DOI: 10.21062/mft.2024.011 http://www.journalmt.com

The Effect of the Solution Annealing Temperature in the Hardening Process on the Properties of Al-Si-Cu Alloys

Tomáš Vlach (0000-0003-2326-4183), Jaromír Cais (0000-0002-1726-5326), Filip Mamoń (0000-0002-5658-9534), Jakub Mareš (0000-0003-0272-6238)
Faculty of Mechanical Engineering, J. E. Purkyne University in Usti nad Labem. Pasteurova 3334/7, 400 01 Usti nad Labem. Czech Republic. E-mail: tomas.vlach@ujep.cz

This article deals with the influence of the applied solution annealing temperatures in the precipitation hardening process on the resulting increase in the mechanical properties of Al-Si-Cu alloy castings with different copper contents in the alloy. AlSi7Cu2 and AlSi7Cu4 alloys were cast by gravity casting in a metal molds. Each of the samples was subjected to the Vickers microhardness measurement of a solid solution of α(Al) and Brinnel hardness measurement. Microscopic analysis and evaluation of the internal structure of each alloy was carried out in relation to used solution-annealing temperature.

Keywords: Al-Si alloys, Precipitation hardening, Microhardness, Heat treatment, Solution annealing

1 Introduction

Al-Si alloys represent the largest part of casting materials that are alloyed with different elements. The precipitation hardening process has been used for aluminum alloys since the beginning of the 20th century.However, the principle of precipitation hardening was discovered only a few years later. This happened in 1938. Plate-shaped areas were formed in the Al-Cu. [1] These formations had an increased concentration of copper and such areas are now called GP zones (according to Guinier and Preston). [2; 3] Precipitation hardening represents thermal cycles that cause changes in the microstructure of the material, thereby increasing the mechanical properties. In practice, it is an increase in hardness, strength, resistance to wear, but at the expense of a reduction in plastic properties. [4] The basic requirement for an alloy to be capable of hardening is that it has a significant change in the solubility of one or more alloying elements depending on the temperature. This condition is met by aluminum alloys that are alloyed with, for example, copper, magnesium or zinc. The content of these elements must be significantly higher than their solubility at room temperature. [5; 6] Precipitation hardening (T6) has 3 stages. Solution annealing, cooling and aging. The solution annealing temperature is chosen according to the chemical composition of the alloy and is a decisive factor. Excessive or insufficient heating must not occur. [7; 8] Cooling takes place at a supercritical rate. The cooling medium is most often water at 20 to 40 °C. The goal is the formation of a supersaturated solid solution α. [8; 9; 10] During aging, the supersaturated solid solution α breaks down. An intermetallic phase $CuAl_2$ is formed. Coherent precipitates gradually change to semicoherent. There is a deformation of the grid and an increase in mechanical properties. [11; 12] Finding the optimal solution annealing temperature is one of the prerequisites for maximizing the mechanical properties.

2 Materials and methods

AlSi7Cu2 and AlSi7Cu4 alloys alloys were used in order to conduct this research. Both alloys are used for casting. AlSi7Cu2 alloy designated according to European standards as EN AC-46600. Alloy is used in the automotive industries due to the ability of hardening. [13, 14]

The chemical composition of the selected alloy according to the standard is presented in Tab 1 below.

***Tab. 1** Chemical composition of AlSi7Cu2 [13]*

Chemical el.	Al	Si	Mn	Cu	Pb	Fe	Zn	Mg
wt [%]	≧80	6.5-8.0	≦0.65	1.5-2.5	≦0.25	≦0.8	≦1	≦0.35

***Tab. 2** Measured chemical composition of AlSi7Cu2*

Chemical el.	Al	Si	Mn	Cu	Fe	Zn	Mg
wt [%]	base	6.9	0.45	2.1	0.45	0.15	0.25

AlSi7Cu4 alloy was chosen for research. Its chemical composition according to standard as EN AC-46300 [15]. The alloy can be hardened by the addition of copper, just like the $AlSi7Cu_2$ alloy. There will likely be Al_2Cu and Al_5FeSi type phases can occure within the alloy microstructure [16, 17]. The chemical composition of the alloy according to the standard is presented in Tab 3 below.

Tab. 3 *Chemical composition of AlSi7Cu4 [15]*

Chemical el.	Al	Si	Mn	Cu	Pb	Fe	Zn	Mg
wt [%]	≧80	6.5-8.0	≦0.65	3.0-4.0	≦0.15	≦0.8	≦0.65	0.3-0.6

Tab. 4 *Measured chemical composition of AlSi7Cu4*

Chemical el.	Al	Si	Mn	Cu	Fe	Zn	Mg
wt [%]	base	6.7	0.49	3.9	0.52	0.21	0.29

2.1 Prepared samples

Melting of AlSi7Cu2 and AlSi7Cu4 alloys was conducted in graphite crucibles in an electric resistance furnace. The casting temperature was 730 °C ± 5°C. The melt was refined using ECOSAL refining salt before casting. Alloys were cast in metal molds. The molds were preheated at temperature of 180 °C. Prepared casts of the both alloys after casting are in Fig 1 below. The prepared castings were then subjected to heat treatment. This heat treatment was precipitation hardening, which consists of solution annealing, rapid cooling and artificial aging. The parameters of the applied precipitation hardening were identical for both alloys. A total of four castings were made for both alloys, while one casting was without heat treatment (část state) for comparison of results. The remaining three castings were subjected to solution annealing at temperatures of 470 °C, 495 °C and 525 °C. The holding time at these temperatures was 3 hours for all castings. The solution annealing was followed by rapid cooling into the cooling medium. The cooling medium was water, which had a temperature of 20 °C. After cooling, artificial aging was carried out at a temperature of 160 °C and the holding time at the temperature was 6 hours. In practice, this method of heat treatment is labeled T6.

a) AlSi7Cu2 b) AlSi7Cu4

Fig. 1 *Preparation of castings*

It was also necessary to mark these samples, where the letter indicated whether the sample was from the bottom or top part of the casting. In Tab. 5 shows an overview of the markings of individual samples depending on the selected alloy and applied heat treatment. A total of 16 samples were prepared.

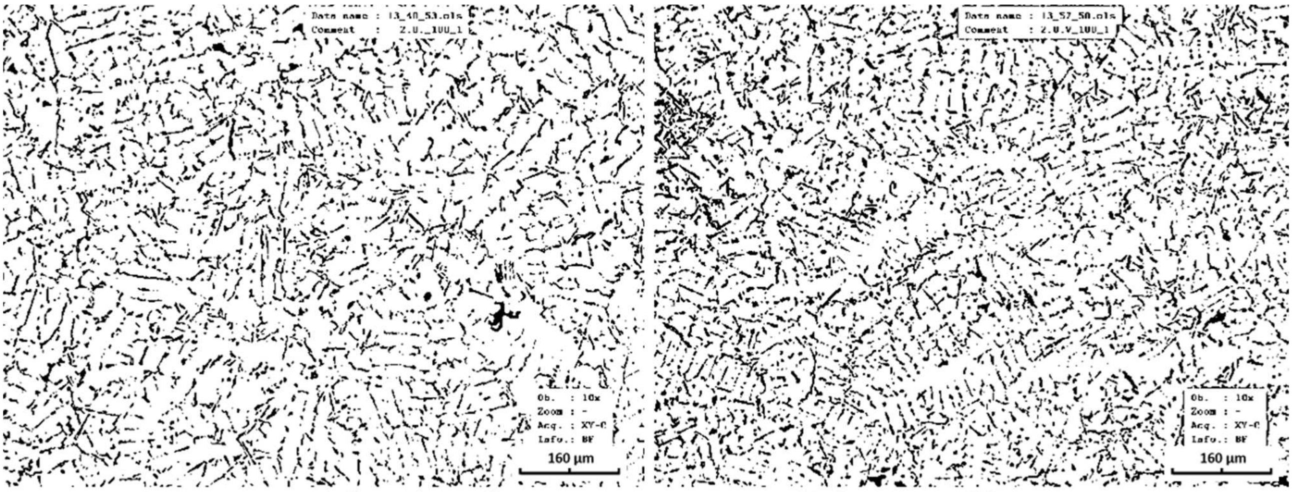
Tab. 5 *Sample identification*

Solution annealing temperature		Without heat treatment	470 °C	495 °C	525 °C
AlSi7Cu2	bottom part of the cast	2.0. S	2.1. S	2.2. S	2.3. S
	top part of cast	2.0. V	2.1. V	2.2. V	2.3. V
AlSi7Cu4	bottom part of the cast	4.0. S	4.1. S	4.2. S	4.3. S
	top part of cast	4.0. V	4.1. V	4.2. V	4.3. V

3 Results

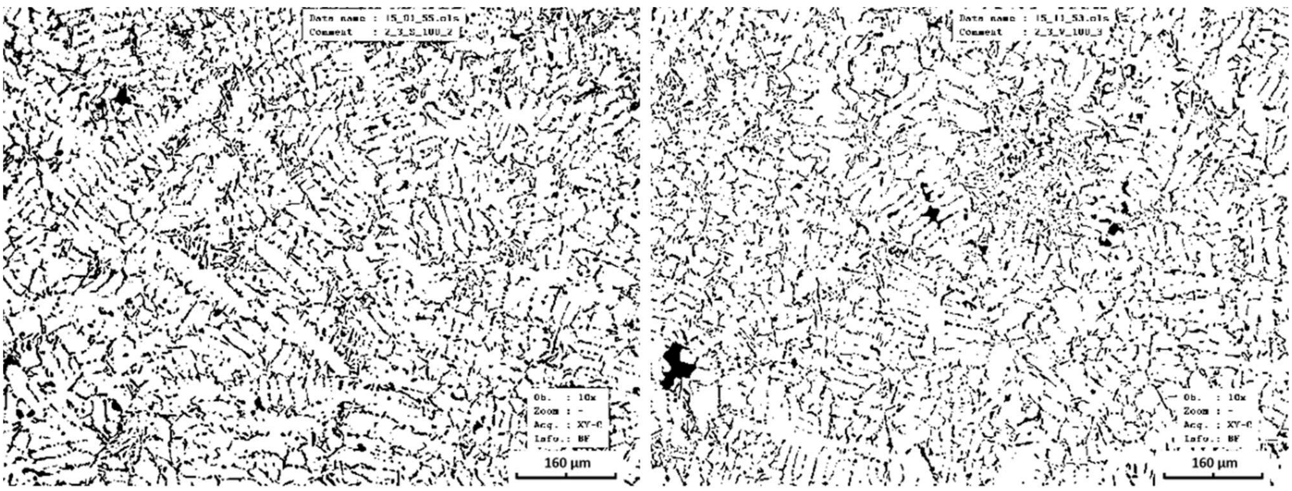
3.1 Confocal microscopy

The structure of the samples consists of a solid solution α and a eutectic. Solid solution α is represented by bright parts on the image, on the contrary, the eutectic is represented by dark needle-like parts. The eutectic has the shape of coarse needles in the plane of the metallographic cut. No significant differences in the microstructure of the material were observed between the samples without heat treatment and after heat treatment. The samples differ only in the different orientation of the eutectic needles. This applies to both AlSi7Cu2 and AlSi7Cu4 samples. A Laser Confocal Microscope Olympus Lext OLS 3100 was used to observe the microstructure of all samples (Fig- 2-5).



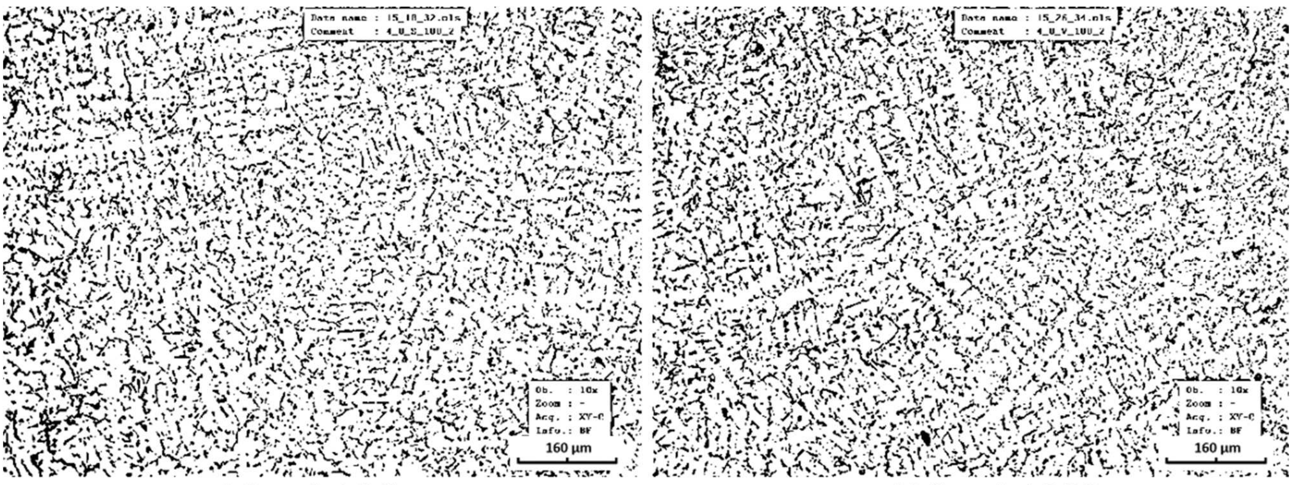
a) Sample 2.0.S *b) Sample 2.0.V*

***Fig. 2** Microstructure of the AlSi7Cu2 alloy*



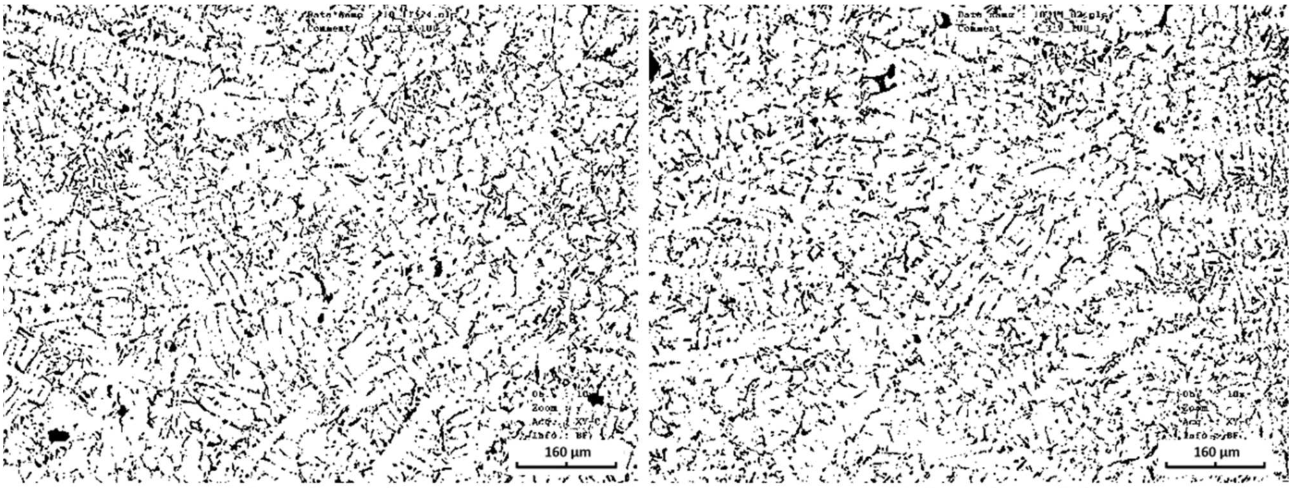
a) Sample 2.3.S *b) Sample 2.3.V*

***Fig. 3** Microstructure of the AlSi7Cu2 alloy*



a) Sample 4.0.S *b) Sample 4.0.V*

***Fig. 4** Microstructure of the AlSi7Cu2 alloy*

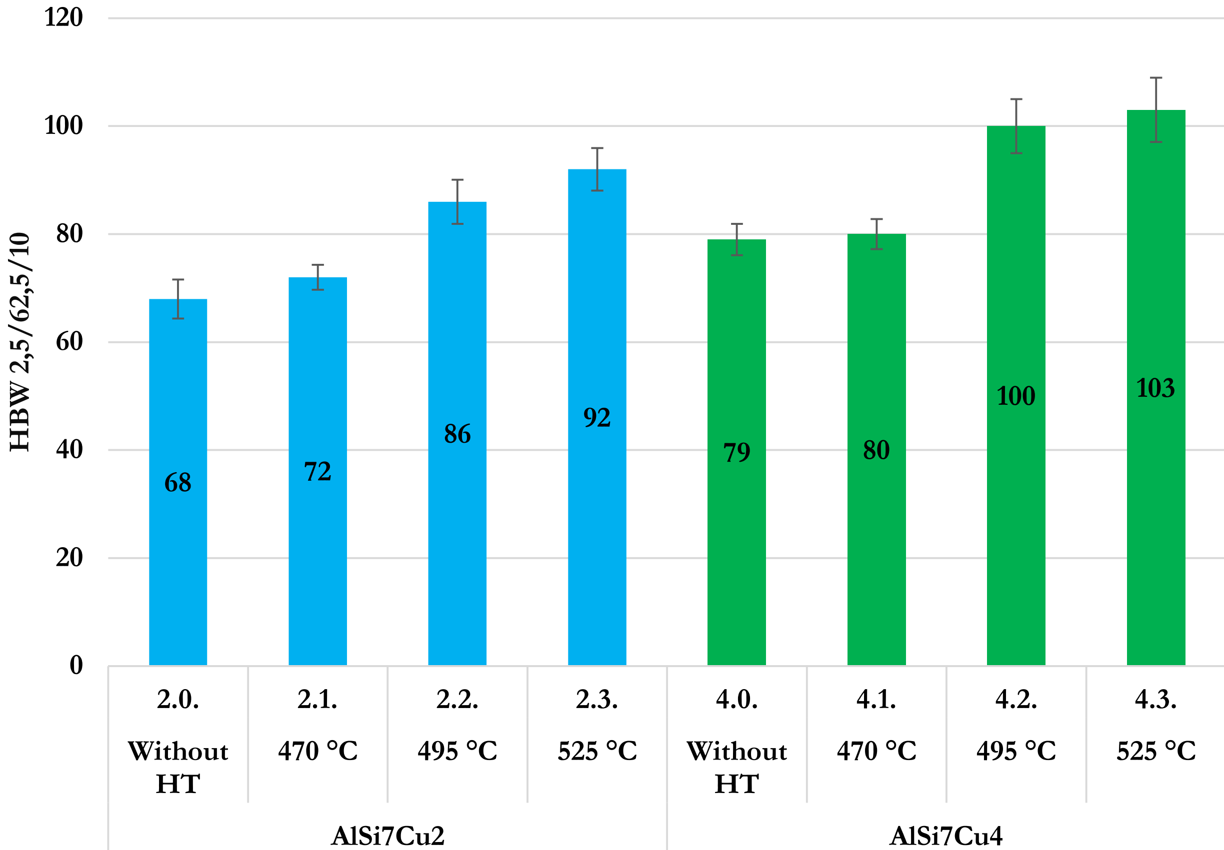


a) Sample 4.3.S *b) Sample 4.3.V*

Fig. 5 *Microstructure of the AlSi7Cu2 alloy*

3.2 Hardness

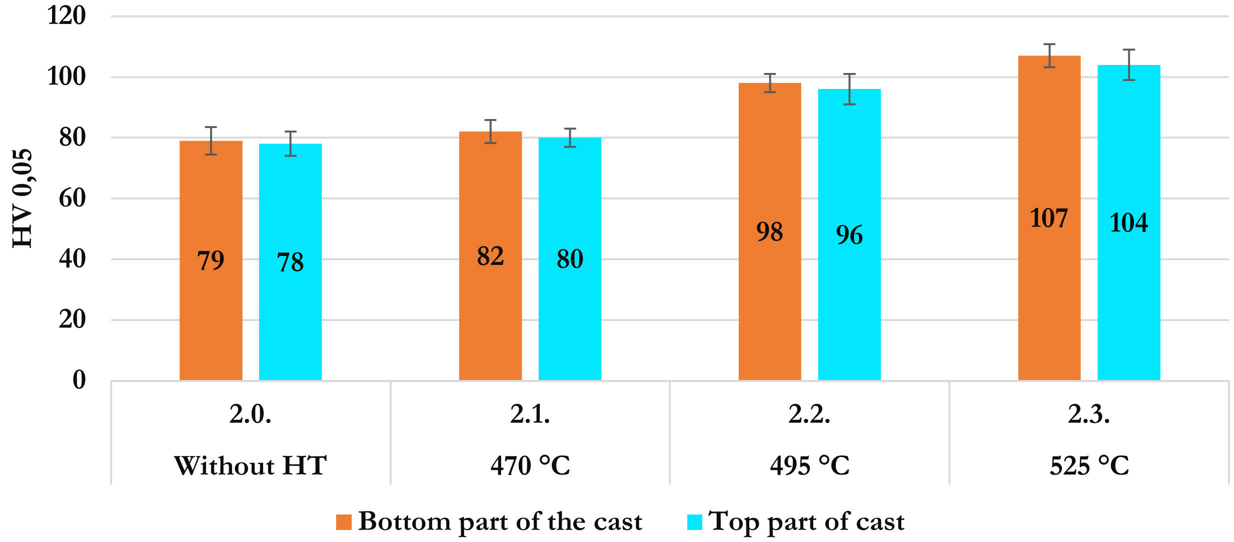
All of the samples were subjected to Brinnell hardness analysis. 10 measurements were conducted via ERNST AT 250 DR-NX Tester. The medians of the measured values of the samples are shown in the Graph 1. For castings where the temperature of solution annealing 495 °C and 525 °C was used, there was a significant increase in hardness compared to the state without heat treatment. For a temperature of 525 °C, there is approximately a 35 % increase for the AlSi7Cu2 alloy and approximately a 30 % increase for the AlSi7Cu4 alloy compared to the state without heat treatment (cast state). At this temperature, the highest hardness values were observed for both investigated alloys. In the range of the temperature, the higher the solution annealing temperature was used, the higher the increase in hardness was achieved. The AlSi7Cu4 alloy had a higher hardness than the AlSi7Cu2 alloy in all states. Hardness of the alloy increases with the copper content.



Graph 1 *Brinnell hardness of AlSi7Cu2 and AlSi7Cu4 alloys*

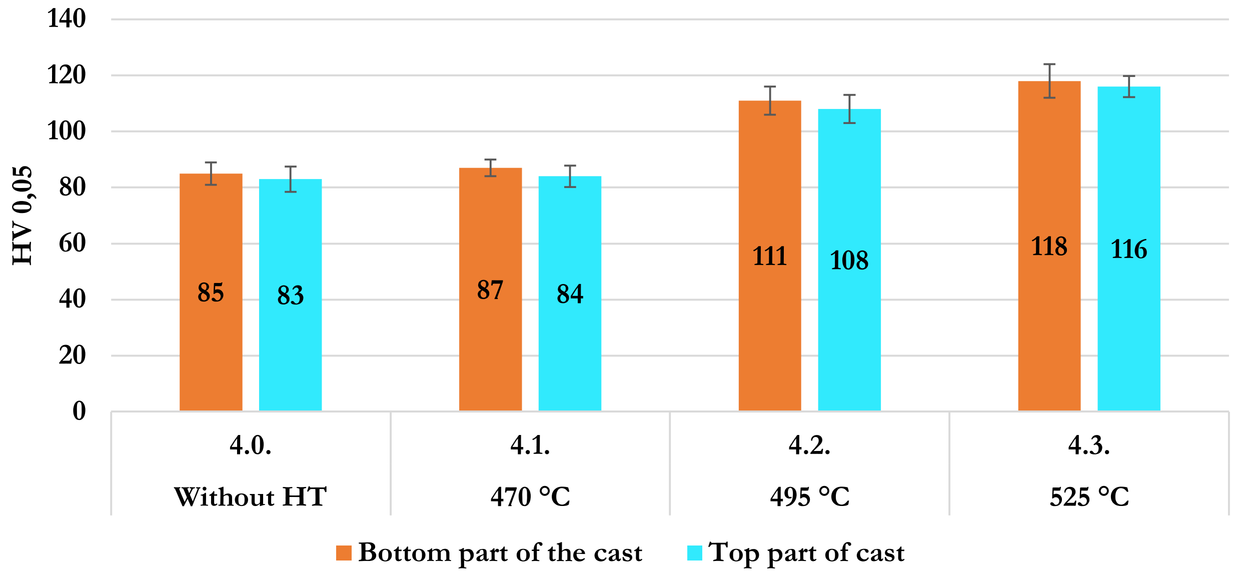
3.3 Microhardness

Microhardness analysis was performed on all samples. Measurements were conducted via SHIMADZU HMV Micro Hardness Tester. The medians of the measured values of microhardness of solid solution α(Al) of all samples were presented in the Graphs 2-3. Samples were taken from the bottom and top of each casting, and microhardness was measured according to Vickers. The Graph 2 shows the minimal increase in microhardness compared to the state without heat treatment for samples where a solution annealing temperature of 470 °C was used. The samples with a solution annealing temperature of 495 °C and 525 °C have a significant increase in microhardness compared to the state without heat treatment. The highest microhardness was observed in samples that were annealed at a temperature of 525 °C.



Graph 2 *Vickers microhardness of solid solution a(Al) AlSi7Cu2 alloy*

The effect of the annealing temperature on the increase in microhardness is similar to that of the previous AlSi7Cu2 alloy. The highest increase in microhardness compared to the state without heat treatment was achieved for samples with the highest temperature of 525 °C. Conversely, the lowest solution annealing temperature of 470 °C has very little effect on the increase in microhardness. In all states of both alloys, a higher microhardness value was measured for samples from the bottom part. This is due to rapid cooling during casting into the metal mold. In the bottom part of the casting, there is a finer structure, which improves the mechanical properties.



Graph 3 *Vickers microhardness of solid solution a(Al) AlSi7Cu4 alloy*

Graph 4 shows a mutual comparison of the resulting values of the microhardness of the castings, depending on what temperature of solution annealing was used for them. From the given values, it can be concluded that the AlSi7Cu4 alloy achieved higher microhardness values than the AlSi7Cu2 alloy in all states of hardening, including the as-cast state without heat treatment.

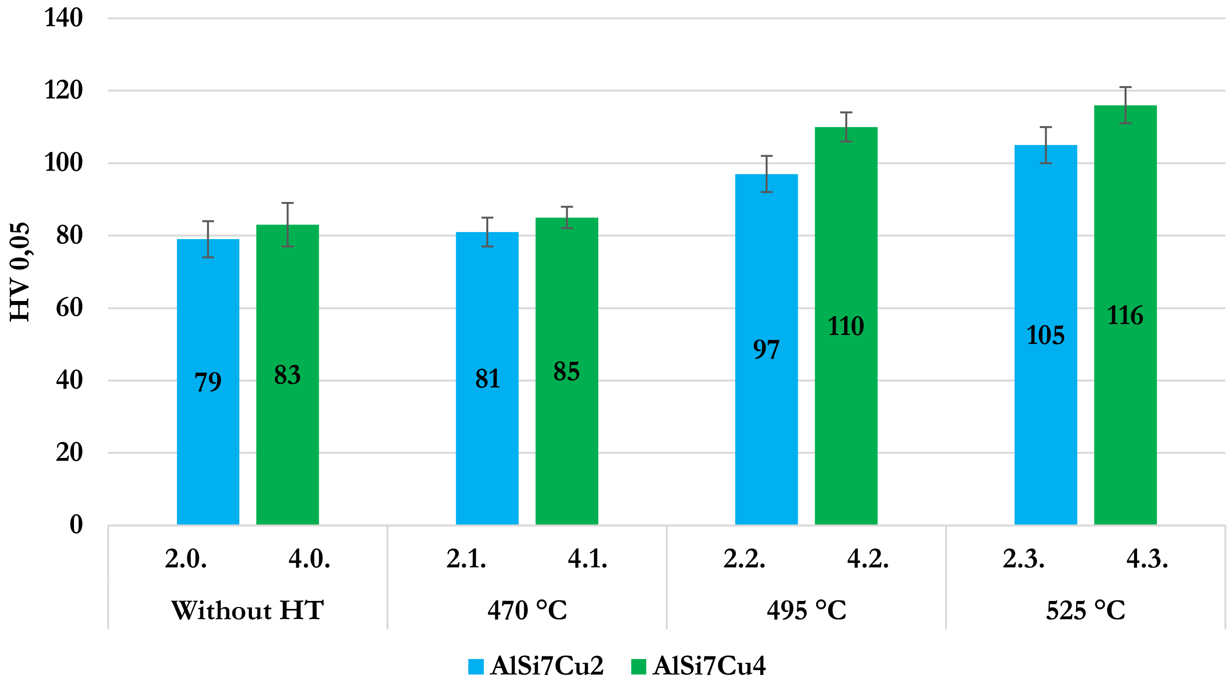
The highest microhardness values were achieved for both alloys at the used solution annealing temperature of 525 °C. Specifically, 105 HV 0.05 for the AlSi7Cu2 alloy (approx. 33 % increase compared to the as-cast condition) and 116 HV 0.05 for the AlSi7Cu4 alloy (approx. 40 % increase compared to the as-cast condition).

When using a lower solution annealing temperature of 495 °C, a significant increase in microhardness was also achieved. For the AlSi7Cu2 alloy, a microhardness value of 97 HV 0.05 was achieved, which corresponds to an increase of approx. 23 % compared to the cast state. For the second AlSi7Cu4 alloy investigated, a value of 110 HV 0.05 was achieved, which corresponds to an increase of approximately 33 % over the as-cast condition.

As with hardness, the lowest solution annealing temperature of 470°C has only a minimal effect on the increase in microhardness. This increase is only about 3% for the AlSi7Cu2 alloy and about 2% for the AlSi7Cu4 alloy compared to the as-cast state without heat treatment. Such an increase is negligible.

It can be noticed that for both investigated alloys, the higher the solution annealing temperature used in the hardening process, the higher the increase in hardness and microhardness was recorded.

Comparison of microhardness values between AlSi7Cu2 and AlSi7Cu4 alloys were presented in the Graph 4.



Graph 4 *Vickers microhardness of solid solution a(Al) AlSi7Cu2 and AlSi7Cu4 alloy*

4 Conclusion

Analyzes prove that precipitation hardening, which used solution annealing temperature 495 °C and 525 °C, has a significant effect on the final hardness and microhardness. The highest increase was achieved for both investigated alloys when using a solution-annealing temperature of 525 °C. For the AlSi7Cu2 alloy, at this solution annealing temperature, a 33 % increase in hardness and a 34 % increase in microhardness were achieved compared to the state without heat treatment. For the AlSi7Cu4 alloy, there was a 30 % increase in hardness and a 39 % increase in microhardness. The solution annealing temperature of 525 °C is optimal for both alloys to increase hardness and microhardness. The AlSi7Cu4 alloy has higher values of hardness and microhardness of the aluminum solid solution in all states than the AlSi7Cu2 alloy. This is probably due to the higher amount of copper in the alloy. For both alloys, it was found that the all bottom parts of the castings have higher values of hardness and microhardness than the all top parts. This is probably due to the cooling rate.

Acknowledgement

This research was supported by the internal UJEP Grant Agency (UJEP-SGS-2022-48-004-2).

References

[1] MICHNA, Š. *Encyklopedie hliníku*. Prešov: Adin, (2005). 700 s. ISBN 80-89041-88-4

[2] MICHNA, Š., MICHNOVÁ L. (2014). *Neželezné kovy*, PrintPoint s.r.o., Praha, ISBN 978-80-260-7132-7

[3] SJÖLANDER, E., SEIFEDDINE, S. (2009). The heat treatment of Al-Si-Cu-Mg casting alloys, *Journal of Materials Processing Technology*, 1249-1259. https://doi.org/10.1016/j.jmatprotec.2010.03.020

[4] RASHED, H. M. M. A., BAZLUR RASHID, A. K. M. (2017). 2.12. Heat treatment of aluminium alloys, *Comprehensive Materials Finishing*, 337-371. https://doi.org/10.1016/B978-0-12-803581-8.09194-3

[5] ROUČKA J., (2004). *Metalurgie neželezných slitin,* CERM s.r.o., Brno, ISBN 80-214-2790-6

[6] POLMEAR, I. STJOHN, D. JIAN-FENG, N. QIAN, M. (2017). 2 – Physical Metallurgy of Aluminium Alloys. *Light Alloys*, 31-107. https://doi.org/10.1016/B978-0-08-099431-4.00002-6.

[7] SHANMUGHASUNDARAM, P., DAHLE, A. K. (2018). Heat treatment of Aluminium Alloys. *Reference Module in Materials Science and Materials Engineering*, https://doi.org/10.1016/B978-0-12-803581-8.03374-9

[8] CAMPBELL, F. C., (2008). Elements of metallurgy and engineering alloys. Materials Park, Ohio: *ASM International* ISBN 978-0-87170-867-0. https://doi.org/10.31399/asm.tb.emea.9781627082518

[9] DINWIDDIE, K. (2016). *Heat treating aluminium*. AZOM https://www.azom.com/article.aspx?ArticleID=12703

[10] PTÁČEK, L. *Nauka o materiálu II*. Brno: CERM, 2002. ISBN 80-7204-130-4

[11] BOLIBRUCHOVÁ, D., MATEJSKA, M., MICHALCOVÁ, A. KASINSKA, J. Study of Natural and Artificial Aging on AlSi9Cu3 Alloy at Different Ratios of Returnable Material in the Batch. *Materials 2020, 13, 4538 https://doi.org/10.3390/ma13204538*

[12] SMALLMAN, R. E., BISHOP, R. J. (1999). Strengthening and toughening. *Modern Physical Metallurgy and Materials Engineering*, 259-296. https://doi.org/10.1016/B978-075064564-5/50008-2

[13] *EN AC-46600 (AlSi7Cu2)* (2023) European Steel and Alloy Grades / Numbers, SteelNumber, steelnumber.com.

[14] BOLIBRUCHOVÁ, D., BRŮNA, M. (2017). Impact of the Elements Affecting the Negative IronBased Phases Morphology in Aluminium Alloys – Summary. Results In: *Manufacturing Technology*. ISSN 1213-2489. Vol. 17, No. 5, p. 675-679

[15] *EN AC-46300 (AlSi7Cu4)* (2023) European Steel and Alloy Grades / Numbers, SteelNumber, steelnumber.com.

[16] LM21. [online]. [Cit. 1.9. 2023]. Dostupné z: http://www.nortal.co.uk/LM21/

[17] VLACH T, CAIS J. The Effect of Casting Mold Material on Microstructure of Al-Si Alloys. *Manufacturing Technology*. 2022;22(5):617-623. doi: 10.21062/mft.2022.072.

[18] NOVAKOVA I, MORAVEC J, KEJZLAR P. Metallurgy of the Aluminium Alloys for High-Pressure Die Casting. *Manufacturing Technology*. 2017;17(5):804-811. doi: 10.21062/ujep/x.2017/a/1213-2489/MT/17/5/804.

[19] HREN I, SVOBODOVA J, MICHNA Š. Analysis of Microstructure Changes for AlSi7Mg0.3 Alloy Caused by Modification. *Manufacturing Technology*. 2019;19(5):767-771. doi: 10.21062/ujep/369.2019/a/1213-2489/MT/19/5/767.

[20] WEISS V, SVOBODOVÁ J. The Use of Colour Metallography and EDS for Identification of Chemical Heterogeneity of Selected Aluminium Alloys Copper and Zinc Alloyed. *Manufacturing Technology*. 2015;15(6):1048-1053. doi: 10.21062/ujep/x.2015/a/1213-2489/MT/15/6/1048.

[21] WEISS V. Research of the Chemical Heterogeneity during Crystallization for AlCu4MgMn Alloy and the Possibility of its Elimination. *Manufacturing Technology*. 2016;16(1):289-294. doi: 10.21062/ujep/x.2016/a/1213-2489/MT/16/1/289.

[22] BOLIBRUCHOVÁ D, MATEJKA M, KURIŠ M. Analysis of the Impact of the Change of Primary and Secondary AlSi9Cu3 Alloy Ratio in the Batch on its Performance. *Manufacturing Technology*. 2019;19(5):734-739. doi: 10.21062/ujep/363.2019/a/1213-2489/MT/19/5/734.