Environment. Technology. Resources. Rezekne, Latvia
Proceedings of the 14th International Scientific and Practical Conference. Volume 3, 83-89

Investigation of the Structure of AlSi25Cu4Cr and AlSi25Cu5Cr Alloys

Boyan Dochev
Technical University of Sofia, Branch Plovdiv
Plovdiv, Bulgaria
boyan.dochev@gmail.com

Desislava Dimova
Technical University of Sofia, Branch Plovdiv
Plovdiv, Bulgaria
desislava608738@gmail.com

Mihail Zagorski
Technical University of Sofia, Faculty of Industrial Technology
Sofia, Bulgaria
mihail.zagorski.tu@gmail.com

Plamen Kasabov
Technical University of Sofia, Branch Plovdiv
Plovdiv, Bulgaria
plamen.kasabov@abv.bg

Georgiya Kamburova
Technical University of Sofia, Branch Plovdiv
Plovdiv, Bulgaria
kgeorgiya@gmail.com

***Abstract*. The hypereutectic aluminium-silicon alloys AlSi25Cu4Cr and AlSi25Cu5Cr are heat treated T5, T6 and T7. The quenching of the alloys was carried out under the same conditions. Artificial aging at T5 was carried out at a temperature of 180º C for 2, 4 and 6h, and at T6 at 180º C for 8, 10, 12 and 14h. The artificial aging of the studied compositions at T7 was carried out at a temperature of 370º C for 20, 40 and 60 min. The influence of heat treatment on the size, shape and distribution of primary and eutectic silicon crystals in the alloy structure was investigated. It was established that the proposed heat treatment regimes do not lead to a significant change in the shape and size of the primary silicon crystals, but contribute to their uniform distribution in the structure of the studied alloys. Rounding of the silicon crystals in the composition of the eutectic of the investigated alloys was observed.**

Keywords: heat treatment, hypereutectic aluminium-silicon alloys, structure.

I. INTRODUCTION

The main application of alloys of the Al-Si system is for the manufacture of pistons for internal combustion engines. The hypereutectic aluminium-silicon alloys have poor casting properties, and because they crystallize over a wide temperature range, microsuction porosity is observed in the castings. To obtain solid castings, various casting methods are used - casting in stilts, semi-liquid stamping, casting under gas pressure [1]-[3].

In recent years, new alloys and composites have been introduced in the automotive industry [4], [5]. In order to obtain aluminum alloys with modified structures and increased mechanical properties, new types of modifiers, rare earth elements are used, and different amounts of phosphorus are experimented with [6]-[14]. Research is being conducted on the operational properties (wear resistance and corrosion resistance) of the alloys intended for the manufacture of pistons for internal combustion engines, as well as new coatings aimed at improving their wear resistance [15]-[19].

The aim of the present work is to study the influence of different heat treatment regimes on the size, shape and distribution of primary and eutectic silicon crystals in the structure of AlSi25Cu4Cr and AlSi25Cu5Cr alloys.

II. MATERIALS AND METHODS

The object of the present study are supraeutectic aluminum-silicon alloys AlSi25Cu4Cr and AlSi25Cu5Cr. The investigated alloys were prepared by two different technologies. One technology for producing the alloys involves melting the pure metals in an electric resistance furnace and casting the resulting alloys into a block. The compositions obtained in this way are re-melted, and immediately before pouring, the metallurgical processing of the melts (refining, degassing and modification) is carried out. Phosphorus in the amount of 0.04% was used to modify the AlSi25Cu4Cr alloy, and the AlSi25Cu5Cr

Print ISSN 1691-5402
Online ISSN 2256-070X
https://doi.org/10.17770/etr2023vol3.7181

alloy was modified with 0.07% P. Experimental castings have been cast. The chemical composition of the prepared alloys is shown in Table 1 and Table 2. Castings obtained by this technology are subjected to thermal treatment T5 and T7. The heating to homogenize the structure before hardening was carried out at a temperature of 510-515ºC, the holding time at the indicated temperature was 6h30min., and for hardening a cooling medium of water with a temperature of 20ºC was used. Artificial aging at T5 was carried out at a temperature of 180ºC and holding times were 2h, 4h and 6h. During heat treatment the T7 temperature for artificial aging is 370ºC and holding times are 20min, 40min and 60min.

TABLE 1 CHEMICAL COMPOSITION OF ALSI25CU4CR (%) REMELTING

Si	Cu	Cr	Fe	Ni	Al
25,13	3,55	0,65	0,135	0,0051	rest

TABLE 2 CHEMICAL COMPOSITION OF ALSI25CU5CR (%) REMELTING

Si	Cu	Cr	Fe	Ni	Al
25,24	4,72	0,589	0,349	0,031	rest

The second technology for obtaining the studied alloys involves melting the pure metals in an electric resistance furnace, refining, degassing and modifying the melts and direct casting of experimental castings (without using remelting of previously prepared alloys). Phosphorus in the amount of 0.04% was used to modify the AlSi25Cu4Cr alloy, and the AlSi25Cu5Cr alloy was modified with 0.07% P. The chemical composition of the alloys thus prepared is shown in Table 3 and Table 4. Castings from the thus prepared compositions were subjected to T6 heat treatment, in which the hardening process was carried out as in T5 and T7. Artificial aging at T6 was carried out at a temperature of 180ºC and holding times were 8h, 10h, 12h and 14h.

TABLE 3 CHEMICAL COMPOSITION OF ALSI25CU4CR (%) PURE METALS

Si	Cu	Cr	Fe	Ni	Al
24,98	3,69	0,538	0,16	0,005	rest

TABLE 4CHEMICAL COMPOSITION OF ALSI25CU5CR (%) PURE METALS

Si	Cu	Cr	Fe	Ni	Al
25,31	4,32	0,528	0,122	0,005	rest

III. RESULTS AND DISCUSSION

The results of the microstructural analysis show that the AlSi25Cu4Cr and AlSi25Cu5Cr alloys obtained by remelting a block and modified with 0.04% P and 0.07% P respectively at a temperature of 830º-850ºC have a modified structure. The primary silicon crystals in the structure of the alloy AlSi25Cu4Cr modified with 0.04% P are finely divided and evenly distributed in its structure, with the main amount of crystals having sizes of 19-27 µm, and crystals with larger sizes are also found. The silicon crystals in the composition of the eutectic are plates, which in the observed field of the sandpaper have a needle-like shape and linear dimensions of 12-15 µm (Fig. 1).

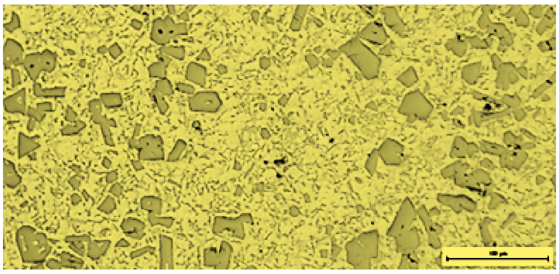

Fig. 1. Microstructure of alloy AlSi25Cu4Cr+0.04%P (remelting) x100.

In the structure of the AlSi25Cu5Cr alloy modified with 0.07% P, a large part of the silicon crystals are in the form of plates with a length not exceeding 45-50 µm and a width of 12-15 µm, single crystals with an irregular shape and a significant amount of primary silicon crystals with sizes in the range of 17 -27 µm, and eutectic silicon measures 5-7 µm (Fig. 2).

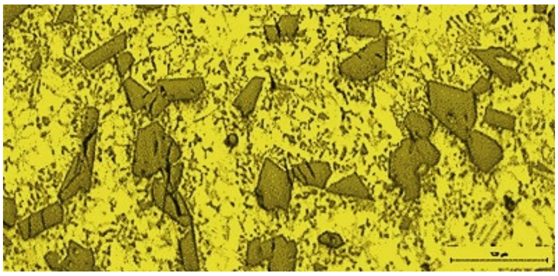

Fig. 2. Microstructure of alloy AlSi25Cu5Cr+0.07%P (remelting) x100.

In AlSi25Cu4Cr and AlSi25Cu5Cr alloys obtained from pure metals and subjected to modifying treatment with 0.04% P and 0.07% P, unmodified primary Si crystals can also be observed in their structure. The reason for this is most likely a loss of part of the used phosphorus modifier, which was introduced into the melts through CuP10 at a temperature of 900º-930ºC [20], [21]. A large part of the primary Si crystals in the AlSi25Cu4C + 0.04%P alloy structure are of irregular shape and cannot be measured; those that have been measured are 35 to 50 µm in size. Eutectic Si crystals are in the form of needles with linear dimensions of 30 - 54 µm. (Fig. 3).

In the structure of the alloy obtained from pure metals AlSi25Cu5Cr and modified with 0.07%P, irregularly shaped Si crystals are observed, which are not subject to measurement. The modified crystals are polyhedral, the measured and calculated conditional average diameter is 32 µm. The silicon in the composition of the eutectic is in the form of needles with an average linear size of 25.7 µm. (Fig. 4).

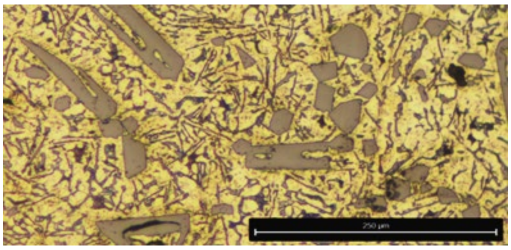

Fig. 3. Microstructure of alloy AlSi25Cu4Cr+0.04%P (pure metals) x100.

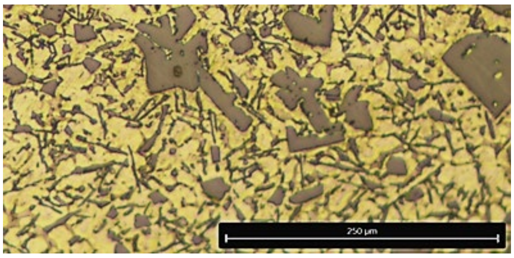

Fig. 4. Microstructure of alloy AlSi25Cu5Cr+0.07%P (pure metals) x100.

The structure of an AlSi25Cu4Cr alloy modified with phosphorus in the amount of 0.04% and subjected to T5, in which the artificial aging was carried out at a temperature of 180ºC and the holding time was 2h is shown in Fig. 5. The conditional average diameter of the primary silicon crystals is in the range of 32-38µm. Crystals in the form of polygons with straight walls predominate, but primary silicon crystals in the form of plates are also observed. The silicon crystals in the composition of the eutectic are in the form of "needles" varying in size from 11 to 14 µm.

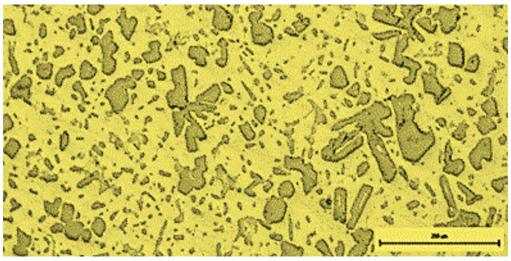

Fig. 5. Microstructure of alloy AlSi25Cu4Cr+0.04%P (remelting) T5 (180ºC/2h) x100.

The microstructure of alloy AlSi25Cu4Cr + 0.04% P and subjected to T5, in which the artificial aging was carried out at a temperature of 180ºC and the holding time was 4h is shown in Fig. 6. The primary Si crystals have sizes in the range of 18-29µm and are evenly distributed in the alloy structure. Some of the eutectic Si crystals have a rounded shape, there are also those in the form of plates, and their sizes are in the range from 8 to 14 µm.

After heat treatment T5, in which the artificial aging was carried out at a working temperature of 180ºC and a holding time of 6h, the AlSi25Cu4Cr + 0.04% P alloy has a structure that is shown in Fig. 7. Fine and evenly distributed primary silicon crystals with sizes in the range of 21-25 µm are observed. The silicon crystals in the composition of the eutectic are rounded in shape and 11 to 14 µm in size.

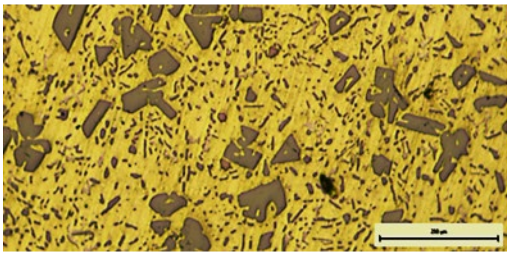

Fig. 6. Microstructure of alloy AlSi25Cu4Cr+0.04%P (remelting) T5 (180ºC/4h) x100.

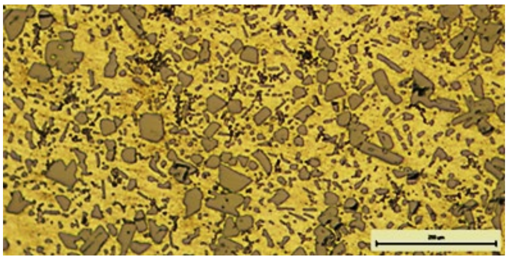

Fig. 7. Microstructure of alloy AlSi25Cu4Cr+0.04%P (remelting) T5 (180ºC/6h) x100.

The AlSi25Cu4Cr alloy, which was produced from pure metals and modified with 0.04% P, was subjected to T6. The structure of the alloy, where the artificial aging was carried out at a temperature of 180ºC and the holding time was 8h, is shown in Fig. 8. A large proportion of the primary Si crystals in the alloy structure are irregularly shaped and not measurable, and those measured are 43 µm in size. The eutectic Si crystals are spheroidal in shape, with one part of them having a nominal average diameter of 17 µm, and others with dimensions of 27 µm.

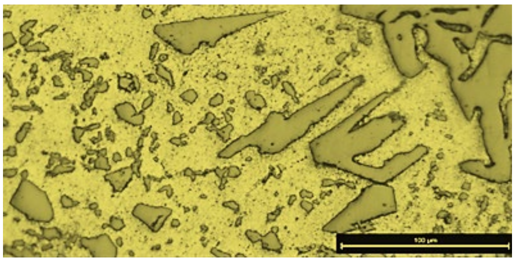

Fig. 8. Microstructure of alloy AlSi25Cu4Cr+0.04%P (pure metals) T6 (180ºC/8h) x100.

After heat treatment T6 and artificial aging at a temperature of 180ºC and a hold time of 10h, the modified silicon crystals in the structure of the alloy AlSi25Cu4Cr + 0.04% P were crushed. They have a conditional average diameter of 22.6 µm. A change in the shape and size of the eutectic silicon crystals is also observed, some of the crystals are spherical in shape and have a conditional average diameter of 4.5 µm, and the other part are in the form of thin plates with linear dimensions of 26.3 µm (Fig. 9).

The alloy AlSi25Cu4Cr + 0.04% P after T6 and artificial aging at 180ºC and retention of 12h has a structure shown in Fig. 10. Eutectic silicon has a rounded shape, the main amount of eutectic silicon crystals have a conditional average diameter of 5.5 µm, a small amount with a conditional average diameter of 18 µm is also observed. The modified Si crystals in the alloy structure are 20 to 50 µm in size.

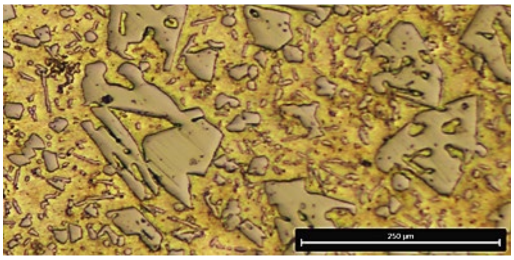

Fig. 9. Microstructure of alloy AlSi25Cu4Cr+0.04%P (pure metals) T6 (180ºC/10h) x100.

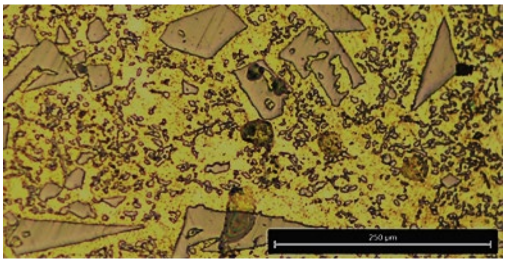

Fig. 10. Microstructure of alloy AlSi25Cu4Cr+0.04%P (pure metals) T6 (180ºC/12h) x100.

Artificial aging at a temperature of 180ºC and holding for 14h after quenching leads to the production of the finest crystals of eutectic silicon in the structure of the alloy AlSi25Cu4Cr + 0.04% P (Fig. 11). They are rounded in shape and have an average diameter of 7 µm. The modified Si crystals in the alloy structure are 16 to 45 µm in size.

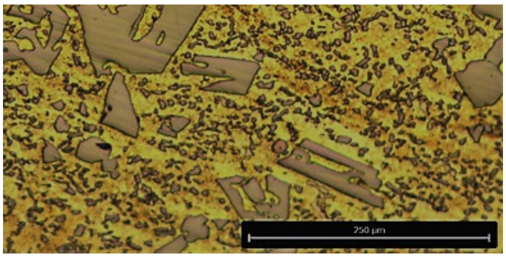

Fig. 11. Microstructure of alloy AlSi25Cu4Cr+0.04%P (pure metals) T6 (180ºC/14h) x100.

With T7 heat treatment and artificial aging at 370ºC and holding for 20 min. the structure of AlSi25Cu4Cr + 0.04% P alloy consists of uniformly distributed primary Si crystals with sizes of 19 to 23 µm. Both rounded eutectic silicon crystals and in the form of plates with sizes in the range of 9-14µm are observed (Fig. 12).

The AlSi25Cu4Cr + 0.04% P alloy subjected to T7 and artificial aging at 370ºC and holding for 40 min. has a structure shown in Fig. 13. The primary silicon crystals are finely divided and uniformly distributed with sizes ranging from 19 to 23 µm. The silicon crystals in the composition of the eutectic have a rounded shape, there are also those that are in the shape of plates, and their sizes are in the range of 5-8µm.

The microstructure of the alloy AlSi25Cu4Cr + 0.04% P subjected to T7 and artificial aging at 370ºC and holding for 60 min. is composed of faceted primary silicon crystals, which have a nominal average diameter of 34-39µm. Individual crystals of primary silicon and of larger sizes are observed. The silicon crystals in the composition of the eutectic are in the form of plates and polygons with sizes from 3 to 7 µm (Fig. 14).

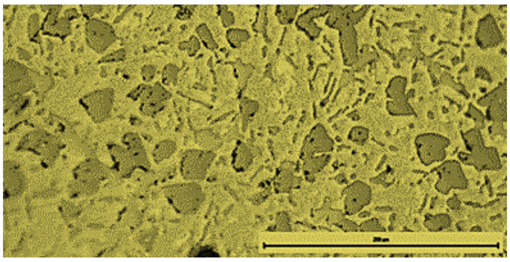

Fig. 12. Microstructure of alloy AlSi25Cu4Cr+0.04%P (remelting) T7 (370ºC/20min.) x100.

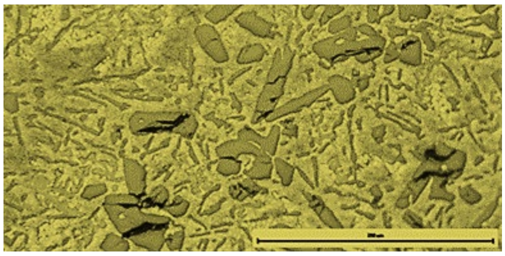

Fig. 13. Microstructure of alloy AlSi25Cu4Cr+0.04%P (remelting) T7 (370ºC/40min.) x100.

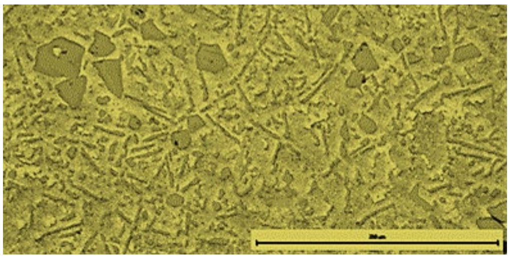

Fig. 14. Microstructure of alloy AlSi25Cu4Cr+0.04%P (remelting) T7 (370ºC/60min.) x100.

The structure of AlSi25Cu5Cr alloy modified with phosphorus in the amount of 0.07% and subjected to T5, in which the artificial aging was carried out at a temperature of 180ºC and the holding time was 2h is shown in Fig. 15. The primary silicon crystals are in the form of polygons with straight walls, there are also crystals with a plate shape. The conditional average diameter of the primary Si crystals is 8-13µm. Single plate-shaped primary silicon crystals 29-43µm in length are observed. The silicon in the composition of the eutectic is in the form of plates with dimensions of 4-6 µm.

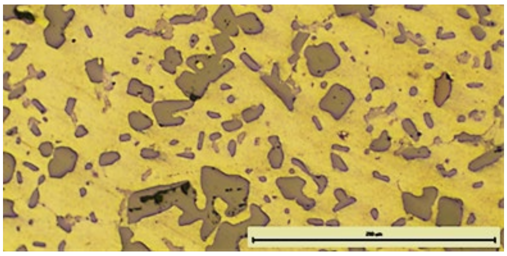

Fig. 15. Microstructure of alloy AlSi25Cu5Cr+0.07%P (remelting) T5 (180ºC/2h) x100.

The microstructure of an alloy AlSi25Cu5Cr + 0.07% P subjected to T5 heat treatment , in which the artificial aging was carried out at a temperature of 180ºC and the holding time was 4h is shown in Fig. 16. The primary silicon crystals are evenly spaced and have the shape of polygons and plates with an overwhelming conditional mean diameter of 19-24µm. The silicon crystals in the composition of the eutectic are in the form of needle-like platelets and rounded grains with dimensions of 9-13µm

After heat treatment T5, in which the artificial aging was carried out at a working temperature of 180ºC and a holding time of 6h, the AlSi25Cu5Cr + 0.07% P, the alloy has a structure that is shown in Fig. 17. Fine primary silicon crystals are observed in the form of polygons and plates distributed uniformly in the structure. The conditional average diameter of the primary silicon grains is in the range of 11-14µm.

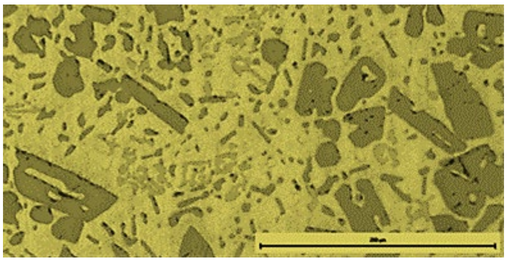

Fig. 16. Microstructure of alloy AlSi25Cu5Cr+0.07%P (remelting) T5 (180ºC/4h) x100.

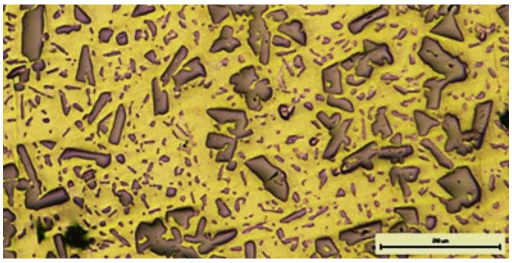

Fig. 17. Microstructure of alloy AlSi25Cu5Cr+0.07%P (remelting) T5 (180ºC/6h) x100.

The alloy AlSi25Cu5Cr, which was produced from pure metals and modified with 0.07% P, was put under T6 heat treatment. The structure of the alloy, where the artificial aging was carried out at a temperature of 180ºC and the holding time was 8h, is shown in Fig. 18. Most of the primary Si crystals in the alloy structure are irregularly shaped and not measurable, and those measured are 25.3 µm in size. The eutectic Si crystals are spheroidal in shape with a conditional average diameter of 6.3 µm, and others are in the form of thin plates with linear dimensions of 22.2 µm.

After heat treatment T6 and artificial aging at a temperature of 180ºC and holding time of 10h, Si crystals with a regular shape (polyhedral with straight walls) and a conditional average diameter of 20-43µm are observed. in the structure of the alloy AlSi25Cu5Cr + 0.07% P. The eutectic silicon crystals have a spheroidal shape and a conditional mean diameter of 6.4 µm (Fig. 19).

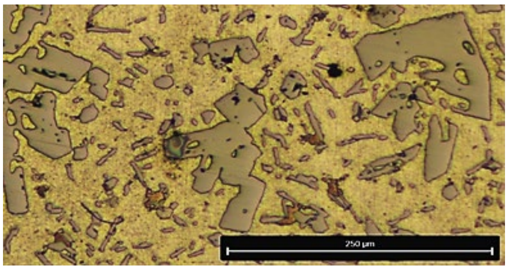

Fig. 18. Microstructure of alloy AlSi25Cu5Cr+0.07%P (pure metals) T6 (180ºC/8h) x100.

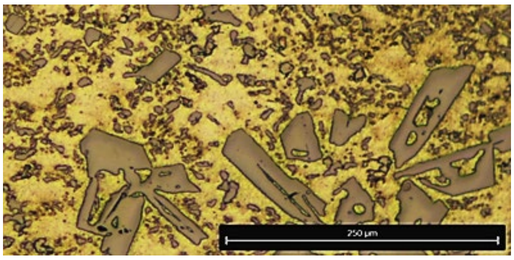

Fig. 19. Microstructure of alloy AlSi25Cu5Cr+0.07%P (pure metals) T6 (180ºC/10h) x100.

The alloy AlSi25Cu5Cr + 0.07% P after T6 heat treatment and artificial aging at 180ºC and retention of 12h has a structure shown in Fig. 20. The Si crystals in the composition of the eutectic are rounded in shape and up to 7 µm in size. The majority of primary Si crystals are of regular shape and reduced sizes in the range of 16 to 27 µm.

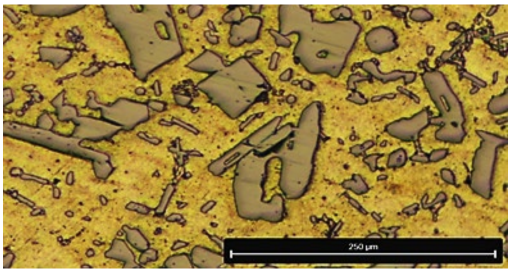

Fig. 20. Microstructure of alloy AlSi25Cu5Cr+0.07%P (pure metals) T6 (180ºC/12h) x100.

Artificial aging at a temperature of 180ºC and hold time of 14h after hardening leads to a change in the structure of the AlSi25Cu5Cr + 0.07% P alloy (Fig. 21). Most of the Si crystals in the composition of the eutectic are rounded in shape and up to 7 µm in size, but part of them are separated in the form of wafer with linear dimensions of 16-30 µm. The modified primary Si crystals are in the form of polygons with straight walls and polyhedral, and the measured and calculated conditional average diameter is 25.6 µm.

With T7 heat treatment and artificial aging at 370ºC and holding for 20 min. the structure of alloy AlSi25Cu5Cr + 0.07% P consists of primary silicon crystals of regular shape - polygons with straight walls, as well as plate-shaped ones with sizes in the range of 18-27 µm. Single crystals with an average diameter of 35-51µm are observed. The silicon in the composition of the eutectic is in the form of rounded crystals and plates resembling needles with dimensions of 8-10 µm. Single plates with a length of 24-28 µm are observed (Fig. 22).

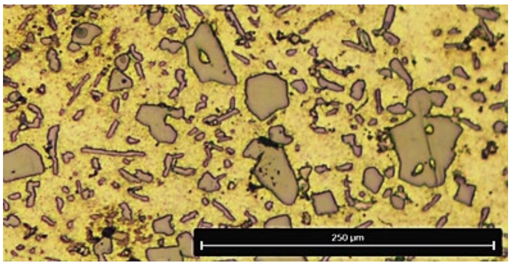

Fig. 21. Microstructure of alloy AlSi25Cu5Cr+0.07%P (pure metals) T6 (180ºC/14h) x100.

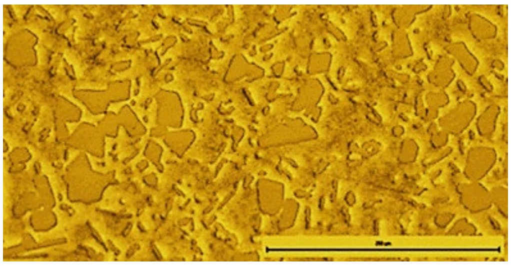

Fig. 22. Microstructure of alloy AlSi25Cu5Cr+0.07%P (remelting) T7 (370ºC/20min.) x100.

The AlSi25Cu5Cr + 0.07% P alloy subjected to T7 and artificial aging at 370ºC and holding for 40 min. has a structure shown in Fig. 23. Part of the silicon crystals in the composition of the eutectic are in the form of plates, but there are also those with a rounded shape and sizes from 7 to 12 µm. The primary silicon crystals have a regular shape (polygons and plates) with dimensions of 17-22 µm.

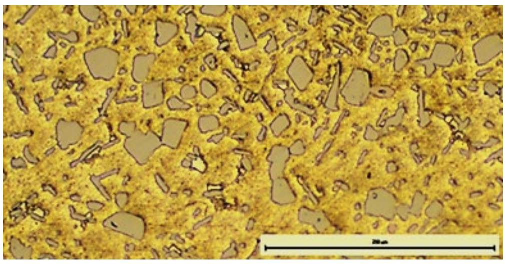

Fig. 23. Microstructure of alloy AlSi25Cu5Cr+0.07%P (remelting) T7 (370ºC/40min.) x100.

The microstructure of the alloy AlSi25Cu4Cr + 0.04% P subjected to T7 and artificial aging at 370ºC and holding for 60 min. consists of primary silicon crystals of regular shape and sizes in the range of 20-24µm. In the composition of the eutectic, finely divided silicon crystals are observed, which are 7-10 µm in size and have a rounded shape (Fig. 24).

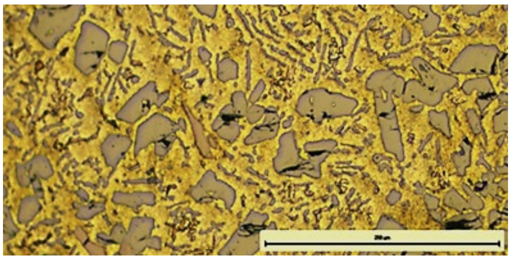

Fig. 24. Microstructure of alloy AlSi25Cu5Cr+0.07%P (remelting) T7 (370ºC/60min.) x100.

In the AlSi25Cu4Cr + 0.04% P alloy subjected to T5 heat treatment, it was observed that with increasing the holding time, the shape of both primary silicon and eutectic silicon crystals was mainly affected. The primary Si crystals are uniformly distributed, of approximately the same size and regular shape. Eutectic Si crystals are rounded in shape.

The AlSi25Cu4Cr alloy, which is produced from pure metals and modified with 0.04% P, is subjected to T6 heat treatment, where the artificial aging temperature is the same as T5 (180ºC). The artificial aging carried out at a temperature of 180ºC and retention of 8h, 10h, 12h and 14h has the strongest effect on the eutectic silicon. It gets a rounded (spheroidal) shape. Finest eutectic silicon in the structure of the investigated alloy AlSi25Cu4Cr + 0.04% P was obtained during artificial aging at 180ºC and retention of 14h.

After the heat treatment T7 in the structure of the AlSi25Cu4Cr alloy modified with 0.04% P, a tendency to increase the primary silicon crystals was observed with an increase in the holding time during the artificial aging carried out at a temperature of 370ºC. With a retention time of 60 min. at 370ºC the primary silicon crystals are of the largest size. No significant change in the shape and size of the eutectic silicon crystals was observed at the three retention times (20min., 40min. and 60min.) at the working temperature of artificial aging.

In the AlSi25Cu5Cr alloy modified with 0.07% P and subjected to T5, a change in the shape of the eutectic and primary silicon was observed. Silicon in the composition of the eutectic acquires a rounded shape, fine plates are also observed. Polygonization of primary Si crystals is observed, they are evenly distributed in the alloy structure.

After heat treatment T6 alloy AlSi25Cu5Cr modified with 0.07% P has in its structure eutectic silicon with a rounded shape. At artificial aging 180ºC and holding for 8h, eutectic Si was observed both in spherical shape and in the form of plates. At a holding time of 10h and 12h, only rounded eutectic silicon crystals are observed in the structure of the alloy, and as the holding time increases to 14h, a tendency to change the shape of silicon in the composition of the eutectic is again observed. In addition to spherical crystals, plate-shaped crystals are also observed.

In the structure of the alloy AlSi25Cu5Cr modified with 0.07% P and subjected to thermal treatment T7, no significant changes in the shape and size of the primary silicon crystals were observed. During artificial aging at a temperature of 370⁰C and holding for 20 min. eutectic silicon is in the form of thin layers, rounded crystals are also found. As the retention time increases to 40 min. silicon in the composition of the eutectic is crushed and a change in the shape of the thin plates is observed as they become more massive. When held for 60 min. at the selected operating temperature of 370⁰C, the eutectic silicon crystals are rounded in shape.

IV. CONCLUSIONS

The proposed heat treatment modes do not lead to a significant change in the shape and size of the primary silicon crystals, but contribute to their uniform distribution in the structure of the studied AlSi25Cu4Cr and AlSi25Cu5Cr alloys modified with 0.04% P and 0.07% P, respectively. Rounding of the silicon crystals is observed in the composition of the eutectic of the studied alloys.

During the T7 heat treatment of AlSi25Cu4Cr alloy modified with 0.04% P, a tendency for the growth of primary silicon crystals was observed. With a retention time of 60 min. at an operating temperature of 370⁰C, the primary silicon crystals are of the largest size.

Acknowledgments: This study was supported by the Bulgarian National Science Fund **№ КП-06-ПМ67/12**, project title: "Investigation of the tribological properties of new nickel-free piston aluminum-silicon alloys"

REFERENCES

[1] A. Velikov, S. Stanev, A. Maneva, R. Angelov, „"Gas pressing" ("GP") - a method of obtaining pistons for internal combustion engines". Proceedings of the III Scientific and Educational Conference "Mechanical Engineering-Traditions and Innovations" (MIT-2010), ISBN 978-5-94057-216, Moscow, November-December, 2010, 53-55. (In Russian)

[2] A. Velikov, S. Bushev, „Foundry-Gas Pressing Method". Bulgarian Society for NDT International Journal "NDT Days", Volume II, Issue 2, 2019, ISSN:ISSN: 2603-4018, eISSN: 2603-4646, 224-229.

[3] S. Miladinović, B. Stojanović, S. Gajević, A. Vencl, „Hypereutectic Aluminum Alloys and Composites: A Review" https://link.springer.com/article/10.1007/s12633-022-02216-2

[4] S. Veličković, B. Stojanović, L. Ivanović, S. Miladinović, Milojević, „Application of nanocomposites in the automotive industry". MVM 2019 - Volume 45 - Number 3 45(3):51–64. 2019 https://doi.org/10.24874/mvm.2019.45.03.05

[5] Mahle GmbH „Piston materials. In: Pistons and engine testing". ATZ/MTZ-Fachbuch. Vieweg+Teubner Verlag, Wiesbaden.2012 https://doi.org/10.1007/978-3-8348-8662-0_4

[6] C. Gong , H. Tu, C. Wu, J. Wang, X. Su, „Study on microstructure and mechanical properties of hypereutectic Al–18Si alloy modified with Al–3B". Journals Materials, Volume 11, Issue 3, 10.3390/ma11030456 11(3):456. 2018 https://doi.org/10.3390/ma11030456

[7] K. Wang, M. Wei, L. Zhang, Y. Du, „Morphologies of primary silicon in hypereutectic Al-Si alloys: phase-field simulation supported by key experiments". Metallurgical and Materials Transactions A volume 47, p.1510–1516, 2016 https://doi.org/10.1007/s11661-016-3358-1

[8] P. Xing, B. Gao, Y. Zhuang, K. Liu, G. Tu, „On the modification of hypereutectic Al-Si alloys using rare earth Er". Acta Metallurgica Sinica (English Letters), Vol. 23, Issue 5, p.327-333, 2010 https://doi.org/10.11890/1006-7191-105-327

[9] J. Jeon, J. Shin, D. Bae, „Si phase modification on the elevated temperature mechanical properties of Al–Si hypereutectic alloys". Materials Science and Engineering: A, Volume 748, 4 March,p.367-370,2019 https://doi.org/10.1016/j.msea.2019.01.119

[10] R. Guan, D. Tie, „A review on grain refinement of aluminum alloys: Progresses, challenges and prospects". Acta Metallurgica Sinica (English Letters) volume 30, p.409–432, 2017 https://doi.org/10.1007/s40195-017-0565-8

[11] M. Zuo, D. Zhao, X. Teng, H. Geng, Z. Zhang, „Effect of P and Sr complex modification on Si phase in hypereutectic Al–30Si alloys". Materials & Design, Volume 47, May, p. 857-864, 2013 https://doi.org/10.1016/j.matdes.2012.12.054

[12] B. Njuguna, J. Li, Y. Tan, Q. Sun, P. Li, „Grain refinement of primary silicon in hypereutectic Al-Si alloys by different P-containing compounds". China Foundry, Volume 18, p.37–44, 2021 https://doi.org/10.1007/s41230-021-0074-2

[13] J. Scepanovic, V. Asanovic, S. Herenda, D. Vuksanovic, D. Radonjic, F. Korac, „Microstructure characteristics, mechanical properties, fracture analysis and corrosion behavior of hypereutectic Al–13.5Si alloy". International Journal of Metalcasting, Volume 13, p.700–714, 2019 https://doi.org/10.1007/s40962-019-00315-2

[14] W. Shi, B. Gao, G. Tu, S. Li, „Effect of Nd on microstructure and wear resistance of hypereutectic Al–20%Si alloy". Journal of Alloys and Compounds, Volume 508, Issue 2, 22 October, p. 480-485,2010 https://doi.org/10.1016/j.jallcom.2010.08.098

[15] K. Jena, J. Majhi, S. Sahoo, S. Pattnaik, „The microstructural and wear properties improvement by manganese addition in Al-14Si hypereutectic alloy". Materials Today, Volume 62, Part10,p.5934-5941,2022 https://doi.org/10.1016/j.matpr.2022.04.638

[16] K. Kamarska, „Corrosion of AlSi18Cu3CrMn aluminum alloy in a chloride-containing medium", AIP Conference Proceedings 2449, 60019, September 2022, https://doi.org/10.1063/5.0090754

[17] K. Kamarska, „ Study of the corrosion behavior of aluminum-silicon alloy AlSi18Cu3CrMn in acidic media", AIP Conference Proceedings 2449, 060018, September 2022, https://doi.org/10.1063/5.0090753

[18] M. Kandeva, Zh. Kalitchin ,Y. Stoyanova," Influence of Chromium Concentration on the Abrasive Wear of Ni-Cr-B-Si Coatings Applied by Supersonic Flame Jet (HVOF)", Metals 2021, 11(6), 915, https://doi.org/10.3390/met11060915

[19] M. Kandeva, T. Penyashki, G. Kostadinov, Zh. Kalitchin, J. Kaleicheva, „Wear of electroless nickel-phosphorus composite coatings with nanodiamond particles", Journal of Environmental Protection and Ecology 19, No 3, p.1200–1214, 2018

[20] J. Piątkowski, „Archives of foundry engineering", Volume 9, Issue 3, p.125-128, 2009

[21] A. Zambon, Phosphorus modification in Al-Si hypereutectic alloys: Norwegian University of Science and Technology, Department of Materials Science and Engineering, Submission date: July 2016.