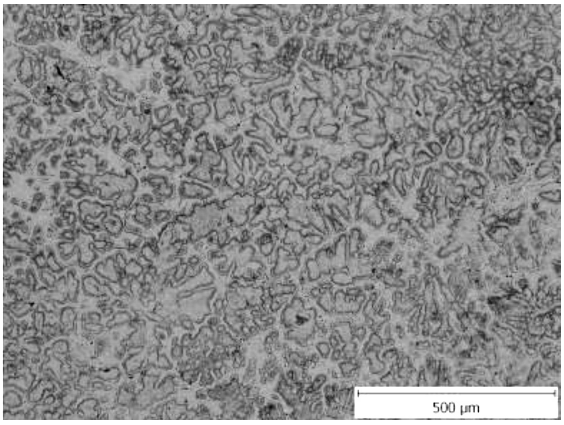

Figure 5: Non-inoculated material AMZ40
Slika 5: Necepljena zlitina AMZ40

shows the microstructure of the AM60 alloy, which consists of a matrix containing a solid solution of α-Mg, a secondary phase of Al-Mn compounds and eutectics. **Figure 4** illustrates the structure of the AM60 alloy after the metallurgical treatment (inoculation). The structure is much finer, and its homogeneity was generally improved, which means that it is possible to achieve better mechanical properties.

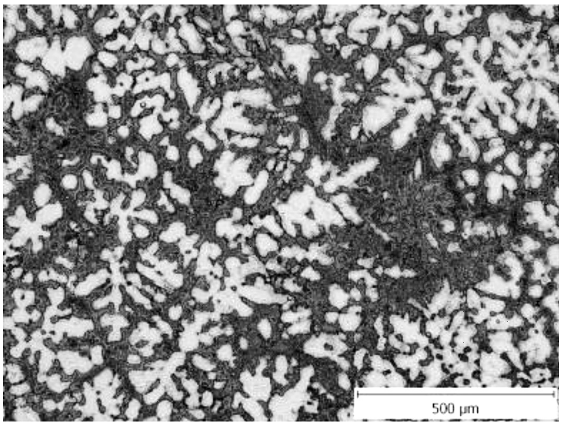

Figure 6: Inoculated material AMZ40
Slika 6: Cepljena zlitina AMZ40

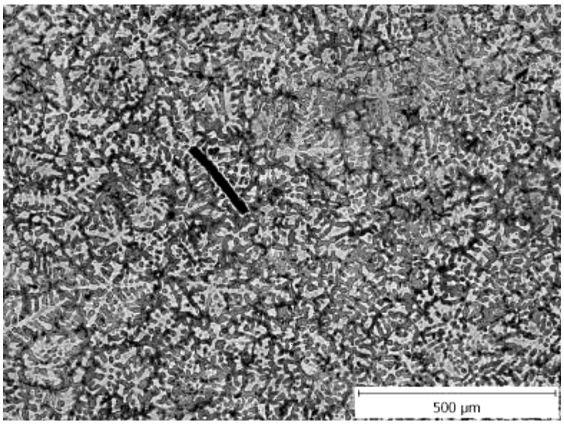

Figure 7: Non-inoculated material AJ62
Slika 7: Necepljena zlitina AJ62

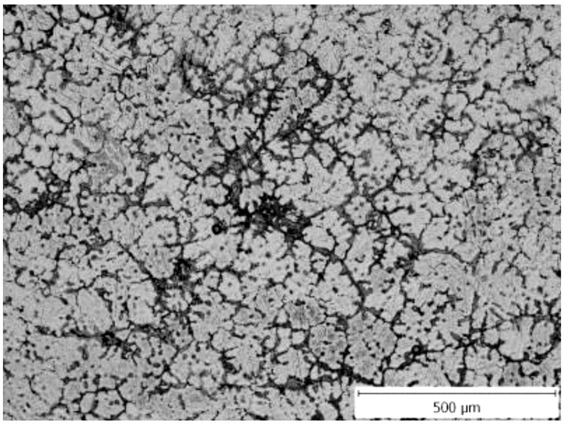

Figure 8: Inoculated material AJ62
Slika 8: Cepljena zlitina AJ62

The effect of inoculation was not manifested in the achieved structure of the AMZ40 alloys (**Figures 5** and **6**). This alloy is characterised by the low content of alloying elements; its structure is formed by the primary α-Mg phase and by eutectics without the presence of precipitates.

Figures 7 and **8** show the microstructure of the alloy AJ62, consisting of the basic solid solution α, as well as several types of intermetallic phases, i.e., (Al, Mg)$_4$Sr, Al$_3$Mg$_{13}$Sr and very small quantity of Mn$_5$Al$_8$. In the case of the inoculated alloy (**Figure 8**) it is possible to find some differences; it is, however, impossible to identify unequivocally the finer structure.

6 MEASUREMENT OF THE PHYSICAL PROPERTIES

Dilatometric analyses were performed in order to verify the behaviour of the materials at elevated temperatures. Use of the given material for thermally stressed components is related, among others, to the dimensional stability of the cast part.

Heat expansion (Equation (1)) of the material is usually characterised by the mean temperature coefficient (coefficient of linear expansion):

$$\alpha_\mathrm{T} = \frac{l_\mathrm{T} - l_\mathrm{T0}}{l_\mathrm{T0}(T - T_0)} = \frac{1}{l_0}\left(\frac{\mathrm{d}l}{\mathrm{d}T}\right) \tag{1}$$

where:
α_T – coefficient of linear heat expansion
l_0 – sample length under reference (e.g. laboratory) temperature
dl – change of the sample length
dT – difference in temperatures.

The linear heat expansion was measured on the above-described samples with use of a Netzsch DIL 402C/7 dilatometer. The experiments ran in the temperature interval from (20 ± 5) °C up to 350 °C with heating and cooling rates of 15.0 K/min, with a holding time of 30 min at the maximum temperature (isotherm) in a protective argon atmosphere (99.9999 % Ar) with a constant gas flow of 20 mL/min. The size of the used samples was as follows: a mean length of 20 mm and a mean diameter of 6 mm. Samples of the non-inoculated (marked in the name of the sample – as "non") and inoculated materials (marked as "in") were divided into two groups. The first group was used in the as-cast state without previous heat stressing and the second one after their heat stressing (250 °C, 30 min) in the argon atmosphere for checking the influence of the increased temperature during the stressing of the castings in real conditions.

Table 2 contains the results of the measurements of the coefficient of linear heat expansion (α_T) for the chosen temperature interval ((20 ± 5) °C up to 350 °C). The table gives the values for the samples without heat stressing (T_lab) and after heat stressing (250 °C, 30 min) – T_{250}. **Figures 9** and **10** show the greatest change of length under a temperature of 350 °C (max $l_{350\ °\mathrm{C}}$).

Table 2: Overview of thermophysical parameters of the Mg alloys
Tabela 2: Pregled toplotno-fizikalnih parametrov Mg-zlitin

Specimen	T_lab	T_{250}
	$\alpha_T \times 10^{-6}$/K^{-1}	$\alpha_T \times 10^{-6}$/K^{-1}
AZ91 non	29.6319	27.7702
AZ91 in	28.8887	27.3736
AM60 non	28.7385	26.2843
AM60 in	26.2465	26.0252
AMZ40 non	28.2639	18.1402
AMZ40 in	17.3364	17.1782
AJ62 non	28.8727	26.1917
AJ62 in	18.1686	17.5744

In the as-cast state, the highest absolute value of α_T (28.8727 × 10^{-6}) was achieved for the AZ91 alloy, and the lowest (17.3364 × 10^{-6} was achieved for the AMZ40 alloy after its metallurgical treatment. It is possible to find from the measured values a correlation between the measured value of the coefficient of linear thermal dilatation and the addition of the inoculant. The structure influenced by the inoculation shows substantially lower values of α_T.

A similar effect was observed in the thermally stressed samples of the magnesium alloys. In these cases the achieved values of the coefficient of linear thermal expansion were also the highest in the AZ91 alloy, followed by the AJ62 alloy, while the lowest values were achieved in the AMZ40 alloy.

The values of the maximum length change achieved at the temperature of 350 °C also correspond with these

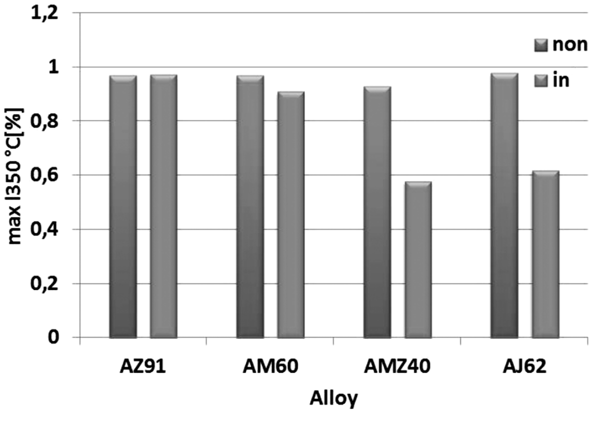

Figure 9: Thermal expansion of material without heat stress
Slika 9: Toplotni raztezek zlitin brez toplotne obremenitve

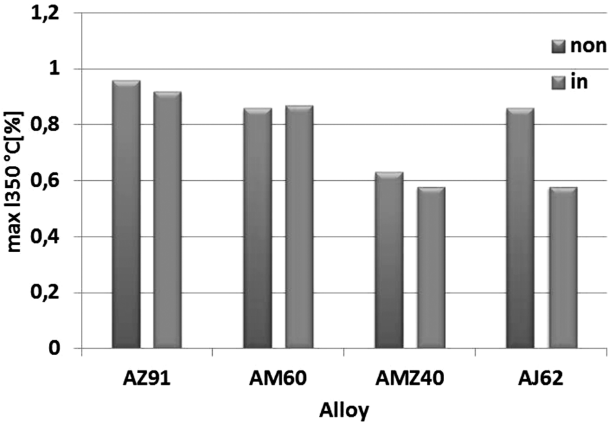

Figure 10: Thermal expansion of material after heat stress
Slika 10: Toplotni raztezek zlitin po toplotni obremenitvi

results. The positive impact of the inoculation was unequivocally demonstrated here, particularly in the case of the AMZ40 alloy. In case of the samples without thermal stressing (**Figure 9**) it was possible to note a considerable difference between the non-inoculated and inoculated materials. On the other hand, in the case of the thermally stressed samples (**Figure 10**), this difference is much smaller. It is therefore possible to assume a distinct influence of a possible heat treatment on these properties.

7 CONCLUSIONS

This study was focused on an evaluation of the thermophysical properties and microstructure of the magnesium alloys AZ91, AM60, AMZ40 and AJ62. On the basis of the realised experiments, it is possible to see a positive impact of the inoculation on the achievement of the smaller dilations of materials, which are important from the perspective of the use of casting for heat-stressed parts. The lowest values of the coefficient of linear thermal expansion and the maximum value of expansion at the temperature of 350 °C were achieved with samples of the alloys AJ62 and AMZ40, which were metallurgically processed. Despite the high cooling effect of the metallic mould, the positive effect of inoculation on the evaluated properties and microstructure of majority of the magnesium alloys were visible.

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