INFLUENCE OF MODIFICATION OF ALUMINUM ALLOYS ON THEIR THERMAL EXPANSION

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Abstract. The change in the dimensions of a component with the change in temperature is described by a quantity called thermal elongation. It is one of the basic properties of every material and it is necessary to take it into account when designing a specific component for a given application. Sometimes higher thermal elongation is considered a positive property, but in most applications, there is an effort to reduce the magnitude of thermal elongation with increasing temperature. Incorrect design can result in component failure or destruction. The following research includes the two most important aluminum sub-eutectic Al-Si alloys, namely AlSi7Mg0.3 and AlSi7Mg0.6 used in the automotive and aerospace industries. They were chosen due to their very good technological and mechanical properties. The silicon content in these alloys is 5-3% by weight. The alloys will be analyzed and their elongation curves will be measured in the temperature range -14 to 400 ºC and the morphology of the structure. To further improve the structure, grains and thus the resulting properties, the modification of alloys with strontium or AlSr10, titanium inoculation with AlTi5B1 and, last but not least, heat treatment - hardening and subsequently a combination of these individual treatments will be used. Again, a morphological analysis will be performed to determine the changes in the structure after individual treatments and to measure the dilatation of the treated alloys in a given temperature range and to measure the coefficient of thermal elongation. The achieved measured results will be compared to determine the appropriate treatment of alloys to reduce the overall coefficient of thermal elongation, or to reduce the coefficient of thermal elongation for a certain temperature range.

Keywords: aluminum alloys, dilatation, modification, metal casting.

Introduction

When casting metal, it heats up and cools. The temperature change is accompanied by a change in the volume of the material, ie its elongation during heating and its shrinkage during cooling. These changes must be taken into account both in the design of the molds and in the subsequent life cycle of the cast part, so that the dimensional change during component heating does not cause the component to fail or the machine to crash (for example, internal combustion engine piston seizures, etc.). The shrinkage of the metal must be taken into account when designing the molds and the mold cavity. The final component depends on the use and function of the product and in most cases it is necessary to take into account both shrinkage on cooling and elongation during heating, and it is therefore necessary to know these volume changes of a particular alloy.

Metal casting is associated with phase transformations, when there is a step change in the volume of the metal, namely an increase in volume during melting and a decrease in volume (shrinkage) during solidification (crystallization). In general, the volume change of a metal can be described with the change in temperature by the coefficient of volume expansion, see equation (1). The coefficient of volume expansion is also temperature dependent [1; 2].

$$\gamma = \frac{\Delta V}{V_0 \Delta T}, \quad (1)$$

where γ – coefficient of thermal elongation, K^{-1};
ΔV – volume change, m^3;
V_0 – initial volume, m^3;
ΔT – temperature change, K.

Other factors that need to be distinguished are alloy shrinkage, ie the change in alloy volume caused by temperature change and casting shrinkage, which is affected by the casting technology, casting temperature, casting design, etc. [3]

In practice, metal alloys are most often used due to their better properties compared to pure metals. The most important alloys include Al-Si alloys, i.e. silumine. Silumines are often used for their good technological and mechanical properties. The advantage is especially the low density and thus the resulting low weight in comparison with the achieved strength, which is used in the automotive or aerospace industry and it is very beneficial to develop knowledge about the behavior of these types of alloys.

The technological and mechanical properties of Al-Si master alloys can be further improved by suitable modifications, such as seeding, crystal size adjustment, modification that change the shape of the silicon grains to increase ductility, or heat treatment.

The following research deals with the dependence of elongation on temperature change and the determination of the coefficient of thermal elongation, which is dependent on temperature. The research is focused only on the analysis of the solid state of the alloy (shrinkage of the alloys during the change of state is not included here). The test specimens are analyzed on a LINSEIS DIL 75 V vertical dilatometer. The temperature range of the measurement is in the temperature range -14 to 400 ºC.

Two Al-Si alloys were selected for the research, namely AlSi7Mg0.6 and AlSi7Mg0.3. The AlSi7Mg0.6 alloy was further inoculated with titanium, modified with strontium and hardened. AlSi7Mg0.3 alloy was only hardened.

Al-Si foundry alloy treatment and morphology

AlSi7Mg0.6 alloy was chosen as the main master alloy, which was subsequently supplemented with AlSi7Mg0.3 alloy to extend the analyzes. The master alloys were analyzed in the untreated state and further after modifications.

- Without modification.
- Titanium inoculation.

The commonly used Alti5B1 master alloy was used for titanium inoculation. The amount of titanium was determined to be 0.15% [4-6].

- Strontium modification.

Strontium modification was performed using AlSr10 master alloy. The amount of strontium was determined to be 0.04% [4-7].

- Heat treatment (hardening).

Hardening was chosen for the heat treatment, both for the untreated alloy and for the inoculated and modified. The solution annealing temperature was set at 535 ºC for 1 hour. Subsequently, the alloy was cooled to 50 ºC water. Furthermore, artificial aging took place at a temperature of 180 ºC for 8 h [4; 5].

- Titanium inoculation + curing.
- Strontium modification + curing.

A general overview of the tested samples and their modifications is shown in Table 1.

Table 1

Modifications of Al-Si alloys

Alloy Al-Si	Without modification	Ti inoculation	Sr modification	Hardening	Ti inoc. + hardening	Sr mod. + hardening
AlSi7Mg0.6	X	X	X	X	X	X
AlSi7Mg0.3	X	-	-	X	-	-

In Fig. 1 we see the alloy AlSi7Mg0.6 without modification, inoculated with Ti and modified with Sr. The occurrence of dendrites and eutectics in the interdendritic space is evident in the untreated alloy. The morphology of silicon has a plate-like shape. The intermetallic phases are plate-shaped and there is also a Chinese script. Dendritic cells and defects occur in the Ti-inoculation alloy. The eutectic is evenly distributed in the interdendritic spaces. Silicon also has a plate-like shape here, as well as intermetallic phases, and the Chinese script is also evident. The modified Sr alloy again contains dendrites, a eutectic in the interdendritic space, but the size of the eutectic nests is smaller compared to the untreated alloy.

There is also a difference in the morphology of silicon, which is fibrous. The intermetallic phases have a plate-like shape.

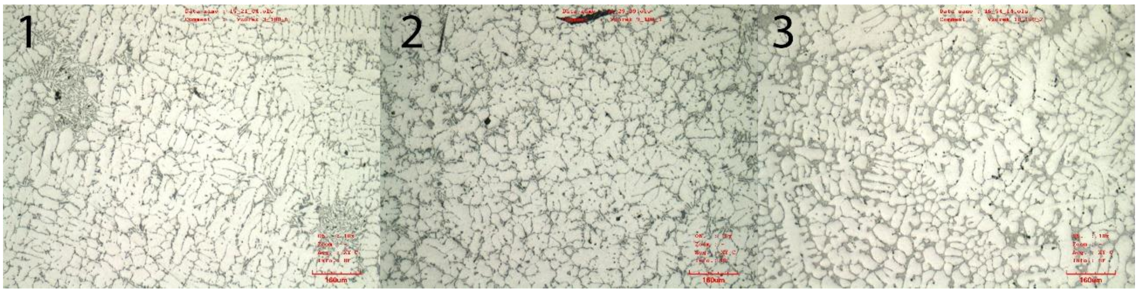

Fig. 1. **Morphology AlSi7Mg0.6:** 1 – without modification; 2 – Ti inoculation; 3 – Sr modification

In Fig. 2 we see the alloy AlSi7Mg0.6 hardened, inoculated with Ti and hardened and modified with Sr and hardened. The hardened alloy shows the presence of dendrites and defects and inclusions. The morphology of silicon, compared to the untreated alloy, has a round shape and a fibrous structure. Compared to the modified alloy, the eutectic is larger with rounder shapes. The intermetallic phases also have round shapes. Interdendritic porosity can be observed in the inoculated and hardened alloy. The eutectic is evenly distributed and the structure is uniform compared to the previous sample. The morphology of silicon is similar to the previous sample. In the modified and hardened alloy, the occurrence of dendrites and interdendritic porosity can be observed in only the modified sample. Silicon has a round and finer structure compared to only hardened alloy. The intermetallic phases are plate.

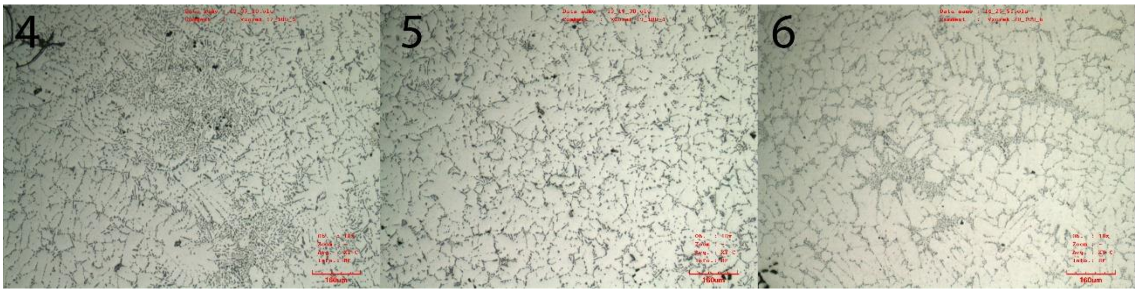

Fig. 2. **Morphology AlSi7Mg0.6:** 4 – hardening; 5 – Ti inoculation + hardening; 6 – Sr modification + hardening

In Fig. 3, the AlSi7Mg0.3 alloy is untreated and hardened. For the untreated alloy, we observe circular defects, eutectic and plate-shaped silicon. Plate-shaped intermetallic phases, which occur to a lesser extent than in the sample of the AlSi7Mg0.6 alloy and the Chinese script. Defects and inclusions are evident in the hardened alloy. The morphology of silicon is finer and fibrous, as well as intermetallic phases, compared to the untreated AlSi7Mg0.6 alloy.

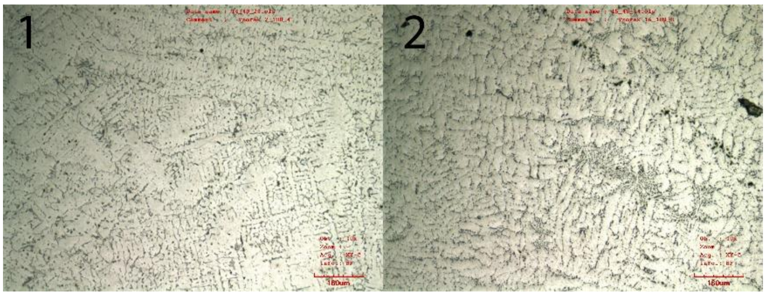

Fig. 3. **Morphology AlSi7Mg0.3:** 1 – without modification; 2 – hardening

Dilatometry

Cylindrical bodies with a diameter of 7 mm and a length of 20 mm were formed from cast and treated alloys and analyzed in a dilatometer. The test piece is placed in the dilatometer at normal room temperature. Subsequently, the body is cooled to -20 ºC at a rate of 1.5 ºC per minute. At this temperature, the temperature in the sample and the measuring chamber is completely homogenized, and then the sample begins to heat at a rate of 3 ºC per minute to a final temperature of 400 ºC, and after a short holding at this temperature, it cools down spontaneously. The resulting values are calculated from the temperature range -14 to 400 ºC, to eliminate errors in the initial phase of measurement. The result is a graph of the elongation ΔL and the coefficient of thermal elongation on temperature.

Figures 4 and 5 show a comparison of the dependence of elongation and the coefficient of thermal elongation on temperature for AlSi7Mg0.6 and AlSi7Mg0.3 alloys without treatment and hardened. The extension of AlSi7Mg0.6 is linear up to a temperature of approx. 220 ºC. This is followed by an increase in the elongation rate to 260 ºC and then the elongation is linear again. Linearity is evident in the hardened sample up to a temperature of approx. 250 ºC, when there is a slight increase in the elongation rate to 315 ºC. We observe a similar course in the AlSi7Mg0.3 alloy without treatment, where an increased dilatation rate between 200 ºC and 260 ºC took place. On the other hand, there was no increase in the dilatation rate of the hardened sample during the test and the course of elongation is linear over the entire range of measured temperatures.

When comparing the course of the coefficient of thermal elongation at the temperature of the alloy AlSi7Mg0.6 without treatment and hardened, a shift of the maximum value of the coefficient of thermal elongation to higher temperatures and at the same time a reduction of its size is noticeable. The unhardened alloy reaches a maximum at 242 ºC with a value of $4.342 \cdot 10^{-5} \cdot K^{-1}$. The hardened alloy has a maximum at a temperature of 278 ºC of $3.342 \cdot 10^{-5} \cdot K^{-1}$ and thus the temperature difference is 36 ºC and the difference in the coefficient of thermal elongation is $1.000 \cdot 10^{-5} \cdot K^{-1}$. For the untreated AlSiMg0.3 alloy, the maximum value of the coefficient is $4.741 \cdot 10^{-5} \cdot K^{-1}$ at 239 ºC. For the hardened sample, the coefficient of thermal elongation is almost linear over the entire temperature range and its maximum is $2.391 \cdot 10^{-5} \cdot K^{-1}$ at 281 ºC.

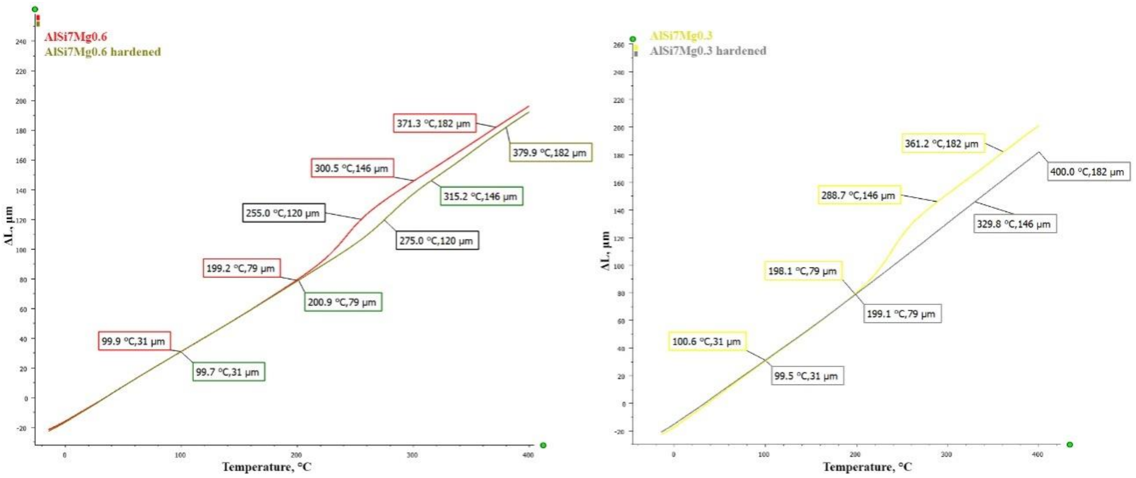

Fig. 4. **Elongation dependence on the temperature of AlSi7Mg0.6 and AlSi7Mg0.3 without modification and hardened**

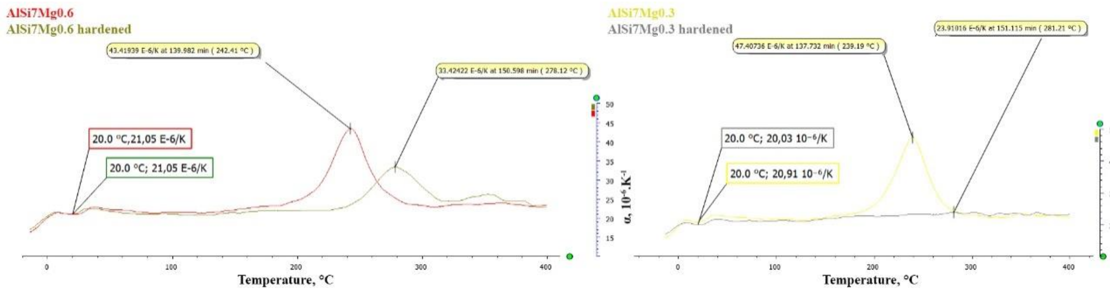

Fig. 5. **Dependence of the coefficient of longitudinal elongation on the temperature of AlSi7Mg0.6 and AlSi7Mg0.3 without modification and hardened**

Figures 6 and 7 show a comparison of the dependence of elongation and the coefficient of thermal elongation on temperature for the alloy AlSi7Mg0.6 without treatment, inoculated Ti, inoculated Ti + hardened, modified Sr and modified Sr + hardened. In the inoculated sample, the increase in elongation accelerated at a slightly lower temperature than in the untreated sample, and at the same time there was an increase in the size of the elongation. On the contrary, in the case of the inoculated and hardened alloy, we observe an increase in nonlinearity only at a higher temperature of about 260 ºC, and at the same time the increase is more gradual. There was no significant change in the modified alloy and the curve almost copies the curve of the alloy without modification. The trend for the modified and hardened sample is similar to that for the sample that was inoculated and hardened, i.e. the onset of nonlinearity at higher temperature and slower growth.

The maximum values of the coefficient of thermal elongation are reached by the AlSi7Mg0.6 alloy without treatment and inoculated at the same temperature of 242 ºC. The coefficient of the inoculated alloy is $4.548 \cdot 10^{-5} \cdot K^{-1}$, ie $0.206 \cdot 10^{-5} \cdot K^{-1}$ more. For the inoculated and hardened alloy, its maximum is reached again at a higher temperature of 283 ºC and at the same time the maximum value is lower, namely $3.577 \cdot 10^{-5} \cdot K^{-1}$. For the alloy without modification and modified, the maximum value of the coefficient of thermal elongation is reached at similar temperatures of about 241 ºC, but compared to the previous case, its value is lower for the modified alloy, namely $4.190 \cdot 10^{-5} \cdot K^{-1}$. The modified and hardened sample shows the same trend as in the case of the inoculated and hardened alloy with a maximum at 277 ºC and a value of $3.699 \cdot 10^{-5} \cdot K^{-1}$.

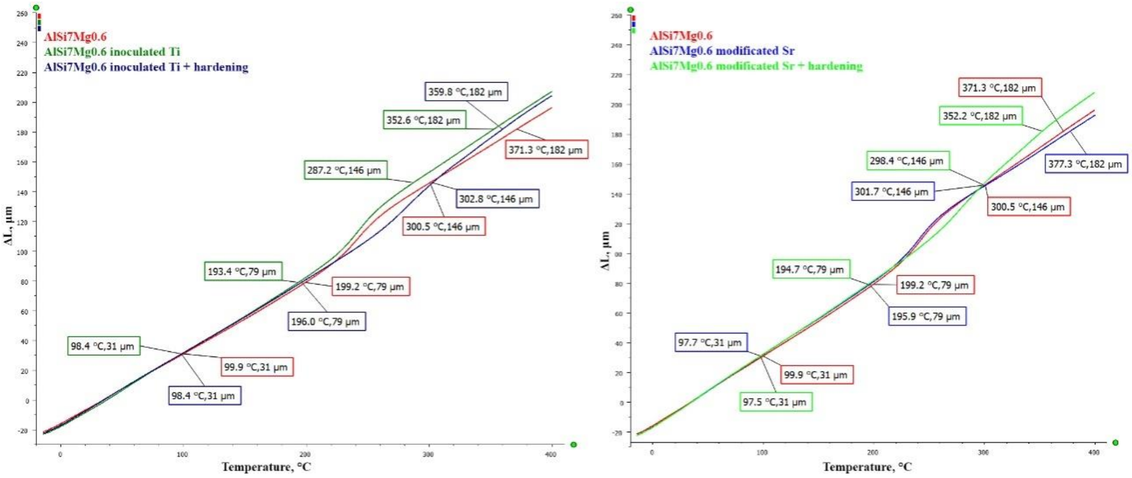

Fig. 6. **Elongation dependence on the temperature of AlSi7Mg0.6 without modification, inoculated, inoculated + hardened, modified, modified + hardened**

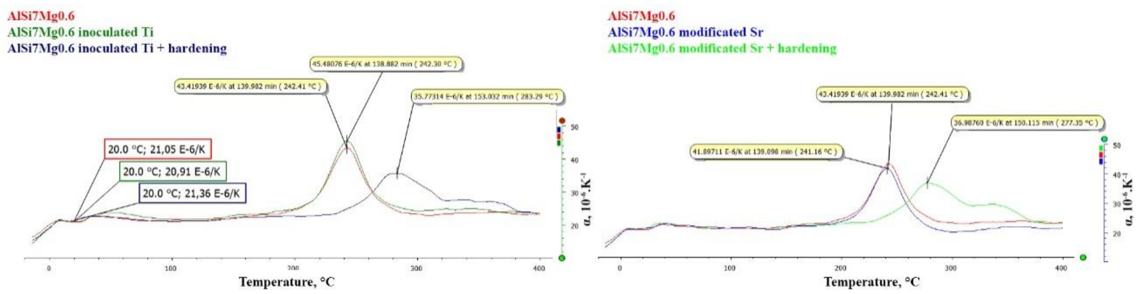

Fig. 7. **Dependence of the coefficient of longitudinal elongation on the temperature of AlSi7Mg0.6 without modification, inoculated, inoculated + hardened, modified, modified + hardened**

Results and discussion

Fig. 8 shows the temperature as a function of the achieved elongation of the sample for values of 31, 79, 146 and 182 μm. For a value of 31 μm, no significant differences between the alloys are apparent and elongation is achieved at approximately 100 ºC. For a value of 79 μm, the temperature differences are more pronounced, but for all alloys they are around 200 ºC. The largest difference is achieved with AlSi7Mg0.6 inoculated (193.4 ºC) and hardened (200.9 ºC). For the elongation value of 146 μm, the differences are more noticeable. As in the previous case, the AlSi7Mg0.6 alloy inoculated at 287.2 ºC first reached this elongation value. On the contrary, both hardened alloys reached an elongation of

146 μm at the highest temperatures, namely AlSi7Mg0.3 at 329.8 ºC and AlSi7Mg0.6 at 315.2 ºC. For the elongation value of 182 μm, the trend is the same for all alloys as for the value of 146 μm, only the temperature differences are larger. This elongation was achieved between 352.2 ºC and 400.0 ºC.

A comparison of the maximum elongation achieved for 400 ºC is shown in Figure 9. The largest dilatation was achieved with the inoculated and modified and hardened AlSi7Mg0.6 alloy, namely an extension of 208.3 μm. Both hardened alloys AlSi7Mg0.3 (182.0 μm) and AlSi7Mg0.6 (192.5 μm) reached the lowest values.

Figure 10 shows the values of the average coefficient of thermal elongation of alloys for the temperature range -14 to 400 ºC. Both hardened alloys AlSi7Mg0.3 ($2.221 \cdot 10^{-5} \cdot K^{-1}$), AlSi7Mg0.6 ($2.340 \cdot 10^{-5} \cdot K^{-1}$) together with the modified alloy AlSi7Mg0.6 ($2.329 \cdot 10^{-5} \cdot K^{-1}$) reached the lowest values here as well. The highest value was reached for the inoculated alloy AlSi7Mg0.6 ($2.498 \cdot 10^{-5} \cdot K^{-1}$).

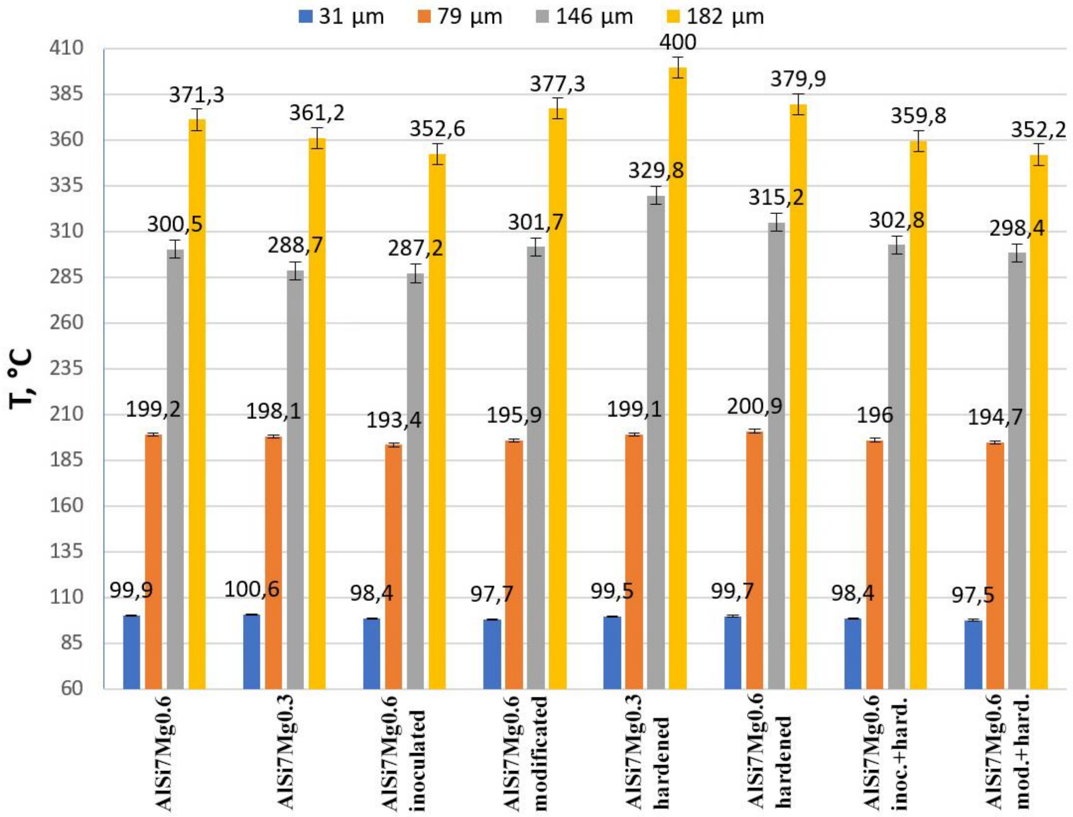

Fig. 8. **Achieved temperature depending on the size of elongation**

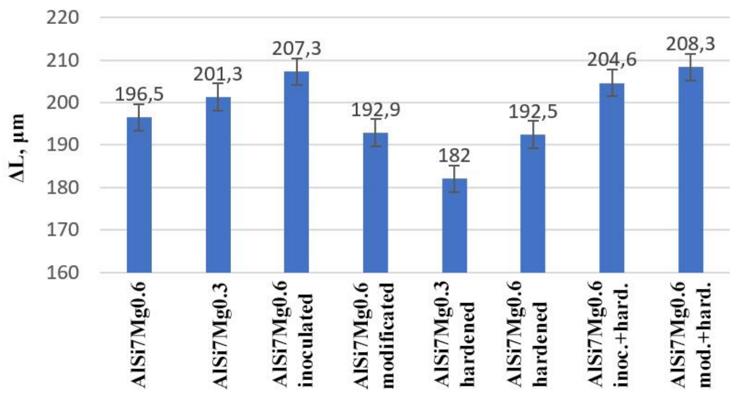

Fig. 9. **Total elongation of the sample at 400 ºC**

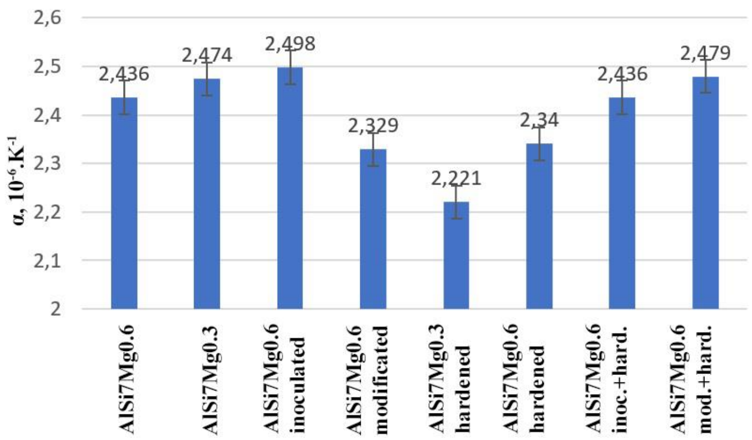

Fig. 10. **Average value of the coefficient of thermal elongation for temperatures -14 to 400 °C**

Conclusions

The research shows that the appropriate choice of alloy treatment, e.g. inoculation or modification, heat treatment or their combination, can significantly affect the overall size of thermal elongation and the coefficient of thermal elongation and choose the most suitable solution for a particular area of application.

Hardening as heat treatment seems to be the most suitable in terms of the lowest possible thermal elongation of the given AlSi7Mg0.3 and AlSi7Mg0.6 master alloys. At the same time, there will be a reduction in the overall average coefficient of thermal elongation in the entire range and a reduction in its nonlinearity and maximum value. The hardened AlSi7Mg0.3 alloy, which reached the lowest overall elongation, the lowest average and maximum coefficient of thermal elongation, did not show the most significant change in this direction.

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