OPTIMIZATION OF HEAT TREATMENT OF CAST PISTONS IN ORDER TO SAVE ENERGY

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Abstract: *This paper presents the results of the effects of optimizing the heat treatment of cast pistons in order to save energy. The piston alloy castings of approximately eutectic composition (AlSi13Cu4Ni2Mg) were examined. Different temperatures and times of solution heat treatment (480 to 510 °C for 1 to 20 h) and of aging (150 to 200 °C for 1 to 20 h) were investigated. The results have shown that it is necessary to find optimal combinations of temperature and time of heat treatment in order to achieve the required performance and economic savings.*

1. INTRODUCTION

Piston alloys are a special group of industrial aluminum alloys that have good mechanical properties at elevated temperatures (approximately up to 400 °C) [1,2] and are resistant to sudden temperature changes [1,2]. During exploitation, these alloys are exposed to the aggressiveness of the environment in which they are used. The properties of material determine the characteristics and method of production as well as construction of piston castings. The casting, metallurgical and mechanical properties of aluminum piston alloys depend on many factors, such as their chemical composition, cooling rate and the parameters of the process of casting and heat treatment [1,2]. Typical aluminum piston alloys are very complex with respect to their chemical composition and the obtained structures. Different piston alloys have various contents of major and minor alloying elements. The usual ranges for some of the alloying elements used by the world famous piston manufacturers KS, Mahle and the Serbian Concern PDM Mladenovac are: 11–23 wt.% Si; 0.5–3 wt.% Ni; 0.5–5.5 wt.% Cu; 0.6–1.3 wt.% Mg; up to 1.0 wt.% Fe and up to 1 wt.% Mn [2,3,5−7,10]. There are at least six elements (Al, Si, Cu, Ni, Mg and Fe), which have a significant impact on the solidification path of these alloys. Interactions among them create different phases and intermetallics, the shape and distribution of which in the as-cast and heat-treated alloys depend on the corresponding process parameters [2,4,5,7,10].

Intermetallic phases resulting in Al-Si piston alloys can be soluble or insoluble. Soluble particles are made of magnesium or copper atoms with or without aluminum. Copper with aluminum builds a θ-Al_2Cu intermetallic phase, and magnesium with silicon builds an *M*-Mg_2Si phase. The characteristic of the *M*-Mg_2Si phase is high strength and hardness, which reinforces Al–Si piston alloys [4]. Precipitate hardening effect is achieved with annealing temperature above the line of dissolution and subsequent heating. However, the simultaneous presence of copper and magnesium in Al–Si alloys, in addition to above phases, leads to the formation of *S*-Al_2CuMg and complex *W*-$Al_xMg_5Cu_4Si_4$ phases. These phases act as additional reinforcement. It was concluded by the examination that the maximum reinforcement is achieved when the contents of *M*-Mg_2Si phase minimally exceeds the limit of solubility in the solid state. If separation of *M*-Mg_2Si occurs at the grain boundary, it will cause the appearance of intercrystalline corrosion [1,4].

Excess copper in piston alloy, which exceeds the limit of solubility in the solid state with manganese compound, formed $Cu_2Mn_3Al_{20}$ [4]. This strengthens the alloy phase and accelerates aging. However, in alloys with lower copper content, the formation of three-element compound reduces the amount of copper necessary for strengthening the matrix, so the effect of aging and the hardening rate decrease. If the percentage was higher in the piston, copper alloys with manganese formed Al_2MnCu phase, while the remaining excess copper with nickel formed Al_6Cu_3Ni. Both phases contribute to the increase in resistance at elevated temperatures.

However, copper and nickel can create Cu_4NiAl_7 phase, which reduces the intensity of hardening alloys with aging and the overall speed of recrystallization. Nickel can appear in the form of compact particles ε-Al_3Ni phase, which is distributed in sequence, or in the form of *T*-Al_9FeNi phase that occurs with ε-Al_3Ni phase [5]. Besides, nickel can be dissolved in stages Cu_2Al_7 and $Al_6(CuFe)$, and iron together with copper in ε-Al_3Ni phase. The presence of manganese leads to the formation of FeMnNi compounds. In the Al–Si alloys, iron forms Cu_2FeAl_7 phase in the presence of copper, while in the presence of magnesium $Al_8FeMg_3Si_6$ is formed [5,7], which is in the form of Chinese script in the case of eutectic separation or in the form of globules in the case of primary separation, while iron with manganese also builds a complex phase in the form of Chinese script ($(FeMn)_3Si_{12}Al_{15}$) [2,10]. However, the formation of these phases has a negative impact on the properties of piston alloys, so the iron content is limited to 0.65%. With this iron content, there can only be the formation of undesirable brittle needle-shaped Al_3Fe crystals. [10]

The simultaneous presence of copper and magnesium leads to the formation of Al_2CuMg compound (*S*-phase) or complex compounds $Al_xMg_5Cu_4Si_4$ (*W*-phase) and $Al_5Cu_2Mg_8Si_{16}$ (h-phase), which also have a positive impact on the mechanical properties of alloys. A part of magnesium gets into the solid solution and a part of it is separated as Mg_2Si phase. During heating for hardening, the phases θ-Al_2Cu, *M*-Mg_2Si, *S*-Al_2CuMg, *W*-$Al_xMg_5Cu_4Si_4$ and *h*-$Al_5Cu_2Mg_8Si_{16}$) get into the solid solution and separate during the release phase in the form of finely dispersed particles that easily improve the mechanical properties. [8,10]

Heat treatment is the final process of casting in the production of pistons from piston alloys. It is a process consisting of heating to the critical temperatures, holding at these temperatures for some time, and then applying certain cooling mode and speed. As the structural and phase changes occur in the solid state, these changes are largely a function of temperature and time and, therefore, it is necessary to precisely define the optimal temperature and hold time.

The most common modes of heat treatment applied in piston alloys are solution heat treatment, aging and stabilization [7–10]. The essence of solution heat treatment comprises heating the piston castings to the maximum allowable temperature, which is very close to the eutectic melting temperature, the period of holding at this temperature and the cooling rate [9,10].

The heating temperature depends on the nature of the alloy and the reinforcing phase dissolution. The length of holding at this temperature depends on the nature of the alloy sheet structure and the heating conditions, *i.e.*, the dissolution of the strengthening component [7,10]. In addition, the duration of the holding time has a significant influence of the wall thickness and configuration as well as on the casting process [7,10]. Aging is often the final technological operation of a heat treatment. The aging temperature and time depend on the size of saturated solid solution [7,10]. Moreover, a stabilization process is performed to remove residual stresses.

The aim of experimental investigations of this study was to analyze the influence of heat treatment on the microstructure and find an optimal combination of time and temperature of heat treatment of piston castings in order to optimize processes and enable economic savings as a key issue of the considered process and to determine the technical and economic parameters.

2. EXPERIMENTAL PROCEDURE

A piston alloy (Table 1) of approximately eutectic composition was used to analyze the influence of heat treatment on the microstructure and price of the cast piston.

Table 1. Nominal chemical composition of the experimental alloy

Alloy	Chemical composition (wt.%)										
	Si	Cu	Ni	Mg	Fe	Mn	Cr	Ti	Zr	V	Al
AlSi13Cu4Ni2Mg	13.05	3.80	2.01	0.90	0.52	0.19	0.09	0.07	≈0.03	≈0.01	residue

The tests were performed on a Ø89 mm piston used for OM604 diesel engine with turbocharger. A CAD model of the cast piston with a pouring system and the cast piston are shown in Fig. 1a. Samples were taken from the whole sample (designated areas in Fig. 1b). The mass of the tested piston cast with a pouring system and feeder is 1275 g and the mass of the cast is 868 g. This is a complex cast piston with ring carrier and sand core.


a)

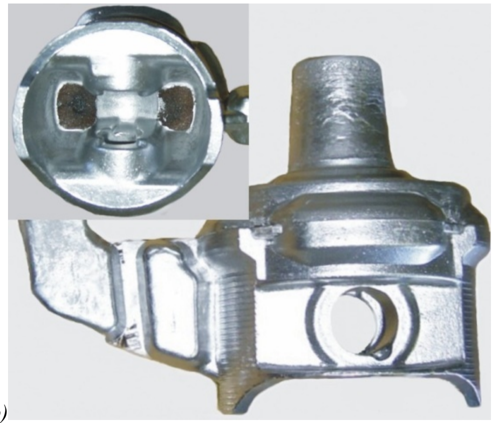
b)

Fig. 1. Investigated cast pistons, a) CAD model of the cast piston with a pouring system and the cast piston and b) cast piston

The melting and preparation of the piston alloy were performed under factory conditions in the Peter Drapsin Company, Mladenovac, Serbia, by the standard procedure prescribed by the manufacturer. Piston castings were cast on the semi-automatic molding machine LK9-PDM, with a temperature of 725 °C and solidification time of 110 sec.

This study investigated different conditions of heat treatment of cast pistons. The alloy constituents were introduced in the solution at a temperature of 480–510 °C for various time intervals of 1–20 h in one cycle. After completion of solution heat treatment, water quenching to 30 °C was performed. The piston castings were automatically quenched by pulling the furnace floor out and lowering the metal basket with pistons directly from the furnace into a water tank. Then the casts were aged at various temperatures. The piston castings were packed in a steel lattice basket, with the whole ear turned down. The space between the rows of pistons was 5–10 mm. The layout and dimensions of the basket were defined by the internal standard of the Petar Drapsin Company, Mladenovac. The batch size of the thermal set was the usable capacity of the furnace. Samples of cast pistons were solution heat treated in a furnace chamber with electric heating, type "KPA 16/32 CER Čačak", with fans for hot air recirculation. The capacity of this furnace is 500 kg/h, its max. temperature is 650 °C and its consumption is 212 kWh. For the aging and stabilization, a "CER Čačak EPC 200/300" furnace with the capacity of 3000 kg/h, max temperature 350 °C and 180 kWh consumption was employed. The temperature in both furnaces was maintained in the prescribed narrow limits (±5 °C), with good atmosphere control.

An optical microscope (Leica DMI type 5000M) was employed for visualization of the microstructure formed with the aim of collecting data for determining the internal construction, *i.e.*, the structure of the material. Further characterization of the structure was performed by reflection electron microscope (REM) with up to 1000 x zoom.

3. RESULTS AND DISCUSSION

3.1. Analysis of the effects of heat treatment on the microstructure

As stated in the introduction, the last stage in the piston casting process, where changes in the structure and physicochemical and mechanical properties can be made, is the heat treatment. These changes are analyzed in the following section of the paper. The microstructure of cast pistons heat-treated for 1 and 4 hours at a temperature of 480 °C are shown in Fig. 2a and 2b. investigated piston alloy. The microstructure of piston alloy after solution heat treatment at 490 °C for a period of 4 hours is shown in Fig. 2c. The uneven distribution of the primary Si crystals can be seen, which means that the time and temperature of the solution heat treatment were not satisfactory. This form and distribution of primary Si crystals and intermetallic phases in the microstructure of the cast piston reduces the mechanical properties of the investigated piston alloys.

The microstructure of piston alloy after solution heat treatment at 500 °C for a period of 4 hours is shown in Fig. 2d. A better distribution of the primary Si crystals, a homogeneous distribution of precipitated θ-Al_2Cu in the matrix and dissolution of the metastable phases are visible.

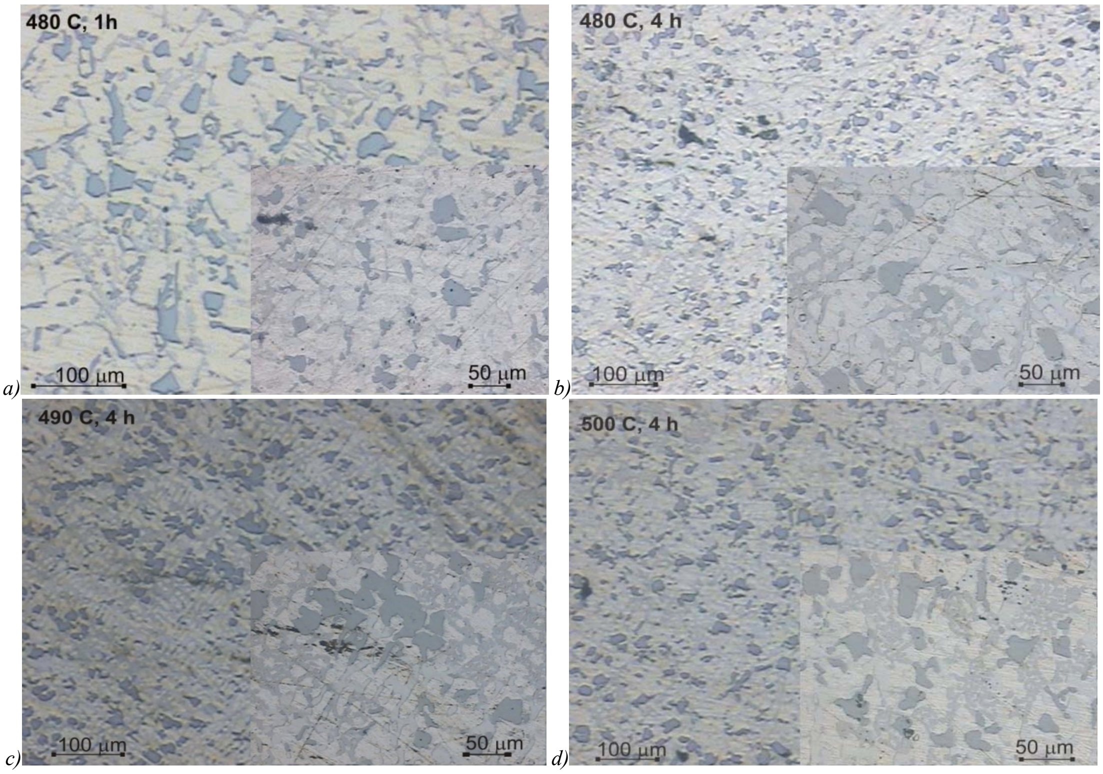

Fig. 2. The shape of the primary Si crystals in the temperature and holding time: a) 480 °C / 1 h, b) 480 °C / 4 h, c) 490 °C / 4 h, d) 500 °C / 4 h

The microstructure of a piston alloy after solution heat treatment at a temperature of 510 °C for a period of 1 h is shown in Fig. 3a. Based on the obtained results, it can be concluded that the process was better than the previous solution heat treatments (Figures 2), but that the time as a solution was not long enough.

Fig. 3b shows that increasing the duration of the solution heat treatment at temperature 510 °C to 4 hours gave better results, *i.e.*, a homogeneous distribution of the primary Si crystals with a rounded shape of the tiles, a homogeneous distribution of precipitates and dissolution of metastable phases. By increasing the solution heat treatment time at 510 °C temperature from 4 to 10 h, better results were obtained (Fig. 3c). The results of the microstructural changes obtained when the solution heat treatment time was extended to 20 h are shown in Fig. 3d.

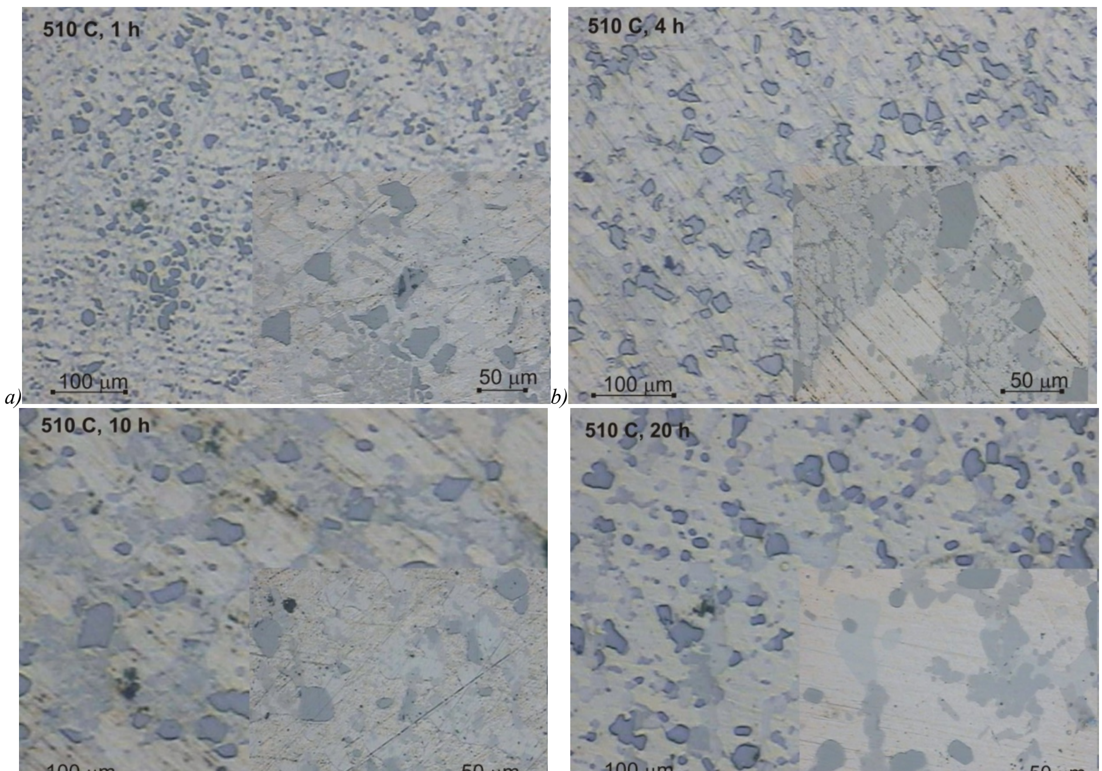

Fig. 3. The shape of the primary Si crystals in the temperature and holding time: a) 510 °C / 1 h, b) 510 °C / 4 h, c) 510 °C / 10 h, d) 510 °C / 20 h

In this part of the obtained results, the microstructural changes after major increases in the time (from 1 to 20 h) of solution heat treatment at temperatures from 480 °C to 510 °C are presented. From the obtained results, rounding of the primary silicon crystals and dissolution of the metastable phases can be seen in alloy. Non-dissolved metastable phases remained in the piston alloys in which the percentages of the alloying elements are greater than the percentages of their maximum solubility. The results shown in Figures 2 to 3 show that heat treatment leads to an interruption of the dendritic structure, a reduction in the segregation of the alloying elements, rounding of the silicon crystals and an improvement of the links between the particles of the other phases and the aluminum matrix.

The results also showed that the time of solution heat treatment was often too long, because, despite the long times, it was not always possible to completely dissolve the metastable phases due to saturation of the solid solutions. High temperatures stimulate diffusion and have a positive impact. In order to benefit from deposition annealing, the alloying elements have to be dissolved in the aluminum matrix. However, the result of boundary dissolution of alloying elements and temperature diffusion depends on the heat treatment temperature. Increasing the temperature of the solution increases both of these parameters, which increases the effect of annealing and consequently improves the mechanical properties and wear resistance of the alloy.

3.2. Analysis of economic indicators of heat treatment

In establishing the price of the finished product sample, an important segment is the price of the heat treatment of the castings. Increasing the cost of heat treatment increases the total cost per unit. Bearing in mind that the market economy and increased competition have produced a better quality and lower costs, it is necessary to analyze and optimize the cost of each segment of the piston fabrication process. The results of the analysis of economic parameters of the piston heat treatment process are presented in Fig. 4. Electricity consumption is given in kWh/t. The price of industrial electricity in Serbia is 0.058 €/kWh.

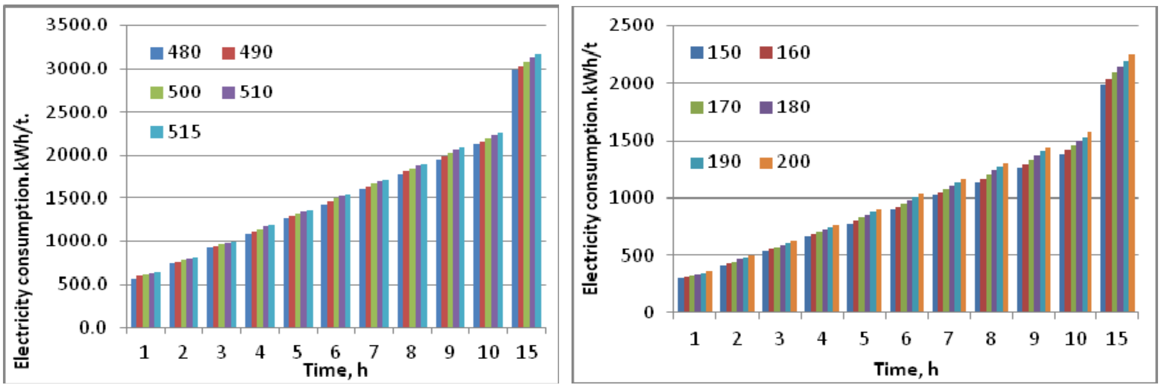

Fig. 4. Electricity consumption kWh/t, a) solution heat treatment, b) aging

Specific electricity consumption (kWh/t) and furnace capacity (t/h), as the two main indicators of the furnace cost-effectiveness, depend not only on the technological process, the composition of the batch, the training of workers etc. but also, to the same extent, on the optimization and proper choice of electric mode of furnace operation.

4. CONCLUSION

Based on the analysis of the results of experimental tests presented in this paper, it could be concluded that:

- A combination of heating, the temperature at which the alloy is being heated, the hold time at this temperature and cooling rate defines the properties of the obtained material.
- A very long time of solution heat treatment gives excellent results but is certainly not economically viable.
- About 172 kWh/t of electricity is consumed for every hour of solution heat treatment in these conditions, or about 180 kWh/t for a 10 °C increase in the treatment temperature.
- It turned out that optimal modes for the investigated piston casting are solution heat treatment at 510 °C for 4 h and aging at 180 °C for 6 h.

Therefore, we recommend determination of the optimal time and temperature of solution heat treatment necessary to achieve a satisfactory structure and obtain the required mechanical properties of castings.

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