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Effect of Heat Treatment on the Microstructure and Mechanical Properties of Aluminum Cylinder Heads

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Abstract

High requirements placed on a castings of combustion engine's cylinder heads are forcing their manufacturers to search after a new solutions of the process aimed at improving quality of the castings, minimization of structural defects (such as porosity or inclusions), and perfection of material's microstructure, which in result would lead to obtaining improved mechanical properties. Meeting these requirements, without necessity of introduction of a new materials requires, among others, optimizing chemical composition of the alloy, developing methods of the casting process, and improving heat treatment processes. In this paper it has been presented results of the research concerning T6 type heat treatment of a combustion engine's cylinder head made of the AlSi7Cu3Mg alloy. It has been confirmed that optimal heat treatment procedure comprises solutioning heat treatment at 500°C for 1 hour, followed by artificial aging at 175°C for 2 hours. In result of implemented process, it have been obtained the tensile strength of R_m = 320 MPa and the hardness of HB having value in range of 105–130, what represents a significant increase compared to the raw casting. Improvement in the mechanical properties was accompanied by a slight decrease in ductility only– the A_5 elongation decreased from 1,5 to 1,2%.

Keywords: Aluminum alloys, Cylinder heads, Heat treatment, Mechanical properties, Microstructure

1. Introduction

The cylinder head, as one of the most complex and the most important parts of combustion engine, is directly exposed to high temperatures resulted from the combustion process, rapid changes of combustion pressure, and mechanical and thermal loads occurring cyclically during operation of the engine [1-5]. In the recent years we can see occurring evolution of combustion engines in direction of restriction of exhaust emissions and fuel consumption with simultaneous increasing their output power. Introduction of advanced combustion systems for both spark-ignition (SI) and compression-ignition (CI) engines makes it possible to generate 100 kW/liter for direct injection Diesel engines [6, 7] and above 100 kW/liter for supercharged direct injection gasoline engines [8-10]. As its consequence, requirements for aluminum cylinder head castings also become higher due to generation of a higher operating temperatures at increased combustion pressures, which in turn results in a greater mechanical stresses in the material [11, 12] Comply with these increasing requirements for the cylinder head, without need to introduce new materials involves, among others, the optimization of its chemical composition [13, 14], development of new casting methods and heat treatment processes [15-18] and possibility of use of additive manufacturing methods [19, 20].

The cylinder heads are most often made by gravity casting into metal molds representing their external shapes. In turn, intake and exhaust channels as well elements of cooling system are reproduced using sand cores positioned inside the molds [21]. Currently, many studies connected with development of usage of aluminum alloys in automotive industry are being conducted [22-27]. The alloys from the Al-Si-Cu group [28, 15, 29] and the Al-Si-Mg alloys [30-32] are widely used as casting materials for cylinder heads, mainly due to advantageous combination of mechanical and physical properties, especially after performed heat treatment operation consisting of three consecutive stages. In the first stage the *solutioning* heat treatment is carried out, consisting in heating the material at temperature of 500-540°C for alloys Al-Si-Cu and 515-530°C for Al-Si-Mg alloys during 2-12 hours in order to dissolve the secondary phases - Mg_2Si, Al_2Cu - in the aluminum matrix, and spheroidizing silicon precipitates. In the next stage the material is *cooled down* at high speed, the most often in water (20–60°C) to retain the alloying elements in the supersaturated matrix without precipitation of secondary phases. The last stage is *artificial ageing* carried out at elevated temperature (150–200°C) for 4 to 12 hours, during which controlled precipitation of secondary phases particles (e.g. Al_2Cu, Mg_2Si) occurs.

The alloys reinforced with Al_2Cu precipitates preserve their mechanical properties even above 250°C [33, 34], while Mg_2Si hardened alloys undergo strength degradation at 170-200°C due to thickening of reinforcing precipitates [35, 36].

To sum up, obtaining an appropriate mechanical properties of the alloy is directly determined by volume fraction and morphology of microstructural components (mainly Si precipitates) as well as additives such as Mg and Cu being a potential source of precipitation processes, and having effect on the mechanical properties at high temperatures.

Taking into account that the cylinder heads operate at high temperatures, cyclic thermal-mechanical loads, optimization of the heat treatment parameters is crucial for both durability of the casting and efficiency of the production process. In industrial practice, the heat treatment process of aluminum alloys, such as Al-Si-Cu and Al-Si-Mg, must be not only technologically effective, but also economically justified. Each stage of this treatment – solutioning, cooling down and aging – is therefore associated with specific costs that have a direct impact on profitability of the entire production process. Therefore, nowadays one strives after introduction of optimal, shortened cycles, usually lasting several hours, which allow for full hardening with minimal energy and time expenditures [37-40].

The study presented in this paper aims at evaluation of effectiveness of the T6 heat treatment, carried out in appropriately selected (limited) ranges of solutioning and aging heat treatment parameters of cylinder head castings with particular emphasis on obtained mechanical properties.

2. Experimental methods

The cylinder head of a four-cylinder spark-ignition combustion engine (Fig. 1) was made using gravity die-casting technology, from the 320.0 (AlSi7Cu3Mg) alloy with chemical composition shown in the Table 1. Due to copyright restrictions related to design of the cylinder heads, the components tested in this study are presented in the form of schematic drawings (Fig. 1). These were developed based on 3D scans of the castings performed using an eviXscan Pro+ scanner, offering accuracy of 0.01–0.025 mm (in accordance with the DE VDI/VDE 2634 Part 2 standard [41]). The scans were processed into editable models using Geomagic Design X software.

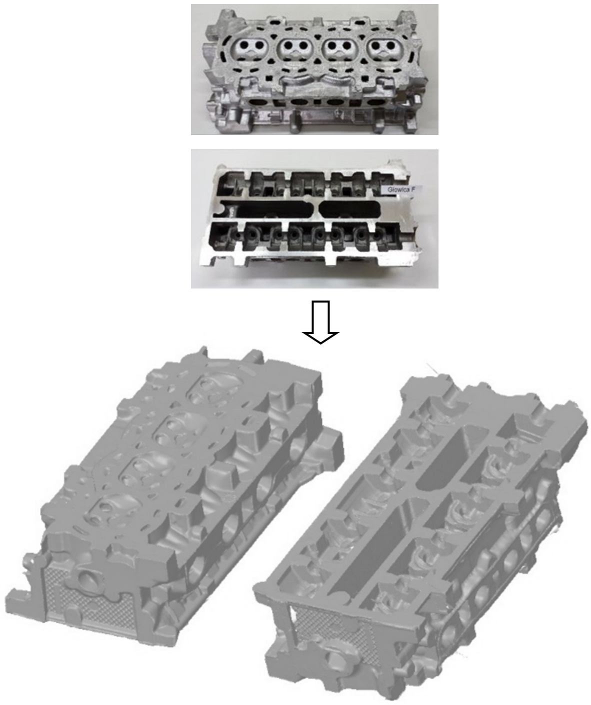

Fig. 1. Cylinder heads casting

Table 1.
Chemical composition of the investigated alloy

Chemical composition / % mass							
Si	Cu	Zn	Fe	Mg	Mn	Pb	Al
7,5	3,0	0,3	0,8	0,41	0,28	0,03	rest.

The chemical composition was analyzed by inductively coupled plasma emission spectrometry method, using the PerkinElmer Optima 4300 DV optical emission spectrometer on a material sample cut from the casting.

The cylinder head casting was heat treated according to the diagram (Fig. 2), based on results of the investigations [42], in course of which the heat treatment of the samples cast from the base material of the cylinder heads was carried out, enabling determination of optimal ranges of parameters of the solutioning and aging operations, determining a significant increase in the mechanical properties of the AlSi7Cu3Mg alloy.

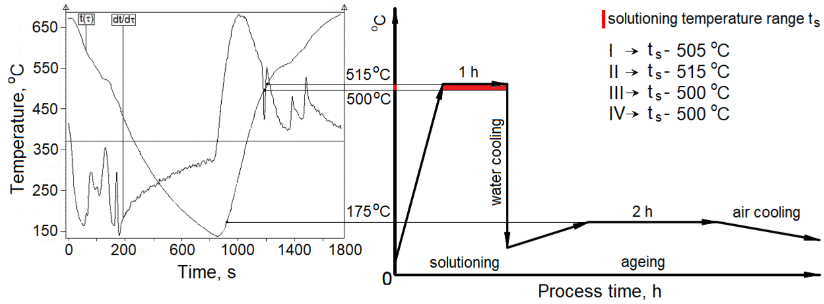

Fig. 2. Scheme of the heat treatment of the cylinder heads

The heat treatment of cylinder heads consisted in heating the castings in furnace to solutioning temperature in the range of 500–515°C, followed by soaking at this temperature for 1 hour. After completion of the solutioning heat treatment, the castings were quenched by cooling in water - at temperature of 20°C for cylinder heads I–III and at 60°C for cylinder head IV. The last stage of the process was artificial aging carried out at temperature 175°C for 2 hours. The solutioning treatment was carried out in an electric resistance furnace, in which the temperature was measured simultaneously for the casting, for the heating elements and for the furnace chamber using Ni-NiCr K-type thermocouples with accuracy of ± 5°C. The aging was carried out in laboratory dryer of the SLN 53 STD type.

After performed heat treatment, the material destined for the samples to evaluation of the strength properties ($R_{0.05}$, $R_{0.2}$, R_m, A5) of the cylinder head castings was cut out in the places, whose location is shown in the Figure 3. Next, they were formed by machining operation in accordance with the PN-EN ISO 6892-1:2010P standard [43] (sample with measuring length of 30 mm and diameter of 6 mm).

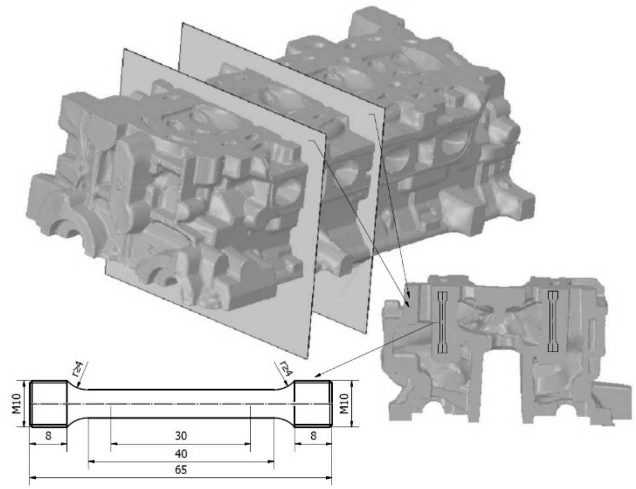

Fig. 3. Locations where samples to the strength test were cut out from the cylinder head casting

The static tensile tests were carried out in accordance with the PN-EN ISO 6892-1:2010P standard using the Instron 33R4467 tensile testing machine equipped with 30kN (Class 1) measuring head. The strain was measured using the extensometer with 25mm base, 0–2.5mm range, 1μm resolution, and Class 1 accuracy. Data recording was performed using the Instron Bluehill 3 software. The Brinell hardness measurement was performed in accordance with the PN-EN ISO 6506-1:2008P standard [44], using the Brinell hardness tester of PRL 82 type. A 10mm diameter steel ball and load of 9800N sustained for 30 seconds were used. Hardness measurements were taken on milled surface from combustion chamber side (Fig. 4).

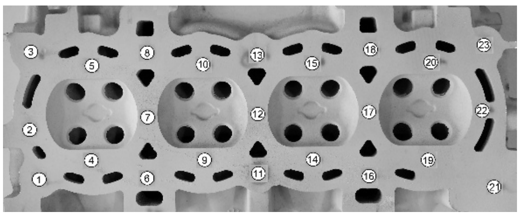

Fig. 4. Locations of hardness measurement of the cylinder heads

In addition, the measurements were made on the cross-sectional surface through valve seats (Fig. 5).

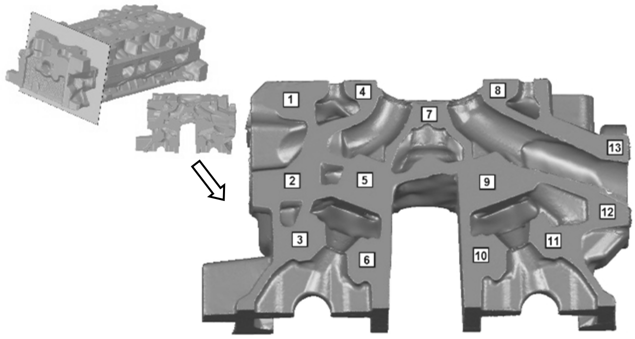

Fig. 5. Surface of cross-section of the cylinder head with marked locations of the hardness measurements

Additionally, metallographic sections were produced based on material collected from selected areas of the analyzed cross-section of the cylinder head to verify changes in the material structure, analyzed after performed heat treatment. Metallographic examinations were performed using the Olympus DSX 500 microscope.

3. Research results and analysis

The test results obtained on the basis of static tensile test of the samples taken from heat-treated castings of the cylinder heads of the engine are presented in the Figure 6 in the form of bar graphs, on which are applied values of individual properties for the initial material (casting without heat treatment - S) and for the material after the heat treatment (heat-treated castings - I÷IV).

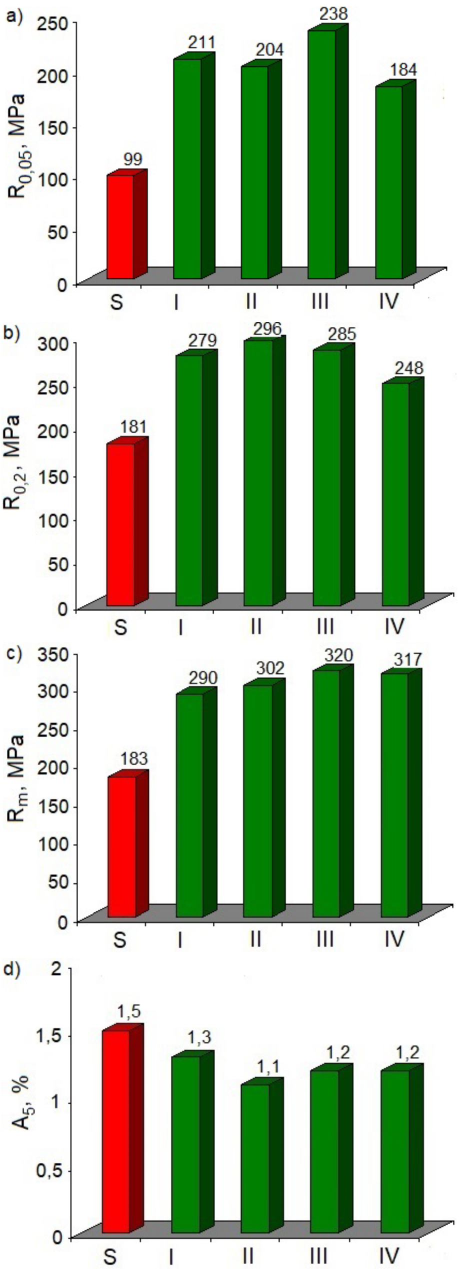

Fig. 6. Mechanical properties of the material of the cylinder head casting: a) elastic limit $R_{0.05}$, b) yield strength $R_{0.2}$, c) tensile strength R_m, d) elongation A_5

Applied method of the heat treatment of the cylinder head castings resulted in a significant increase in the mechanical properties of the alloy. Nearly twofold increase in the elastic limit $R_{0.05}$ and the yield strength $R_{0.2}$ (approx. 100% compared to non-heat-treated alloy) was observed, also increase in the tensile strength R_m in the range of 58–74%. At the same time, a decrease in A_5 elongation by 15–30% compared to the initial value was observed. Similar results were reported in the study [45], where comparable mechanical properties were obtained only after twice longer solutioning time (at temperature 498°C) and aging carried out at temperature higher by 55°C and for a time shorter by 30 minutes. In the study of Peng Hu et al [14], to achieve values of $R_{0.2}$=314 MPa and R_m=379 MPa, it was necessary to carry out solutioning treatment for 5 hours (503°C) and aging treatment for successive 5 hours at 210°C. However, a significant decrease in elongation was the side effect of this treatment – to a level of only 30% of the value observed for the initial (not heat-treated) state. Samuel [46] recommends treatment of the solutioning at 500—510°C for 12 hours and next, artificial aging for 2—5 hours at temperature 160—180°C, enabling to obtain $R_{0.2}$=150 MPa, R_m=250 MPa, elongation 3%.

Sokolowski [47] proposed an alternative method of two-stage solutioning and aging, which allowed to obtain mechanical parameters at the level of about 60% of the values from the presented research, using a milder thermal conditions. Interesting results were also presented by Mao et al. [48], who developed three-stage heat treatment cycle for the alloy containing 50% less copper than in own research. A favorable combination of A5 elongation at the level of 10%, $R_{0.2}$ value comparable to the presented values and Rm value higher by 30% was obtained then, at total process duration of 20 hours. Similar directions of the proceedings are also observed in the case of other alloys used for cylinder heads, including AlSi9Cu3 [49, 50], AlSi7Cu0,5Mg [51, 52] and 356.0 [53, 54, 17], for which processes of the heat treatment are usually carried out in an extended manner (lasting several times longer), and optimized in terms of compromise between the strength and the plasticity.

In the light of literature from this subject-matter, the obtained results can be considered as optimal in terms of compromise between the strength and the elongation. Compared to other authors who achieved similar or slightly higher mechanical parameters at much longer times of solutioning and aging heat treatment, the applied approach is characterized by a greater effectiveness of time and energy, which makes it attractive from the point of view of industrial practice.

In the Table 2 are presented ranges of the HB hardness obtained during measurements on surface of the cylinder head casting (in accordance with the Fig. 4).

Table 2.
HB hardness of surface of the cylinder head casting

S	I	II	III	IV
76-84	129-138	125-129	129-138	107-114

As the result of performed heat treatment of the cylinder head castings made of the AlSi7Cu3Mg alloy, a significant increase in the hardness of the material was observed, ranging from 37% to 66% compared to the initial state (casting not subjected to the heat treatment). This effect was also confirmed by local measurements made on surface of the cross-section of the cylinder head (Fig. 7), where values of the hardness according to the Brinell HB scale increased from 76–82 to 120–125.

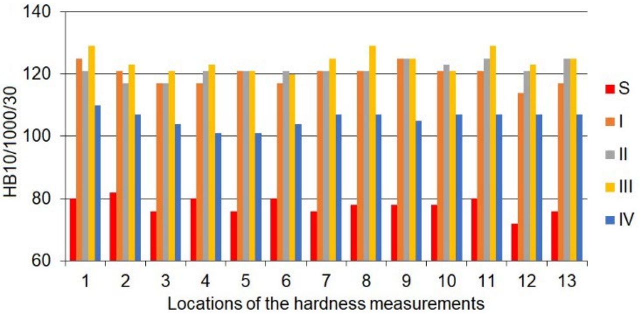

Fig. 7. Distribution of the HB hardness on the cross-section (Fig. 5): S – untreated head, I÷IV - heat treatment variants

Similar tendencies can be noticed in the literature. Zhi-xiang Huang et al. [55] obtained value of 129.3 HV hardness after a two-step solutioning heat treatment (500°C for 6 hours and 520°C for 4 hours) followed by aging treatment for 7 hours at 175°C. Increase in the hardness in this case amounted to 25.4% compared to the material without the heat treatment. Maghini et al. [56] achieved increase in the hardness to 130 HV (about 60%) with use of optimized thermal scheme, consisting of short solutioning heat treatment (1 hour at 495°C), followed by aging treatment for 1.5 hours at 210°C, and introduction of the intermediate stage of the T4 treatment lasting 24 hours. In turn, Mori et al. [57] showed that the maximum strengthening of the material is achieved by 4 hours of aging at 180°C and earlier solutioning treatment at 500°C for 6 hours. Slight differences between the measured hardness at individual points are resulting from run of solidification process of the material mainly, determined by different cooling rate of the alloy, and thus from non-homogeneous structure of the material [58], which as results finds its reflection in the hardness of the material after the heat treatment [42]. The Figure 8 shows the microstructures of selected cross-sections of the head casting.

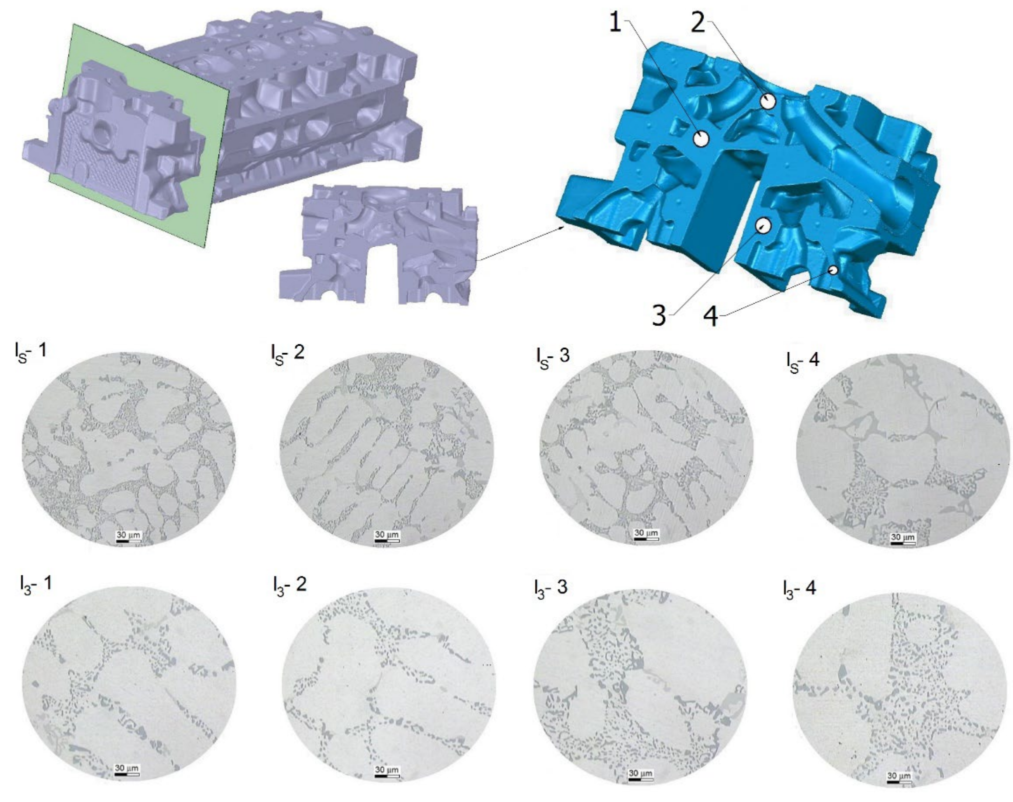

Fig. 8. Microstructure in a selected places of cross-section of the cylinder head: I_S – casting without the heat treatment, I_3 – casting after the heat treatment (500°C/1 h + 175°C/2 h)

The optimal mechanical properties of the alloy are obtained with small, spherical and evenly distributed particles [49]. Optical microscopy analyses revealed presence of the α-Al matrix surrounded by eutectic regions and intermetallic particles. Structure of the alloy consists of the α-phase dendrites, eutectic (mixture of the phase α, and eutectic silicon) as well as intermetallic phases. Eutectic Si underwent spheroidization and coarsening during treatment with the solution. Treatment of the solution causes a significant degree of spheroidization and coarsening in modified eutectic phases [50, 51, 59, 60].

The heat treatment led to spheroidization of eutectic silicon, and the α phase emerged as large and rounded grains. There is no significant difference in microstructure images. Hardness and strength were achieved in the region of coherent formation of precipitates, probably at the beginning of deposition of partially coherent θ′ phase (Al_2Cu) [39-41, 51].

Performed heat treatment resulted in a significant degree of spheroidization and thickening of Si in modified eutectic phases. [17, 51, 60]. Process of spheroidization of silicon, as result of the heat treatment, takes place in two stages: fragmentation or dissolution of eutectic fibers/branches and spheroidization of separated branches. Rate of spheroidization depends on size of fragmented segments – in the case of the analyzed structures, modified structure of the alloy in the as-cast state (I_s – Fig. 8) had a positive impact on shortening of time needed to completion of this process. At the same time, as a result of these changes, increase in the hardness and the final strength can be also observed [50, 56].

4. Conclusions

Performed investigations have confirmed that applied procedure of the heat treatment – consisting of solutioning of the AlSi7Cu3Mg alloy at temperature of 500–515°C for 1 hour, and next, water cooling and artificial aging at temperature of 175°C – effectively improves mechanical properties of the material used to production of the cylinder heads.

It has been observed a substantial, nearly two-fold increase in the yield point from 99 MPa in case of the alloy without the heat treatment to 238 MPa for the alloy after the heat treatment and in the plasticity (285 MPa) compared to the alloy without the heat treatment, as well as a significant increase in the tensile strength from the level of 183 MPa to 320 MPa after the heat treatment. Simultaneously, a moderate decrease in the plasticity (reduction of the elongation from 1.5% to 1.2%) was observed. It was observed a significant, almost two-fold increase in the elastic and plastic limit compared to unheat-treated state, as well as a significant increase in tensile strength, with a simultaneous moderate decrease in plasticity. From industrial application points of view, it is important that such beneficial effects were obtained with a relatively short time of the solutioning and aging treatments, which, in comparison with literature data, proves the high efficiency of the applied scheme. Shortening of duration of the solutioning and ageing heat treatment operations, while maintaining appropriate temperatures, allows for optimization of the technology in terms of energy costs and production efficiency, without significant reduction of strength properties of the material. This points at reasonableness of further research towards shortening of thermal cycles while simultaneously controlling the microstructure and mechanical properties of the castings made of the Al-Si-Cu-Mg alloys.

References

[1] Béranger, M., Morin, G., Saanouni, S., Koster, A. & Maurel, V. (2018). Fatigue of automotive engine cylinder heads – A new model based on crack propagation. In the 12th International Fatigue Congress (FATIGUE 2018), 27 May -1 June 2018 (pp.1-7). France: *MATEC Web Conf.* 165, 10013. DOI: 10.1051/matecconf/201816510013.

[2] Choi, G.H., Choi, K.H., Lee, J.T., Song, Y.S., Ryu, Y. & Cho, J.W. (1997). Analysis of combustion chamber temperature and heat flux in a DOHC engine. *SAE Technical Papers.* 106, 970895, 1499-1507. DOI: https://doi.org/10.4271/970895.

[3] Natesan, E., Eriksson, S., Ahlström, J. & Persson, C. (2020). Effect of temperature on deformation and fatigue behaviour of A356–T7 Cast aluminium alloys used in high specific power IC engine cylinder heads. *Materials*. 13(5), 1202, 1-27. DOI: https://doi.org/10.3390/ma13051202.

[4] Su, X., Zubeck, M., Lasecki, J., Engler-Pinto, C.C., Tang, C., Sehitoglu, H. & Allison, J. (2002). Thermal fatigue analysis of cast aluminum cylinder heads. *SAE Transactions*. 111, 418-424. http://www.jstor.org/stable/44718668.

[5] Mendes, A. & Cardoso, A. (2007). Structural analysis of the aluminum cylinder head for a high-speed diesel engine. *SAE Technical Papers.* 2007-01-2562. DOI: https://doi.org/10.4271/2007-01-2562.

[6] Pesce, F. C., Vassallo, A., Beatrice, C., Di Blasio, G., Belgiorno, G., Avolio, G., Kastner, O. & Leuteritz, U. (2016). Exceeding 100 kW/l milestone: the next step towards defining high performance diesel engines. In the 25th Aachen Colloquium Automobile and Engine Technology, 10-12 October (pp.159-183). Aachen, Germany.

[7] Liu, L., Yan Peng, Y., Wenzheng Zhang, W. & Xiuzhen Ma, X. (2023). Concept of rapid and controllable combustion for high power-density diesel engines. *Energy Conversion and Management*. 276, 116529, 1-16. https://doi.org/10.1016/j.enconman.2022.116529.

[8] Cooper, A., Stodart, A., Hancock, D., Duke, S., Miller, J. & Reader, S. (2019). Development of two new high specific output 3 cylinder engines for the global market with capacities of 1.2l and 1.5l. *SAE Technical Paper.* 2019-01-1193. https://doi.org/10.4271/2019-01-1193.

[9] Wasserbäch, T., Osborne, R., Luchansky, K. & Alt, M. (2019). New spark ignition engines. *Sonderprojekte ATZ/MTZ* . 24(1), 38. DOI: https://doi.org/10.1007/s41491-019-0011-5.

[10] Sjölander, E. & Seifeddine, S. (2012). The influence of natural ageing on the artificial ageing response of Al-Si-Cu-Mg casting alloys. *La Metallurgia Italiana*. 11-12, 39-43.

[11] Zhao, X., Huang, W., Ren, P., Xia, P., Kuang, J. & Tang, J. (2025). Research on stress distribution and dispersion of cylinder head. *Journal of Physics: Conference Series*. 2992, 012033, 1-13. DOI:10.1088/1742-6596/2992/1/012033.

[12] Shojaefard, M.H., Ghaffarpour, M.R., Noorpoor, A.R. & Alizadehnia S. (2006). Thermomechanical Analysis of an Engine Cylinder Head. *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*. 220(5), 627-636. DOI:10.1243/09544070JAUTO182.

[13] Wang, Q., Bobel, A., Walker, M., Hess, D., Doty, H. & Gerard, D (2025). Evaluation of two new cast aluminum alloys for high performance cylinder heads. *International Journal of Metalcasting*. 19, 52-58. https://doi.org/10.1007/s40962-024-01341-5

[14] Peng Hu, P., Lei Pan, L. & Chen, X.-G. (2024). Elevated-temperature performances of Al-Si-Cu casting alloys for

cylinder head applications. *Materials Characterization*. 218(1), 114484, 1-14. https://doi.org/10.1016/j.matchar.2024.114484.

[15] Campbell, J. (2011). *Complete casting handbook: metal casting processes, metallurgy, techniques and design*. Oxford: Elsevier.

[16] Langmayr, F. & Zieher, F. (2004). Thermomechanik in Zylinderköpfen, Ventiltrieb und Zylinderkopf. *VDI Berichte*. 1813, 227-243.

[17] Tillová, E., Chalupová, M., Kuchariková, L., Belan, J., & Závodská, D. (2018). Selection of optimal solution heat treatment of the casting cylinder heads. In *MATEC Web of Conferences* (Vol. 157, pp. 02053). EDP Sciences.

[18] Yuan Li, Y., Jinxiang Liu, J., Qiang Zhang, Q. & Weiqing Huang, W. (2012). Casting defects and microstructure distribution characteristics of aluminum alloy cylinder head with complex structure. *Materials Today Communications*. 27, 102416, 1-11. https://doi.org/10.1016/j.mtcomm.2021.102416.

[19] Willkomm, J., Kuhlbach, K., Merget, D., Wagner, M., Reich, S., Ziegler, S. & Schleifenbaum, J. H. (2021). Design and manufacturing of a cylinder head by laser powder bed Fusion. *IOP Conference Series: Materials Science and Engineering.* 1097, 012021, 1-9. DOI: 10.1088/1757-899X/1097/1/012021.

[20] Gray, J., Depcik, C., Sietins, J. M., Kudzal, A., Rogers, R. & Cho, K. (2023). Production of the cylinder head and crankcase of a small internal combustion engine using metal laser powder bed fusion. *Journal of Manufacturing Processes*. 97, 100-114. https://doi.org/10.1016/j.jmapro.2023.04.054.

[21] Camicia, G. & Timelli, G. (2016). Grain refinement of gravity die cast secondary AlSi7Cu3Mg alloys for automotive cylinder heads. *Transactions of Nonferrous Metals Society of China*. 26(5), 1211-1221. DOI: /10.1016/S1003-6326(16)64222-X.

[22] Dillibabu, S.P., Vasudevan, B., Megaraj, M., Palanivel, A., Durvasulu, R. & Manjunathan, K. (2023). Aluminum and its alloys in automotive and aerospace applications review Available to Purchase. *AIP Conference Proceedings.* 2766(1), 020027. https://doi.org/10.1063/5.0139311.

[23] Alam T, & Ansari, A.H. (2017). Review on Aluminum and Its Alloys for automotive applications. *International Journal of Advanced Technology in Engineering and Science.* 5, 278-294. ISSN (2348-7550).

[24] Hao, Z., Ju, Y. & Chen, L. (2023). The use of aluminium and magnesium alloys in automotive lightweight technologies. *Journal of Mechanical Science and Technology*. 37, 4615-4622. https://doi.org/10.1007/s12206-023-0712-2.

[25] Baser, T.A., Umay, E. & Akıncı, V. (2022). New trends in aluminum die casting alloys for automotive applications. *The Eurasia Proceedings of Science Technology Engineering and Mathematics.* 21, 79-87. https://doi.org/10.55549/epstem.1227541.

[26] Sourav, Patil, S., Chandra, N., Kumar, N., Kumar, D. & Shetty, R. P. (2024). Analysis of mechanical properties of casted aluminium alloy for automotive safety application. *Engineering Proceedings*. 59(1), 157, 1-12. https://doi.org/10.3390/engproc2023059157.

[27] Niu, G., Wang, Y., Zhu, L., Ye, J. & Mao, J. (2022). Fluidity of casting Al–Si series alloys for automotive light-weighting: a systematic review. *Materials Science and Technology*. 38(13), 902-911. DOI:10.1080/02670836.2022.2068274.

[28] Mahton, Y., Jha, V. & Saha, P. (2024). Effect of heat treatment on microstructure, mechanical, and corrosion properties of Al 319.0 alloy. *International Journal of Metalcasting*. 18, 512-529. https://doi.org/10.1007/s40962-023-01030-9.

[29] Vandersluis, E., Lombardi, A., Ravindran, C., Bois-Brochu, A., Chiesa, F. & MacKay, R. (2015). Factors influencing thermal conductivity and mechanical properties in 319 Al alloy cylinder heads. *Materials Science & Engineering: A.* 648, 401-411. https://doi.org/10.1016/j.msea.2015.09.091.

[30] Natesan, E., Meyer, K.A., Eriksson, S., Ahlström, J. & Persson, C. (2020). Effects of dwell time on the deformation and fatigue behaviour of A356-T7 cast aluminium alloys used in high specific power ic engine cylinder heads. *Materials*. 13(12), 2727, 1-27. https://doi.org/10.3390/ma13122727.

[31] Kaufman, J.G. & Rooy, E.L. (2004). Aluminium Casting Alloys*.* In J.G. Kaufman & E.L. Rooy (Eds.), *Aluminum alloy castings: properties, processes, and applications* (pp. 17-19). ASM International. Materials Park, OH.

[32] Akar, N., Sahin, O. & Kilicli, V. (2025). Effect of two-step solution treatments on the microstructure and mechanical properties of B357 aluminum alloy. *International Journal of Metalcasting*. 19(1), 544-558. https://doi.org/10.1007/s40962-024-01320-w.

[33] Rakhmonov, J., Liu, K., Pan, L., Breton, F. & Chen, X.G. (2020). Enhanced mechanical properties of high-temperature-resistant Al–Cu cast alloy by microalloying with Mg. *Journal of Alloys and Compounds*. 827, 154305, 1-9. DOI: 10.1016/j.jallcom.2020.154305.

[34] Li, D., Liu, K., Rakhmonov, J. & Chen, X.G. (2021). Enhanced thermal stability of precipitates and elevated-temperature properties via microalloying with transition metals (Zr, V and Sc) in Al–Cu 224 cast alloys. *Materials Science & Engineering: A*. 827, 142090, 1-12. DOI: 10.1016/j.msea.2021.142090.

[35] Jeong, C.-Y. (2013). High temperature mechanical properties of Al–Si–Mg–(Cu) alloys for automotive cylinder heads. *Materials Transactions*. 54(4), 588-594. https://doi.org/10.2320/matertrans.M2012285.

[36] Tzeng, Y. C., Chengn, V. S., Nieh, J. K., Bor, H. Y. & Lee, S. L. (2017). Microstructure and thermal stability of A357 alloy with and without the addition of Zr. *Journal of Materials Engineering and Performance.* 26(11), 5511-5518. DOI: 10.1007/s11665-017-2921-2.

[37] Menargues, S., Martín, E., Baile, M.T. & Picas, J.A. (2015). New short T6 heat treatments for aluminium silicon alloys obtained by semisolid forming. *Materials Science and Engineering: A*. 621, 236-242, https://doi.org/10.1016/j.msea.2014.10.078.

[38] Pezda, J. & Jezierski, J. (2020). Non-standard T6 heat treatment of the casting of the combustion engine cylinder head. *Materials*. 13(18), 4114, 1-13. DOI: 10.3390/ma13184114.

[39] Akhtar, M., Qamar, S.Z., Muhammad, M. & Nadeem, A. (2018). Optimum heat treatment of aluminum alloy used in manufacturing of automotive piston components. *Materials and Manufacturing Processes*. 33(16), 1874-1880. https://doi.org/10.1080/10426914.2018.1512128.

[40] Dong, Z. Q., Wang, J.G., Guan, Z.P., Ma, P.K., Zhao, P., Li, Z.J., Lu, T.S. & Yan, R.F. (2021). Effect of short t6 heat treatment on the thermal conductivity and mechanical properties of different casting processes Al-Si-Mg-Cu alloys. *Metals*. 11(9), 1450, 1-11. https://doi.org/10.3390/met11091450.
[41] VDI/VDE 2634 Blatt 2:2002-08: Optical 3D-measuring systems - Optical systems based on area scanning.
[42] Pezda, J. (2015). Effect of shortened heat treatment on change of the R_m tensile strength of the 320.0 aluminum alloy. *Archives of Foundry Engineering*. 15(1), 75-78.
[43] PN-EN ISO 6892-1:2010P: Metals. Tensile test. Part 1: Room temperature test method.
[44] ISO 6506-1:2014. Metallic materials - Brinell hardness test - Part 1: Test method.
[45] Chaudhury, S.K., Apelian, D., Meyer, P. Massinon, D. & Morichon, J. (2015). Fatigue performance of fluidized bed heat treated 319 alloy diesel cylinder heads. *Metallurgical and Materials Transactions A*. 46(7), 3015-3027. DOI: 10.1007/s11661-015-2901-9.
[46] Samuel, F.H. (1998). Incipient melting of Al5Mg8Si6Cu2 and Al2Cu intermetallics in unmodified and strontium-modified Al–Si–Cu–Mg (319) alloys during solution heat treatment. *Journal of Materials Science.* 33, 2283-2297. https://doi.org/10.1023/A:1004383203476.
[47] Sokolowski, J.H., Djurdjevic, M.B., Kierkus, C.A., & Northwood, D.O. (2001). Improvement of 319 aluminum alloy casting durability by high temperature solution treatment. *Journal of Advanced Materials Processing Technology*. 109(1-2), 174-180. https://doi.org/10.1016/S0924-0136(00)00793-7.
[48] Mao, H., Bai, X., Song, F., Song, Y., Jia, Z., Xu, H., & Wang, Y. (2022). Effect of Cd on mechanical properties of Al-Si-Cu-Mg alloys under different multi-stage solution heat treatment. *Materials*. 15(15), 5101, 1-14. https://doi.org/10.3390/ma15155101.
[49] Matvija, M., Kuchariková, L., Tillová, E., Chalupová, M. & Belan, J. (2017). Study of the precipitation hardening process in recycled Al-Si-Cu cast alloys. *Archives of Metallurgy and Materials.* 62(1), 397-403. DOI: 10.1515/amm-2017-0062.
[50] Morin, S., Elgallad, E.M., Doty, H.W., Valtierra, S. & Samuel, F. H. (2016). Effect of Mg content and heat treatment on the mechanical properties of low pressure die-cast 380 alloy. *Advances in Materials Science and Engineering*. 2016(1), 7841380, 1-12, http://dx.doi.org/10.1155/2016/7841380.
[51] Mičian, M., Kantoríková, E., Borowiecka-Jamrozek, J. & Kasińska, J. (2025). Analysis of heat treatment of AlSi7Cu0.5Mg alloy. *Materials.* 18(4), 733, 1-19. https://doi.org/10.3390/ma18040733.
[52] Wang, R., Gonzalez, C.B., Stauder, B., Gutierrez, R.F., Albu, M., Sommadossi, S., Povoden-Karadeniz, E. & Poletti, M.C (2024). Influence of the heat treatment path on the precipitation sequence in an AlSi7Cu0.5Mg-alloy. *Journal of Alloys and Compounds*. 990, 174450, 1-13. https://doi.org/10.1016/j.jallcom.2024.174450.
[53] Doty, H.W., Samuel, E., Samuel, A.M., Songmene, V. & Samuel, F.H. (2025). Effect of melt treatment and heat treatment on the performance of aluminum cylinder heads. *Materials*. 18(5), 1024, 1-25. https://doi.org/10.3390/ma18051024.
[54] Robles Hernandez, F.C., Herrera Ramírez, J.M. & Mackay, R. (2017). *Al-Si Alloys: Applications in the Automotive and Aerospace Industries*. Springer International Publishing: Cham, Switzerland.
[55] Huang, Z-X., Yan, H. & Wang, Z.-W. (2018). Microstructure and mechanical properties of strontium-modified ADC12 alloy processed by heat treatment. *Journal of Central South University*. 25(6), 1263-1273. https://doi.org/10.1007/s11771-018-3823-7.
[56] Maghini, D., Bogdanoff, T., Fortini, A. & Merlin, M. (2025). In-situ investigation of a heat-treated AlSi7Cu3Mg cast alloy: influence of solidification rate on the cyclic fatigue behaviour. *Materials Science and Engineering, A*. 936, 148370, 1-16. DOI: https://doi.org/10.1016/j.msea.2025.148370.
[57] De Mori, A., Timelli, G., Berto, F. & Fabrizi, A. (2020). High temperature fatigue of heat treated secondary AlSi7Cu3Mg alloys. *International Journal of Fatigue*. 138, 105685, 1-10. https://doi.org/10.1016/j.ijfatigue.2020.105685.
[58] Camicia, G. & Timelli, G. (2016). Grain refinement of gravity die cast secondary AlSi7Cu3Mg alloys for automotive cylinder heads. *Transactions of Nonferrous Metals Society of China*. 26(5), 1211-1221. https://doi.org/10.1016/S1003-6326(16)64222-X.
[59] Mohamed, A.M.A. & Samuel, F.H. (2012). A review on the heat treatment of Al-Si-Cu/Mg casting alloys. In F.Czerwinski (Eds.), *Heat Treatment - Conventional and Novel Applications (pp. 55-72).* InTech.
[60] Wang, J., Zhu, J., Liu, Y., Peng, H. & Su, X. (2018). Effect of spheroidization of eutectic Si on mechanical properties of eutectic Al-Si alloys. *Journal of Materials Research*. 33(12), 1-9. DOI: 10.1557/jmr.2018.144.