

# Effect of Inhibitor Coating of a Ceramic Mould on the Surface Quality of an AM60 Alloy Cast with Cr and V

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## Abstract

The work presents the results of the investigations of the effect of inhibitors coated on the internal walls of a ceramic mould on the quality of the obtained casts made of the AM60 alloy containing additions of chromium and vanadium. In order to reduce the reactivity of magnesium alloy cast by the technology of investment casting with the material of the mould and the ambient atmosphere, solid inhibitors were applied in the form of a mixture of  $KBF_4$  and  $H_3BO_3$  after the stage of mould baking and before the mould's being filled with the liquid alloy. For the purpose of examining the effect of the inhibitors on the surface quality of the obtained casts, profilometric tests were performed and the basic parameters describing the surface roughness,  $R_a$ ,  $R_z$  and  $R_m$ , were determined.

**Keywords:** Innovative materials and technologies, Surface roughness, Magnesium alloys, Solid inhibitors, Investment casting

## 1. Introduction

Magnesium alloys are usually cast by the technology of pressure casting and in the recent years, the method of investment casting has also been used for this purpose, which involves the use of ceramic moulds reacting with magnesium and its alloys [1-7]. Due to the reactions occurring at the boundary metal-mould, the produced casts exhibit surface defects.

The surface defects of the magnesium alloy casts produced by special techniques according to the Polish standard PN-H-83105:1985 include, among others: roughness, metal penetration, blisters, creases, sand buckles, crushes, partial melting, impurities etc.

The causes of the presence of those defects are connected with:

- improper cast structure,
- faulty structure or workmanship of the model,
- inappropriate moulding material,
- inappropriate workmanship of the mould,
- improper alloy preparation,
- badly-selected conditions for mould filling,
- inappropriately performed striking, cleaning and finishing of the cast.

However, the most frequent cause of the mentioned defects is the mould (inappropriate moulding material, improper workmanship) as well as the conditions of the mould filling.

In order to evaluate the roughness of the cast surface, the following basic parameters of surface roughness are used, according to the PN-EN ISO 4287:1999 standard:

- mean arithmetical deviation of surface roughness  $R_a$ ,  $\mu\text{m}$ ,
- ten-point height of irregularities  $R_z$ ,  $\mu\text{m}$ ,
- maximal peak to valley height  $R_m$ ,  $\mu\text{m}$ .

For a general determination of the roughness, it is better to apply the parameter  $R_a$ , whereas for the evaluation of a local area, the parameters  $R_z$  and  $R_m$  (maximal peak to valley height) are recommended. The degree of the cast's surface roughness depends on the type of the cast, but above all on the mould technology, the atmosphere in the mould and the liquid alloy's parameters before the mould filling.

Magnesium is a highly reactive element [8, 10, 14]. It reacts with most of the elements present in the air. The main chemical substances and compounds used as inhibitors in magnesium casting are [1÷3]:

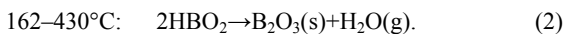
- potassium tetrafluoroborate  $\text{KBF}_4$ ,
- sodium tetrafluoroborate  $\text{NaBF}_4$ ,
- sulphur S,
- boric acid  $\text{H}_3\text{BO}_3$ ,
- ammonium fluorosilicate  $(\text{NH}_4)_2\text{SiF}_6$ ,
- sodium fluorosilicate  $\text{NaSiF}_6$ ,
- ammonium bifluoride  $\text{NH}_4\text{HF}_2$ ,
- combinations of the above.

Up till now, few papers have been published describing the effect of inhibitors in magnesium casting which applies the investment casting method.

According to the research performed by Cingi C., the application of  $\text{KBF}_4$  as an inhibitor in magnesium precision casting in ceramic moulds has not provided the expected results [4]. While a slight increase of the cast quality has been reported, these results are far from satisfactory. The reason for this has probably been the unconsidered location of  $\text{KBF}_4$  as an inhibitor, the latter having dissolved and damaged the protective surface of the mould during the baking stage.

The present work discusses the results of the investigations of the surface quality of a  $\text{MgAl6MnVCr}$  alloy cast in the case when an innovative method is used, which consists in applying a solid inhibitor in the form of a mixture of  $\text{KBF}_4$  and  $\text{H}_3\text{BO}_3$  after the stage of mould baking and before the mould's being filled with the liquid alloy.

The products of the thermal decomposition of the solid inhibitors  $\text{KBF}_4$  and  $\text{H}_3\text{BO}_3$  change the ambient atmosphere inside the mould. Under the influence of the temperature,  $\text{H}_3\text{BO}_3$  undergoes dehydration within the following respective temperature ranges [1]:



$\text{KBF}_4$ , in turn, under the effect of the temperature within the range of 300–400°C, undergoes decomposition [1]:



with the following possible reactions in the presence of Mg [10, 13]:



## 2. Test methodology

The  $\text{MgAl6Mn}$  alloy (AM60) with the addition of chromium and vanadium equaling 0.1% each, characterizing in elevated mechanical properties [5] was melted in a laboratory crucible resistance furnace with the capacity of 5 kilograms - S235JRG2 PN-EN 10025-2:2005 steel crucible. Inside the furnace, a protective gaseous atmosphere was applied consisting of a mixture of argon and sulphur hexafluoride with the pressure of  $0.15 \div 0.20$  MPa. The gas flow equaled, respectively:

- 10  $\text{cm}^3/\text{min}$  for  $\text{SF}_6$ ,
- 500  $\text{cm}^3/\text{min}$  for Ar.

Due to the high tendency of the additions (chromium and vanadium) for gravitational segregation, before the mould filling, the alloy was intensely stirred in the crucible.

The experimental casts in the shape of cylinders, with the solidification modulus  $M=1.29$  cm, were obtained in ceramic moulds made according to the investment casting technology. The moulds were made of refractory materials REFRACOARSE (flour and sands). Seven mould coatings were made in the mixers and the fluidizer at the foundry „Armatura” Łódź, Poland. Each coating was created as a result of applying a binder on the wax model, followed by the coating being covered with a refractory material REFRACOARSE of a certain granularity [7]. After the ceramic mould had dried, the moulding sand was melted at the temperature of 960°C in the autoclave of a tunnel furnace and next cooled down to the ambient temperature. The mould prepared in this way then impregnated with an aqueous saturated solution of  $\text{H}_3\text{BO}_3$  and  $\text{KBF}_4$  for 20 s or 40 s, respectively. Next, the mould was dried by being heated up to the temperature of 180°C.

The filling of the ceramic mould prepared in this way with the liquid metal was performed at the temperatures of  $800^\circ\text{C} \pm 5^\circ\text{C}$  and  $740^\circ\text{C} \pm 5^\circ\text{C}$ , respectively.

The profilometric tests were conducted by means of the contact profilometer Hommel Tester T1000. The measurements were implemented on selected surface fragments of the casts and the moulds. The roughness tests were performed by the tracer method (shifting of a diamond needle on the examined surface). Three surface roughness parameters were investigated:  $R_a$ ,  $R_z$  and  $R_m$ .

## 3. Discussion of results

### 3.1. Characteristics of cast and mould surface

Figure 1 (a–h) shows macro- and microscopic images of the representative surface of the  $\text{MgAl6MnCrV}$  alloy cast and the mould, for different conditions of the casting technology (pouring temperature: 800°C and 740°C) and the mould preparation for

being filled with the liquid alloy (mould: without an solid inhibitor and with a solid inhibitor). The MgAl6MnCrV alloy cast, made at 800°C, characterizes in numerous defects, which cause the lack of homogeneity of the external surface. The latter includes metal penetrations, sand buckles, impurities and tarnishes (Fig. 1a). These defects are caused by the intense reactions of the alloy, rich mostly in magnesium, with the components of the mould (SiO<sub>2</sub>, Al<sub>6</sub>Si<sub>2</sub>O<sub>13</sub>, other) and the ambient atmosphere (O<sub>2</sub>, CO<sub>2</sub>, other). The Mg reactions with the mould and the ambient atmosphere components take place on the surface

and next they penetrate into the cast, which, in consequence, reduces the healthy surface by about 36.0 μm (Fig. 1b). The products of the Mg reaction can adhere to the cast or the mould (Fig. 1 a, c). The ceramic mould is disposable, yet the quality of its surface after the cast has been knocked out carries a series of information about the thermochemical processes taking place in it during the liquid alloy casting as well as the processes of its solidification.

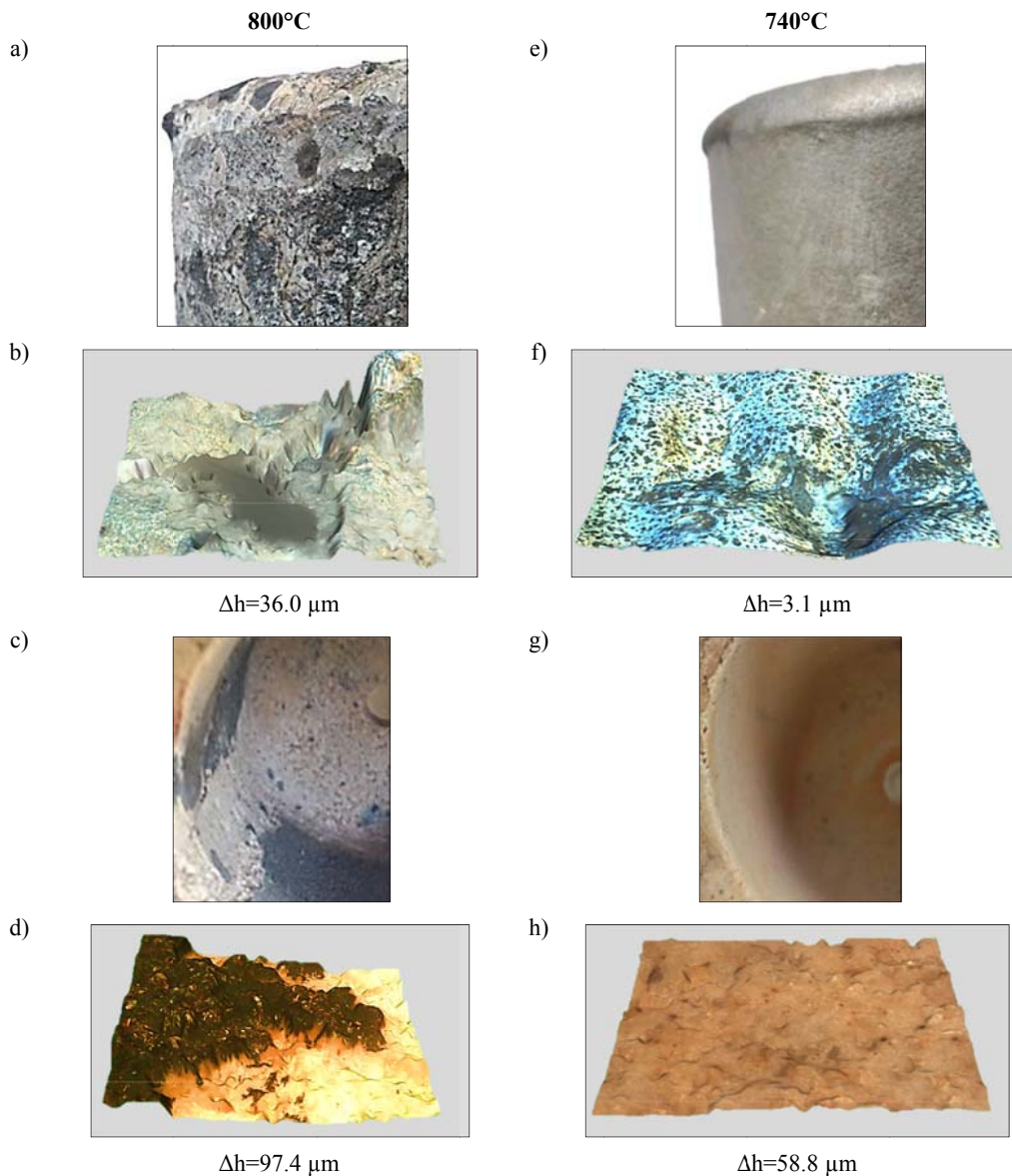


Fig. 1. Representative surface of the MgAl6MnCrV alloy cast and the mould: casting temperature: 800°C (a–d), 740°C (e–h); unsaturated mould (c, d), mould saturated for 20 s (g, h)

These processes take place mostly on the surface of the ceramic mould, after it has been filled with the liquid alloy, and they significantly degrade its quality. The difference in height  $\Delta h$

between the maximal caving of the mould's surface and the maximal elevation of the surface of the products of the magnesium reaction adhering to the mould's surface equals about

97.4  $\mu\text{m}$  (Fig. 1d). The quality of the magnesium alloy cast can be significantly improved mostly by way of lowering the mould filling temperature. However, an important issue is also the castability of the alloy in the case of thin-walled casts. That is why the mould filling temperature should be lowered in such a way so as to maintain the proper castability for the characteristic geometry of the cast.

A much better quality (homogeneity) of the cast's external surface (Fig. 1e) was obtained after lowering the temperature (740°C) of pouring the alloy into the ceramic mould with a solid inhibitor (accumulated mostly on the surface shaping the cast as well as in its pores). The Mg reactions with the components of the mould and the ambient atmosphere took place in a much smaller area and, in consequence, they reduced the healthy surface of the cast by about 3.1  $\mu\text{m}$  (Fig. 1f). Small amounts of the products of the Mg reaction (Fig. 1g) with the components of the mould and the ambient atmosphere were observed on the surface of the mould.

The difference in height  $\Delta h$  between the maximal caving in the surface of the mould and its maximal elevation equals about 58.8  $\mu\text{m}$  (Fig. 1h). The irregularities in the mould's surface are mainly caused by the stresses in the prime coat produced by:

- inhomogeneity of the first ceramic coating applied on the wax model,
- mould baking process – rate of temperature elevation and temperature height,
- degree of the pores being filled with the solid inhibitor,
- pressure of the gases formed by the thermal decomposition of the inhibitors during the heating of the mould to 180°C and its filling with the liquid alloy.

### 3.2. Cast and mould surface roughness

Figure 2 shows the roughness parameters  $R_a$ ,  $R_z$  and  $R_m$  of the MgAl6MnCrV alloy cast and the mould (without (Fig. 2a) and with the inhibitor (Fig. 2b)). The high casting temperature 800°C favours intense reactions of Mg with the components of the mould and the ambient atmosphere. They occur on the external surface of the cast and then proceed into its deeper areas. The solid products of these reactions have a porous structure and adhere relatively strongly to the metal surface of the cast. After their elimination, the cast's surface characterizes in high values of the parameters  $R_a \approx 11 \mu\text{m}$ ,  $R_z \approx 60 \mu\text{m}$  and  $R_m \approx 81 \mu\text{m}$  (Fig. 2a). After the solid inhibitors had been introduced onto the surface and into the pores of the mould, these parameters were lowered (Fig. 2b) by about:  $\delta R_a \approx 4 \mu\text{m}$ ,  $\delta R_z \approx 20 \mu\text{m}$  and  $\delta R_m \approx 9 \mu\text{m}$ , respectively. It is characteristic for the high temperature of the MgAl6MnCrV alloy casting to obtain lower values of the parameters describing the roughness of the mould's surface after the cast has been knocked out of it than in the case of the surface of the cast. This proves that the Mg reactions with the components of the mould and the ambient atmosphere are the most intense at the beginning stage of the process of the liquid alloy cooling after it has been poured into the mould, before a continuous layer of a solidified metal is formed at the boundary cast/mould. That is why the products of the chemical reactions of magnesium with the components of the mould and the ambient atmosphere are forced into the, cooling and then solidifying, metal, causing high roughness of the cast's surface.

The presence of the inhibitor on the surface of the mould shaping the cast, and especially in the pores of the mould, causes an increase of the parameters describing its roughness after the cast has been knocked out (Fig. 2 a,b):  $\delta R_a \approx 2 \mu\text{m}$ ,  $\delta R_z \approx 3 \mu\text{m}$  and  $\delta R_m \approx 3 \mu\text{m}$ . This is caused not only by the thermal stresses themselves but also, probably, by the thermal decomposition of the inhibitors into gaseous compounds, which, because of their high pressure at the stage of formation during the mould's heating up to 180°C and its filling with the liquid alloy, cause an additional increase of the stresses in the top layer of the mould and its more intense spalling.

Lowering the casting temperature down to 740°C significantly reduced the intense reaction of Mg with the components of the mould and the ambient atmosphere. This mostly lowered the values of the roughness parameters of both the cast and the mould. Figure 3 shows the roughness parameters  $R_a$ ,  $R_z$  and  $R_m$  of the MgAl6MnCrV alloy cast and the mould (without (Fig. 3a) and with the inhibitor (Fig. 3b)), characteristic for the casting temperature 740°C. After the cast had been knocked out of the mould, defects in the form of  $\leq 4 \text{ mm}$  diameter metal penetrations and burn-ons, distributed locally, were observed on its surface. After they had been eliminated, the surface of the cast characterized in the following values of the roughness parameters:  $R_a \approx 4 \mu\text{m}$ ,  $R_z \approx 24 \mu\text{m}$  and  $R_m \approx 28 \mu\text{m}$  (Fig. 3a).

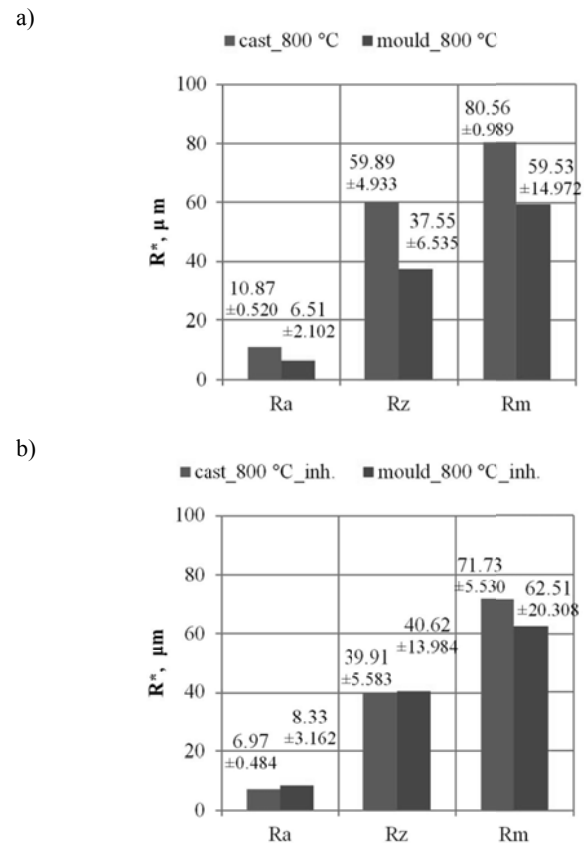


Fig. 2. Parameters of surface roughness  $R_a$ ,  $R_z$ ,  $R_m$  of the MgAl6MnCrV alloy cast and the mould, casting temperature: 800°C: a) mould without inhibitors, b) mould with an inhibitor

After introducing the solid inhibitors onto the surface and into the mould's pores, the parameters were decreased (Fig. 3b) by about:  $\delta R_a \approx 1 \mu\text{m}$ ,  $\delta R_z \approx 4 \mu\text{m}$  and  $\delta R_m \approx 6 \mu\text{m}$ , respectively. On the surface of the cast, micro-penetrations were visible, with the linear dimensions below  $1 \mu\text{m}$  (Fig. 1f).

The presence of the inhibitor on the surface of the mould shaping the cast, and especially in the mould's pores, causes an increase of the parameters describing its roughness after the cast has been knocked out (Fig. 3a, b) by:  $\delta R_a \approx 2 \mu\text{m}$ ,  $\delta R_z \approx 12 \mu\text{m}$  and  $\delta R_m \approx 19 \mu\text{m}$ , respectively. This is caused by the significantly lower thermal stresses in the top layer of the mould than in the case of the casting at  $800^\circ\text{C}$  as well as the thermal decomposition of the inhibitors into gaseous compounds, which intensifies its spalling.

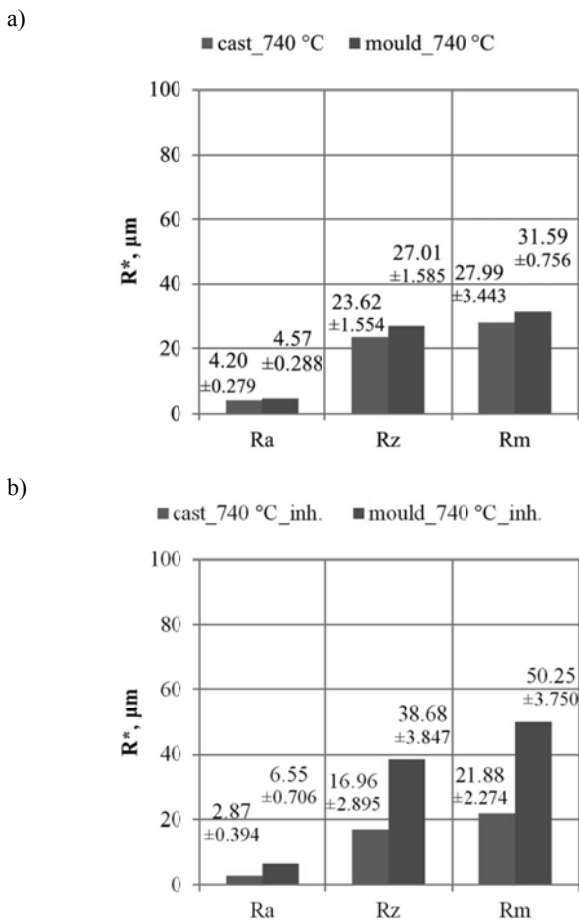


Fig. 3. Parameters of surface roughness  $R_a$ ,  $R_z$ ,  $R_m$  of the MgAl6MnCrV alloy cast and the mould, casting temperature:  $740^\circ\text{C}$ : a) mould without inhibitors, b) mould with an inhibitor

## 4. Summary

The performed investigations verify the necessity of applying a possibly low casting temperature and of the presence of inhibitors in the material of the mould, in the case of magnesium alloys. In order to maintain the homogeneity of the external surface of the cast, without surface defects, the inhibitors are especially needed on the surface of the mould shaping the cast. As a result of the presence of inhibitors in the mould's pores, it undergoes additional stresses during its heating to  $180^\circ\text{C}$  and the dehydration of  $\text{H}_3\text{BO}_3$  and  $\text{HBO}_2$  according to reactions (1) and (2), as well as during its filling with the liquid alloy at a high ( $800^\circ\text{C}$ ) and a low temperature ( $740^\circ\text{C}$ ), the stresses being caused by the formation of gaseous products of the inhibitor  $\text{BF}_3$  decomposition according to reaction (3). From the point of view of the quality of the mould's surface, this decomposition affects it negatively. On the other hand, the formed compounds (gaseous and solid - reactions (3) and (4)) limit the magnesium's reactions with the mould's material.

Figure 4 shows a comparative compilation of the percentage change of the values of the surface roughness parameters, for the MgAl6MnCrV alloy cast at  $800^\circ\text{C}$  and  $740^\circ\text{C}$ , for the casts produced in a mould without inhibitors as well as one with inhibitors (a) and the moulds (b), as well as the roughness parameters of the cast (a) and the mould (b) at the given temperature.

Lowering only the casting temperature of the examined alloy from  $800^\circ\text{C}$  to  $740^\circ\text{C}$  reduces the roughness parameters of the cast within the range of about 28–47%, and in the case of applying the solid inhibitors on the surface of the mould shaping the cast, the reduction is in the range of about 58–70% (Fig. 4a). At the same time, lowering the casting temperature and pouring the alloy into a mould with inhibitors lowered the roughness parameters of the cast within the following ranges: from  $10.87 \mu\text{m}$  to  $2.87 \mu\text{m}$  for  $R_a$ , from  $59.89 \mu\text{m}$  to  $16.96 \mu\text{m}$  for  $R_z$  and from  $80.56 \mu\text{m}$  to  $21.88 \mu\text{m}$  for  $R_m$ .

Lowering only the casting temperature from  $800^\circ\text{C}$  to  $740^\circ\text{C}$  reduces the roughness parameters of the mould to a smaller degree than in the case of the cast, within the range of about 28–47%, and when the solid inhibitors are applied on the surface of the mould shaping the cast – within the range of about 5–21% (Fig. 4b). At the same time, lowering the alloy's casting temperature and its pouring into a mould with inhibitors did not change the roughness parameters of the mould  $R_a$  and  $R_z$ , while lowering the mean value of  $R_m$  from about  $60 \mu\text{m}$  to about  $50 \mu\text{m}$ .

Lowering the roughness of the raw surfaces of the precision magnesium alloy casts causes the following:

- increase of the wear resistance,
- increase of the corrosion resistance,
- increase of the fatigue strength,
- increase of the thermal and electric conduction,
- increase of the accuracy in the cooperation between the mechanical elements.

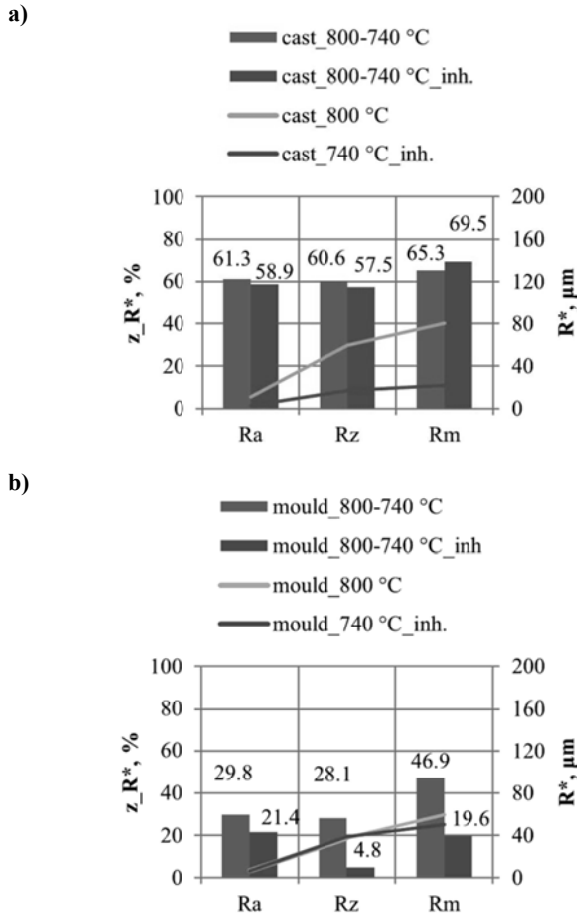


Fig. 4. Percentage change  $z_R^*$  of the values of the surface roughness parameters  $R_a$ ,  $R_z$ ,  $R_m$  of the MgAl6MnCrV alloy cast (a) made in a mould without and with inhibitors (b), cast at: 800°C and 740°C and the roughness parameters of the cast (a) and the mould (b) at the given temperature

## 5. Conclusions

With the purpose of obtaining magnesium alloy casts of high homogeneity of the external surface and its low roughness parameters  $R_a \approx 3 \mu\text{m}$ ,  $R_z \approx 17 \mu\text{m}$  and  $R_m \approx 22 \mu\text{m}$ , by the investment casting process, one should:

- apply a possibly low casting temperature 740°C, (guaranteeing the proper castability for the cast's geometry),
- apply solid inhibitors on the surface shaping the cast in the form of a mixture of  $\text{KBF}_4$  and  $\text{H}_3\text{BO}_3$  after the baking of the mould,
- heat the mould coated with the inhibitor mixture up to 180°C directly before the mould is filled with the liquid alloy.

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