UDK 669.715:621.78
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 47(5)585(2013)

EFFECT OF HEAT TREATMENT ON THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF PISTON ALLOYS

VPLIV TOPLOTNE OBDELAVE NA MIKROSTRUKTURO IN MEHANSKE LASTNOSTI ZLITIN ZA BATE

Srećko Manasijević[1], Srdjan Marković[2], Zagorka Aćimović - Pavlović[2], Karlo Raić[2], Radomir Radiša[1]

[1]LOLA Institute, Kneza Viseslava 70a, 11000 Belgrade, Serbia
[2]Faculty of Technology and Metallurgy, University of Belgrade, Karnegijeva 4, 11000 Belgrade, Serbia
srecko.manasijevic@li.rs

Prejem rokopisa – received: 2012-12-10; sprejem za objavo – accepted for publication: 2013-02-19

This research paper presents the results of the effects of heat treatment on the microstructure and mechanical properties of aluminum piston alloys. Four piston alloys of different chemical compositions were experimentally investigated. Different temperatures and times (480 °C to 515 °C for 1 h to 60 h) of the solution heat treatment were investigated. Additionally, the influence of the aging time and temperature (140–200 °C for 1 h to 30 h) on the hardness was studied. The results have shown that it is necessary to find the optimum combinations of the temperature and the time of heat treatment in order to achieve the required performance and economic savings.

Keywords: piston, aluminum alloys, heat treatment

V članku so predstavljeni rezultati vpliva toplotne obdelave na mikrostrukturo in mehanske lastnosti aluminijevih zlitin za bate. Eksperimentalno so bile preiskane štiri zlitine za bate z različno kemijsko sestavo. Preiskovane so bile pri različnih temperaturah in časih (480–515 °C od 1 h do 60 h) raztopnega žarjenja. Dodatno je bil preučevan vpliv časa in temperature (140–200 °C od 1 h do 30 h) staranja na trdoto. Rezultati so pokazali, da je za zagotavljanje lastnosti in ekonomičnosti potrebno poiskati optimalno kombinacijo temperature in časa toplotne obdelave.

Ključne besede: bat, aluminijeve zlitine, toplotna obdelava

1 INTRODUCTION

Aluminum piston alloys are a special group of industrial aluminum alloys[1–5] that have good mechanical properties at elevated temperatures (approximately up to 400 °C).[1–5] At the same time, these alloys are resistant to sudden temperature changes.[1–19] Due to this, in the design of this type of alloys, their mechanical and thermal strains have to be critically considered without neglecting the aggressive environments, to which they are exposed during exploitation.[1,2,4,5] In order to accomplish such a set of requirements, aluminum alloys assigned for piston production need to have an appropriate microstructure. Together with their chemical composition, the process parameters and heat treatment affect their microstructure, which is an important parameter that has a significant impact on the mechanical properties of cast parts.[3,5,7,10,12,13,18]

Different grades of piston alloys have different contents of the major and minor alloying elements. The usual ranges for some of the alloying elements used by the world famous manufacturer of the KS pistons, Mahle, and the Serbian Concern PDM Mladenovac are in mass fractions: 11–23 % Si; 0.5–3 % Ni; 0.5–5.5 % Cu; 0.6–1.3 % Mg; up to 1.0 % Fe and up to 1 % Mn.[5–8] Typical aluminum piston alloys are very complex with respect to their chemical compositions and the obtained structures. There are at least six major alloying elements, Al, Si, Cu, Ni, Mg and Fe, which have a significant impact on the solidification path of these alloys.[1–5,8,9] 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.[1,5,6,12,15,18,19]

The zones subjected to greater strains during the exploitation (the pin support and the zone of the piston rings) require a greater resistance to plastic deformation. This requires a fine grain structure in these zones as fine grain structures can accumulate larger quantities of energy.[2,4,5] The size of the primary silicon crystals in these zones ranges from 21–29 µm.[2,4,5] In the zone subjected to higher temperatures (the piston head, i.e., the combustion chamber) but lower mechanical strains, coarse grains are required. The size of the primary silicon crystals in this zone ranges from 50–75 µm.[2,4,5] Given that higher temperatures can stress out thermally actuated processes (diffusion), the material has a potential to compensate deformations that were formed during a temperature decrease. Likewise, an increase in the grain size results in a slower expansion of deformation. Thus, the structure of a material directly affects the physical and mechanical properties of the cast.[2,4,5]

Al–Si alloys should have a high strength at elevated temperatures. In order to increase the mechanical properties of such alloys at elevated temperatures (approximately around 350 °C), it is necessary to introduce, into the solidified structure, new thermally stable intermetallics formed through complex eutectic or peritectic reactions.[1,4,5] At elevated temperatures, thermally stable intermetallics should prevent or retard the movement of dislocations and thus increase the mechanical properties of an alloy at elevated temperatures. The strengthening effect of such intermetallics depends on their stability at elevated temperatures. More thermally stable intermetallics achieve a better strengthening effect.[1,3,5,10,11,14]

The formatted intermetallic phases in piston alloys can be soluble or insoluble. Soluble particles are formed by the atoms of magnesium or copper, in the presence or absence of aluminum.[1,5] Copper forms a θ-($CuAl_2$) intermetallic phase with aluminum,[1,3,5,7–9,12,14] while Mg reacts with Si and produces a complex intermetallic and the β-(Mg_2Si) intermetallic mainly affects the strength of the alloy at ambient temperature.[5,7–10,12,14,15] The main characteristics of the Mg_2Si intermetallic phase are high strength and hardness.[5,10] Therefore, this intermetallic has been used as a strengthener in pistons produced using a series of Al–Si alloys. The good mechanical properties of Al–Si piston alloys have been further improved by choosing the optimum heat-treatment procedure.[5,6,12,15] The presence of copper and magnesium as additional alloying elements in pistons alloys leads to a formation two additional intermetallic phases: Al_2CuMg, the so-called *S*-phase, and the more complex $Al_xMg_5Cu_4Si_4$ (*W*-phase).[5,7,12]

Heat treatment is the final process of treating castings in the Al–Si alloy piston production stage. Heat treatment includes the processes of heating the castings to the critical temperatures, holding them at these temperatures for a certain time and then cooling them in a certain way and at a certain rate. This is an unavoidable way of improving the properties of piston alloys in the production process, where the phase and structural changes primarily take place in the solid state. The process of heat treatment of piston castings, which are very sensitive to the conditions of the treatment, requires a very precise process control. First, it is necessary to accurately define the mode of heat treatment on the basis of the initial properties of the casting and desired thermomechanical properties that a piston should achieve. Bearing in mind that the phase and structural changes depend on the time and temperature, it is therefore necessary to precisely define the optimum temperature and time of holding. Otherwise, the set goals cannot be achieved.

The most common modes of heat treatment applied to piston alloys are solution heat treatment, aging and stabilization.[5] 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 them at this temperature and the cooling rate. The heating temperature depends on the nature of an alloy and the reinforcing phase dissolution, and its determination is based on the equilibrium diagram. The length of maintaining this temperature depends on the nature of the alloy sheet structure and the heating conditions, i.e., the dissolution of the strengthening component.[5,15] In addition, the duration of the holding time has a significant influence on the wall thickness and configuration as well as on the casting process.[5] Aging is often the final technological operation of heat treatment. The aging temperature and time depend on the size of the saturated solid solution.[6,12,15,18,19] Moreover, a stabilization process is performed to remove residual stresses.

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

2 EXPERIMENTAL PROCEDURE

Four different piston alloys (**Table 1**) of approximately eutectic composition were used to analyze the influence of heat treatment on the microstructure. The mass content of the alloying elements varied between 11.20–13.12 % Si, 1.11–5.41 % Cu, 0.89–1.91 % Ni, 0.53–1.02 % Mg and 0.37–0.59 % Fe, to ensure a separation of the dominant phase in each of the test structures. In the real case, there is a change in the mean concentrations of alloying elements due to a redistribution of the rich or depleted melt, which can lead to a change in the mean concentrations being significantly above or below the nominal value and to the creation of the conditions for a formation of new phases. Any chan-

Table 1: Nominal chemical compositions of the experimental alloys in mass fractions
Tabela 1: Kemijska sestava preizkusnih zlitin v masnih deležih

Alloys	Chemical composition (*w*/%)									
	Si	Cu	Ni	Mg	Fe	Mn	Cr	Ti	Zr	V	Al
A	13.12	1.11	0.89	0.85	0.59	0.18	0.09	0.07	≈0.03	≈0.01	residue
B	13.05	3.58	1.01	0.90	0.52	0.19	0.09	0.07			
C	12.95	3.91	1.91	1.02	0.42	0.18	0.09	0.07			
D	11.20	5.41	1.90	0.53	0.37	0.25	0.09	0.07			

ge during the entire curing process (primary, secondary and tertiary) of piston alloys has a significant impact on the concentration profiles of the alloying elements in the solid phase.[5] Therefore, several alloys with different ratios of the main alloying elements were investigated.

The Al–Si piston-alloy testing was performed on a Φ 89 mm piston used for an OM604 diesel engine with a turbocharger. 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. Taking into account that the structure of the material has a direct impact on the physical and mechanical properties of the cast, it is therefore necessary to define and describe its macrostructure and microstructure (**Figure 1**).

All the investigated alloys of the required elemental contents were prepared under industrial conditions in the Petar Drapsin Company, Mladenovac, Serbia with the standard procedure for the melting and preparation of piston alloys prescribed by the manufacturer.

This study investigated different conditions of heat treatment of cast pistons. The alloy constituents were introduced to the solution at a temperature of 480–515 °C for various time intervals of 1–60 h in one cycle, or a combination of two or three temperatures for different time intervals. After completing the solution heat treatment, water quenching to 30 °C was performed. Then the casts were aged at various temperatures. All the castings were marked in order to monitor the changes in the results.

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. The samples of cast pistons were solution heat treated in a furnace chamber with electric heating, type KPA 16/32 CER Čačak, with the fans for the hot-air recirculation. The capacity of this furnace is 500 kg/h and the consumption is 212 kW h. The piston castings were automatically quenched by pulling the furnace floor out and lowering the metal basket with the pistons directly from the furnace into a water tank. For the aging and stabilization, a CER Čačak EPC 200/300 furnace with a capacity of 3000 kg/h and consumption of 180 kW h was employed. The temperature in the furnace was maintained within the prescribed narrow limits (±5 °C) with a good atmosphere control.

A 38532-type device (Karl Frank GmbH) was used to measure the hardness of the pistons. The measurements were performed using a Brinell JUS.C.A4103 (5/250/30) 5 mm ball and a 250 N load for 30 s. An optical microscope (Leica DMI 5000M) was employed for a visualization of the microstructure formed with the aim of collecting data for determining the internal construction, i.e., the structure of the material. A further characterization of the structure was performed with a reflection electron microscope (REM) with a magnification of up to 1000-times.

3 RESULTS AND DISCUSSION

3.1 Analysis of the effects of heat treatment on the microstructure

The solidification of the investigated piston alloys (**Table 1**) starts with a separation of the primary silicon crystals ($L \rightarrow$ (Si)).[1,5,6,8] Further growth of the formed silicon crystals reduces the surrounding space and creates the conditions for a development of the secondary or eutectic reaction ($L \rightarrow (Al)+(Si)$).[1,5,6,8] Further, depending on the chemical composition and the conditions of solidification, one of the following three reactions takes place: $L \rightarrow$ (Al)+(Si)+Y and $L+Y \rightarrow$ (Al)+(Si)+Y, where $Y(\varepsilon, \theta, M, \delta, \gamma, T, \beta, \pi$ and $Q)$.[5,6,8] After the completion of the solidification process, there are different intermetallic phases in the microstructure in addition to the primary silicon crystals (Si) and $\alpha(Al)$ of the solid solution. Their shape, size and distribution depend on the nominal chemical composition of the alloy and the cooling conditions. Therefore, four Al–Si

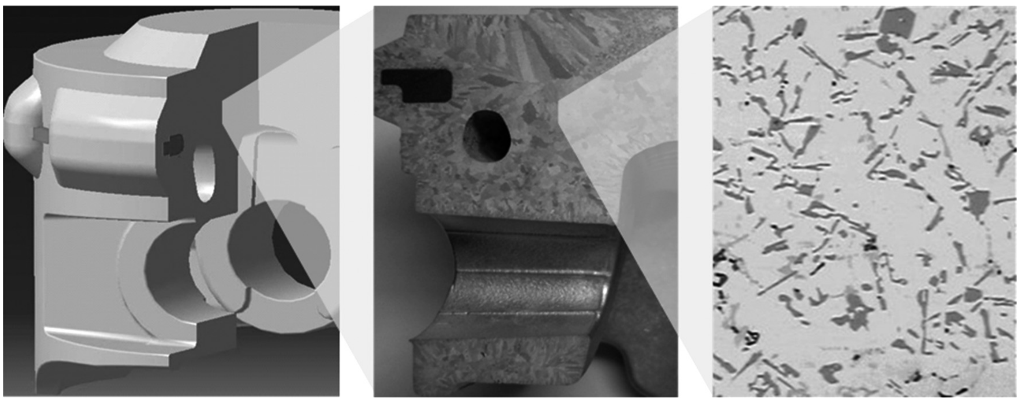

Figure 1: Macrostructure and microstructure of the piston cast of alloy A
Slika 1: Makrostruktura in mikrostruktura bata, ulitega iz zlitine A

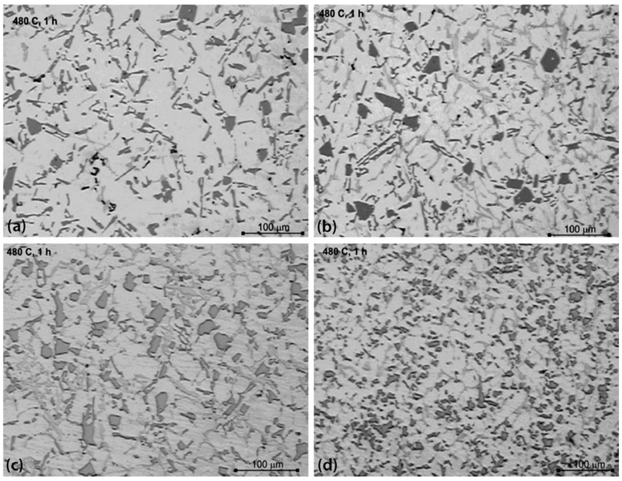

Figure 2: Shape of the primary Si crystals at a temperature of 480 °C and with the holding time of 1 h: a) alloy A, b) alloy B, c) alloy C and d) alloy D

Slika 2: Oblika primarnih kristalov Si po zadržanju 1 h na temperaturi 480 °C: a) zlitina A, b) zlitina B, c) zlitina C in d) zlitina D

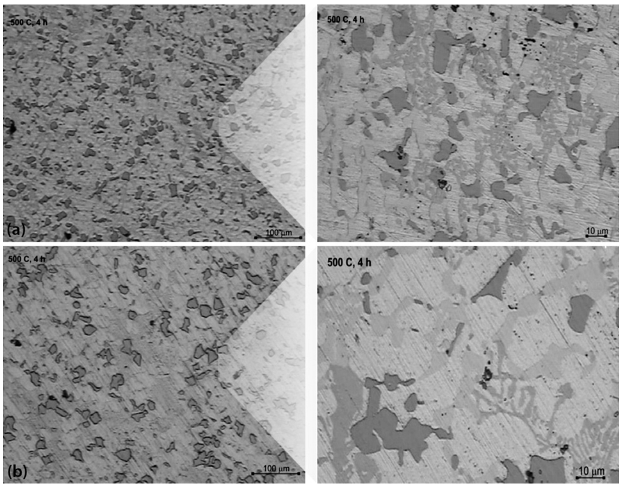

Figure 4: Morphologies of the alloys solution heat treated for 4 h at 500 °C: a) alloy C and b) alloy D

Slika 4: Morfologija zlitine, raztopno žarjene 4 h na 500 °C: a) zlitina C in b) zlitina D

piston alloys that have different initial microstructures were selected for the heat treatment.

As stated in the introduction, the last stage in the piston casting process, where the 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 microstructures of the cast pistons heat treated for 1 h at a temperature of 480 °C are shown in **Figure 2**, (alloy A (**Figure 2a**), alloy B (**Figure 2b**), alloy C (**Figure 2c**) and alloy D (**Figure 2d**)).

The microstructure of the cast pistons (alloy C) heat treated for 4 h at the temperatures of 480 °C and 490 °C are shown in **Figure 3**. The uneven distribution of the primary Si crystals can be seen in all the alloys, which means that the time and temperature of the solution heat treatment were not satisfactory. This form and distribution of the primary Si crystals and intermetallic phases in the microstructure of a cast piston reduce the mechanical properties of the investigated piston alloys.

The microstructure of the piston alloy C after the solution heat treatment at 500 °C for a period of 4 hours is shown in **Figure 4a**. The microstructure of the piston alloy D after solution heat treatment at a temperature of 500 °C for a period of 4 h is shown in **Figure 4b**. Based on the obtained results, it can be concluded that the process was better than the previous solution heat treatments (**Figures 2** and **3**), but that the time of the solution heat treatment was not long enough. A better distribution of the primary Si crystals, a homogeneous distribution of the precipitated Al_2Cu in the matrix and a dissolution of the metastable phases are visible.

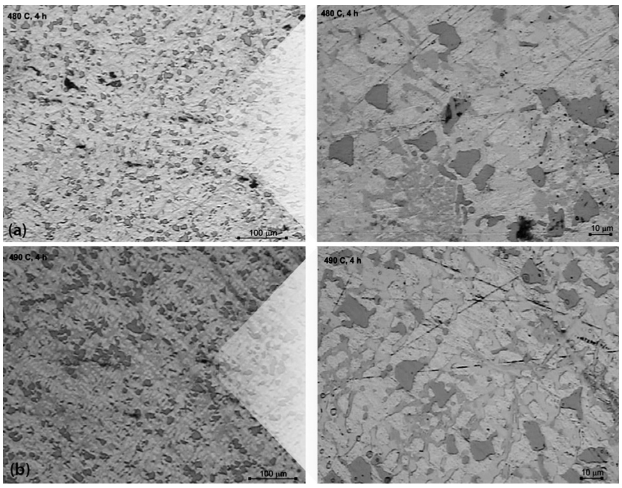

Figure 3: Shape of the primary Si crystals at the temperatures of 480 °C and 490 °C and with the holding time of 4 h, alloy C

Slika 3: Oblika primarnih kristalov Si v zlitini C, po zadržanju 4 h na temperaturah 480 °C in 490 °C

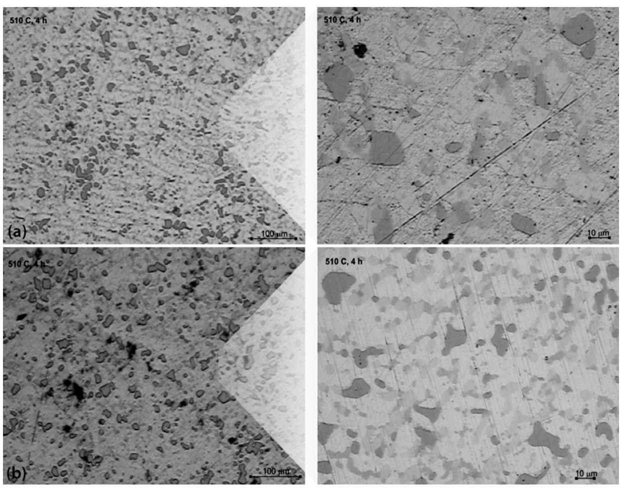

Figure 5: Morphologies of the alloys solution heat treated for 4 h at 510 °C: a) alloy C and b) alloy D

Slika 5: Morfologija zlitine, raztopno žarjene 4 h na 510 °C: a) zlitina C in b) zlitina D

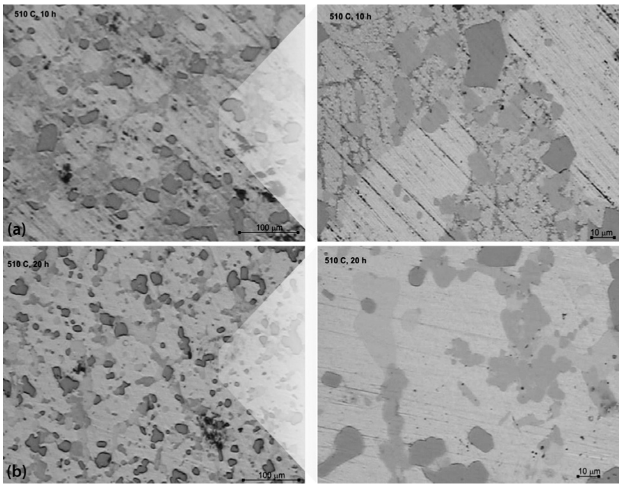

Figure 6: Morphology of alloy D, solution heat treated at 510 °C: a) 10 h, b) 20 h
Slika 6: Morfologija zlitine D, raztopno žarjene na 510 °C: a) 10 h, b) 20 h

Figure 5 shows that increasing the duration of the solution heat treatment at the temperature of 510 °C to 4 h gave better results, i.e., a homogeneous distribution of the primary Si crystals with a rounded shape of the tiles, a homogeneous distribution of the precipitates and dissolution of the metastable phases.

By increasing the solution heat-treatment time (alloy D) at the temperature of 510 °C from 4 h to 10 h, better results were obtained (**Figure 6a**). The results of the microstructural changes obtained when the solution heat-treatment time was extended to 20 h are shown in **Figure 6b**.

In this part of the obtained results, the microstructural changes after the major increases in the time of the solution heat treatment at the temperatures of 500 °C, 510 °C and 515 °C are presented. The results of the combined solution heat treatment of the investigated

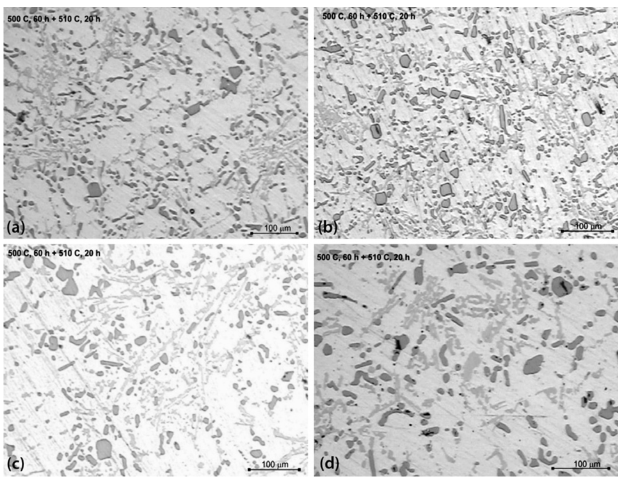

Figure 7: Solution heat treatment for 60 h at 500 °C + 20 h at 510 °C: a) alloy A, b) alloy B, c) alloy C and d) alloy D
Slika 7: Raztopno žarjeno 60 h na 500 °C + 20 h na 510 °C: a) zlitina A, b) zlitina B, c) zlitina C in d) zlitina D

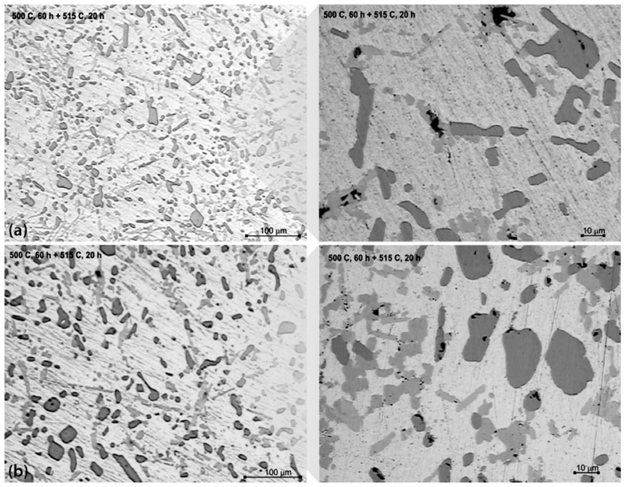

Figure 8: Solution heat treatment for 60 h at 500 °C + 20 h at 515 °C: a) alloy B and b) alloy D
Slika 8: Raztopno žarjeno 60 h na 500 °C + 20 h na 515 °C: a) zlitina B, b) zlitina D

piston alloys A, B, C and D (**Table 1**) at the temperature of 500 °C for 60 h and for a further period of 20 h at 510 °C are presented in **Figure 7**.

Figure 8 shows the combined solution temperatures of 500 °C for 60 h and 515 °C for 20 h. From the obtained results, a rounding of the primary silicon crystals and a dissolution of the metastable phases can be seen in all the alloys. The non-dissolved metastable phases remained in the piston alloys, for which the percentages of the alloying elements are greater than the percentages of their maximum solubility.

The results shown in **Figures 2** to **8** show that heat treatment leads to an interruption of the dendritic structure, a reduction in the segregation of the alloying elements, a rounding of the silicon crystals and an improvement of the links between the particles of the other phases and the aluminum matrix. In the previous research,[5,16] it was shown that an improved distribution and slow rounding of the silicon crystals affected the crack propagation, to which the improved wear resistance is attributed.[1,7]

Based on the results shown, it may be concluded that the homogenization time is too long, because, despite the long homogenization time, a complete dissolution of the metastable phases is not possible due to the supersaturation of the solid solution. 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 results of the boundary dissolution of the alloying elements and the temperature diffusion depend on the heat-treatment temperature. Increasing the temperature of the solution increases both of these parameters and, in this way, also the effect of annealing and, consequently, it improves the mechanical properties and wear resistance of the alloy.[5]

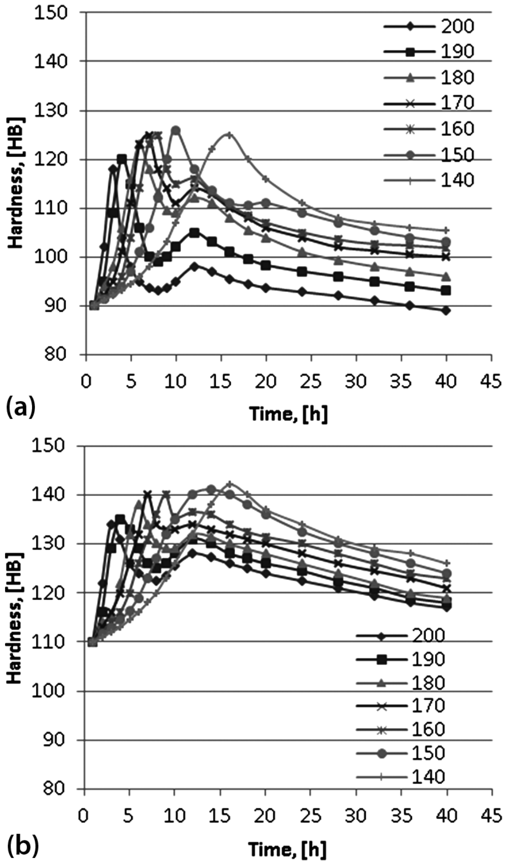

Figure 9: Hardness curves after aging at different temperatures and times: a) alloy A and b) alloy C

Slika 9: Krivulje trdote po staranju pri različnih temperaturah in časih: A) zlitina A in b) zlitina C

3.2 Analysis of the impact of heat treatment on hardness

The process of solution heat treatment at the temperatures below the eutectic temperature and quenching in water down to 20–30 °C results in oversaturated solid solutions. It is then necessary that the obtained supersaturated solid solutions undergo an aging process in order to improve their mechanical properties. The strength curves for alloys A and C (**Table 1**) depending on the temperature and time of aging are shown in **Figure 9**. On both curves, there are two peaks of increasing hardness. The first increase in the hardness is due to a formation of the GP zones. The decrease in the hardness after the first peak results from a transformation of the GP zones into an intermediate metastable phase, which increases the hardness after a certain time and leads to the second peak.[5,12] Bearing in mind that the initial composition of these two piston alloys was different, the proportion and arrangement of the formed metastable phases are therefore different, resulting in the samples having different mechanical properties.

3.3 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. An increase in the cost of heat treatment increases the total cost per unit. Bearing in mind that the market economy and increased competition have led to 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 the economic parameters of the piston heat-treatment process are presented in **Table 2**. Electricity consumption is given in kW h/t. The price of industrial electricity in Serbia is 0.058 €/(kW h).

4 CONCLUSIONS

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

- The choice of heat treatment of alloys depends on the nature of an alloy and the demand. Obtaining the final properties of piston alloys depends on the heat treatment. A combination of heating, the temperature, at which the alloy is being heated, the holding time at this temperature and the 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 kW h/t of electricity is consumed for every hour of a solution heat treatment in these conditions, or about 180 kW h/t for a 10 °C increase in the treatment temperature.
- It turned out that the optimum modes for the investigated piston casting are the solution heat treatment at 510 °C for 4 h and aging at 180 °C for 6 h.

Table 2: Consumption of electricity

Tabela 2: Poraba električne energije

Process	Consumption of electricity (kW h/t)								
Solution heat treatment	4 h at 480 °C	4 h at 500 °C	1 h at 510 °C	4 h at 510 °C	10 h at 510 °C	15 h at 500 °C	15 h at 510 °C	60 h at 500 °C	60 h at 510 °C
	1090.4	1139.4	628.0	1165.4	2240.0	44265	3135.5	11037.9	11195.4
Aging	4 h at 150 °C	4 h at 160 °C	4 h at 180 °C	7 h at 150 °C	7 h at 160 °C	7 h at 180 °C	7 h at 200 °C	15 h at 200 °C	30 h at 200 °C
	658.7	678.8	720.6	1019.5	1048.7	1108.4	1170.3	2252.1	4280.4

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

5 REFERENCES

[1] S. Manasijevic, R. Radisa, S. Markovic, K. Raic, Z. Acimovic–Pavlovic, Implementation of the infrared thermography for thermo-mechanical analysis of the Al–Si cast piston, Practical Metallography, 46 (**2009**), 565–579

[2] S. Manasijevic, R. Radisa, S. Markovic, Z. Acimovic–Pavlovic, K. Raic, Thermal analysis and microscopic characterization of the piston alloy AlSi13Cu4Ni2Mg, Intermetallics, 19 (**2011**), 486–492

[3] E. R. Wang, X. D. Hui, G. L. Chen, Eutectic Al–Si–Cu–Fe–Mn alloys with enhanced mechanical properties at room and elevated temperature, Materials and Design, 32 (**2011**), 4333–4340

[4] S. Manasijevic, Z. Acimovic–Pavlovic, K. Raic, R. Radisa, V. Kvrgic, Optimization of cast pistons made of Al–Si piston alloy, International Journal of Cast Metals Research, 26 (**2013**) 5, 255–261

[5] S. Manasijevic, Aluminum piston alloys, LOLA Institute, Belgrade 2012

[6] M. Zeren, The effect of heat treatment on aluminum-based piston alloys, Materials and Design, 28 (**2007**), 2511–2517

[7] R. Gholizadeh, S. G. Shabestar, Investigation of the effects of Ni, Fe and Mn on the formation of complex intermetallic compounds in Al–Si–Cu–Mg–Ni alloys, Metallurgical and Materials Transactions A, 42 (**2011**), 3447–3458

[8] N. A. Belov, D. G. Eskin, N. N. Avxentieva, Constituent phase diagrams of the Al–Cu–Fe–Mg–Ni–Si system and their application to the analysis of aluminum piston alloys, Acta Materialia, 53 (**2005**) 17, 4709–4722

[9] R. C. Hernández, J. H. Sokolowski, Thermal analysis and microscopical characterization of Al–Si hypereutectic alloys, Journal of Alloys and Compounds, 419 (**2006**), 180–190

[10] Z. Qian, X. Liu, D. Zhao, G. Zhang, Effects of trace Mn additional on the elevated temperature tensile strength and microstructure of a low-iron Al-Si piston alloy, Materials Letters, 62 (**2008**), 2146–2149

[11] C. L. Chena, R. C. Thomson, The combined use of EBSD and EDX analyses for the identification of complex intermetallic phases in multi-component Al–Si piston alloys, Journal of Alloys and Compounds, 490 (**2010**), 293–300

[12] R. X. Li, R. D. Li, L. Z. He, C. X. Li, H. R. Gruan, Z. Q. Hu, Age-hardening behavior of cast Al–Si base alloy, Materials Letters, 58 (**2004**), 2096–2101

[13] Y. Yang, Y. Li, W. Wu, D. Zhao, X. Liu, Effect of existing form of alloying elements on the microhardness of Al–Si–Cu–Ni–Mg piston alloy, Materials Science and Engineering A, 528 (**2011**), 5723–5728

[14] Y. Yang, K. Yu, Y. Li, D. Zhao, X. Liu, Evolution of nickel-rich phases in Al–Si–Cu–Ni–Mg piston alloys with different Cu additions, Materials and Design, 33 (**2012**), 220–225

[15] R. Sharma, D. K. Dwivedi, Solutionizing temperature and abrasive wear behavior of cast Al–Si–Mg alloys, Materials and Design, 28 (**2007**), 1975–1981

[16] A. Humbertjean, T. Beck, Effect of the casting process on microstructure and lifetime of the Al piston alloy AlSi12Cu4Ni3 under thermo-mechanical fatigue with superimposed high-cycle fatigue loading, International Journal of Fatigue, 53 (**2013**), 67–74

[17] R. Taghiabadi, H. M. Ghasemi, S. G. Shabestari, Effect of iron-rich intermetallics on the sliding wear behavior of Al–Si alloys, Materials Science and Engineering A, 490 (**2008**), 162–170

[18] M. A. Azmah Hanim, S. Chang Chung, O. Khang Chuan, Effect of a two-step solution heat treatment on the microstructure and mechanical properties of 332 aluminum silicon cast alloy, Materials and Design, 32 (**2011**), 2334–2338

[19] Í. Özbek, A study on the re-solution heat treatment of AA 2618 aluminum alloy, Materials Characterization, 58 (**2007**), 312–317