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The Influence of Overheating Temperature on the Shape Change of Primary Silicon Crystals and the Mechanical Properties of AlSi17 Alloy

K.K. Hillebrandt-Szymańska [a], *, J. Piątkowski [b]
[a] Łódź University of Technology, Poland
[b] Silesian University of Technology, Poland
* Corresponding author: E-mail address: klaudia.hillebrandt-szymanska@p.lodz.pl

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Abstract

The article presents the concept of overheating the liquid AlSi17 alloy significantly above the $T_{liq.}$ temperature, holding it at this temperature for a specified time, and casting it into two moulds with different cooling rates: a bentonite-based sand mould and a copper chill mould. Based on the obtained research results, it was found that overheating the AlSi17 alloy to temperatures of 920-960°C significantly improves mechanical properties, namely: tensile strength by approximately 40%, yield strength by approximately 70%, elongation by approximately 89% (for the sand mould - SM) and approximately 61% (for the copper metal mould - MM), reduction of area/ narrowness by approximately 67% (for SM) and approximately 51% (for MM) compared to the alloy without overheating. This process also reduces the scatter of the tested properties, indicating better homogeneity of the cast structure. Overheating the AlSi17 alloy to the optimal temperature range above $T_{liq.}$ (in terms of the tested mechanical properties) also affects the morphology of primary silicon crystals. Such a structure, improving mechanical properties, increases the application area of hypereutectic Al-Si alloys, especially in the automotive and aerospace industries for heavily loaded castings operating under extreme thermal-mechanical stress conditions.

Keywords: Hypereutectic Al-Si alloy, Overheating degree, Primary silicon crystals, Mechanical properties, Microstructure of Al-Si alloys

1. Introduction

Hypereutectic Al-Si alloys (15-24wt.%Si) are widely used wherever castings made from them are exposed to excessive thermal-mechanical stresses. This applies, for example, to the automotive, aerospace, and space industries [1-4]. A characteristic feature of these alloys is, among others, high strength at elevated temperatures (350-450°C), low thermal expansion coefficient (approx. 20µm·(m·K)$^{-1}$), high resistance to corrosion and abrasive wear [5-7]. Unfortunately, the industrial application of these alloys as a structural material is limited due to difficult mechanical processing, especially low plasticity (yield strength, elongation, reduction of area). These properties largely depend on the form of the eutecticα(Al)+β(Si) and the size and morphology of primary silicon crystals β(Si). Traditionally made castings from hypereutectic silumins tend to have large (approx. 100µm) primary silicon crystals unevenly distributed in the α(Al)matrix and a needle-like (coarse-grained) form of the eutectic. These crystals most often take on a polygonal, star-shaped, or thick plate morphology with sharp edges and pointed corners with twin growth planes [8-10]. This structure is probably the result of a specific mechanism of surface and edge growth of silicon plates, proposed by Wagner [11], Hamilton, and Seidensticker [12]. Fredriksson's concept [13] of flat silicon crystal growth, known as the Twin Plane Reentrant Edge-TPRE mechanism, is also quite popular. Kobayashi and Hogan [14] studied the crystallographic structure of silicon crystals in hypereutectic Al-Si alloys and found that these crystals are star-shaped based on twin, decahedral nuclei. Such an unfavourable structure, resulting from uncontrolled growth of polyhedral silicon crystals, can be changed by, among others, modification [15-18] or mixing in an electromagnetic field [19, 20].

Recent research results suggest that the unfavourable morphology of primary β(Si) can also be changed by overheating the liquid alloy significantly above the liquidus temperature $T_{liq.}$ [21-23]. Unfortunately, the Authors of these studies do not provide the optimal range of overheating for hypereutectic Al-Si alloys, nor do they discuss the impact of overheating on the mechanical properties of these alloys.

Therefore, it seems justified to undertake research on the influence of overheating temperature on the size and morphology of primary silicon crystals, which determine the performance properties, especially the mechanical properties of hypereutectic Al-Si alloys. Knowledge of these phenomena can be helpful in predicting the predisposition of the liquid alloy to form different types of crystal structures, and consequently, in increasing the application area of castings from hypereutectic Al-Si alloys or identifying new ones.

2. Scope and aim of investigations

The aim of the research was to determine the optimal range of overheating of the liquid AlSi17 alloy in terms of achieving the highest mechanical properties (Brinell Hardness - HB; tensile strength -UTS) and plastic properties (yield strength -YS; elongation - A and reduction of area after fracture - Z). To demonstrate the effect of the degree of superheating, the examined properties were compared with the AlSi17 alloy cast under standard conditions (without superheating but after modification with CuP master alloy). To eliminate the influence of other additives on the tested properties, pure AlSi17 alloy was used.

The scope of the research included:

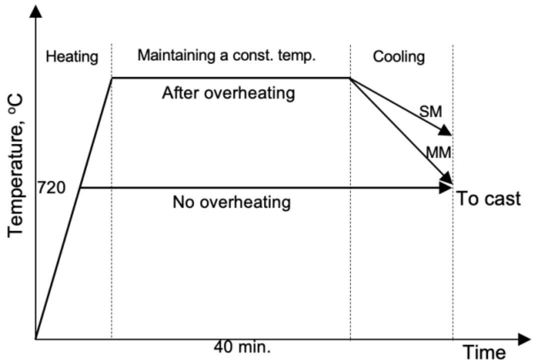
- development of the technological concept of overheating the liquid alloy – experiment plan,
- studies of selected mechanical and plastic properties from the static tensile test at room temperature (20°C). These results were compared to the mechanical properties of the alloy cast without superheating.,
- microstructure studies with particular emphasis on the shape of primary silicon crystals β(Si) in the AlSi17 alloy after overheating and casting into moulds with different cooling rates: sand mould and copper chill mould,
- summary and conclusions.

3. Test materials and methods

The selected AlSi17 alloy for the study was melted from pure components (99.99% Al) and (99.2% Si). The research methodology was adapted to the adopted technological concept, which assumed overheating the liquid alloy significantly above $T_{liq.}$, maintaining it at this temperature for a specified time, and casting it into two types of moulds with different cooling rates, namely:

- a traditional bentonite-based sand mould with an average cooling rate (from $T_{liq.}$, to $T_{sol.}$) of approximately 30-40^{o}C·s^{-1}, and
- a copper chill mould (approximately 98wt.% Cu) with a vertical parting plane with an average cooling rate (from $T_{liq.}$, to $T_{sol.}$) of approximately 300-350^{o}C·s^{-1}. Each time, the mold was preheated to a temperature of approximately 200°C.

The AlSi17 alloy was melted in a Balzers VSG02/631 induction furnace in a vacuum with a SiC crucible of 0.5-liter capacity. To avoid the negative effects of phenomena related to the gassing of the liquid alloy, which result from significant superheating above the liquidus temperature ($T_{liq.}$), a protective coating of Protecol-Degasal was used. This mixture (0.4 wt.%) was introduced by immersion under the surface of the liquid alloy. Then, 0.2 wt.% of Rafglin-3 was introduced under the layer of slag formed. At a temperature of approximately 760°C, 0.05 wt.% of phosphorus (P) in the form of CuP10 master alloy was added. After reaching the selected overheating temperature according to the research plan (Fig. 1), the alloy was held in the furnace for approximately 40 minutes and then cast into moulds. The holding time of 40 minutes for the alloy in the furnace was selected based on the studies presented in literature [24].



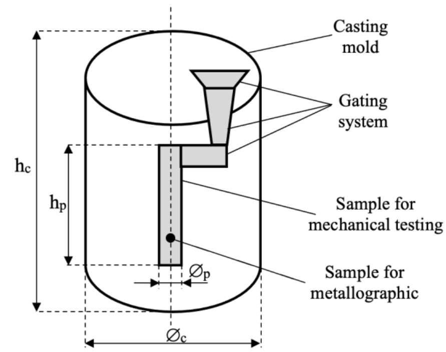
Overheating temperature T_p, °C	Sand Mould SM	Metal Mould MM
760	SM1	MM1
800	SM2	MM2
840	SM3	MM3
880	SM4	MM4
920	SM5	MM5
960	SM6	MM6

Fig. 1. Diagram and research plan of the overheating process of the AlSi17 alloy

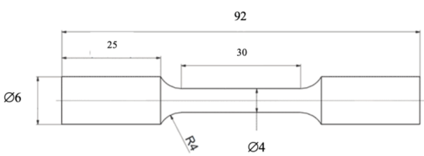
Both moulds had a cylindrical shape with a total diameter of $\varnothing_c$=60 mm and a total height of h_c=160 mm (Fig. 2).

Thus, 12 castings were obtained (6 from the sand mould and 6 from the copper chill mould), from which samples for static tensile testing were made according to DIN 50125:2022-08. Brinell hardness measurements were performed according to PN-EN ISO 6506-1:2021 on a Zwick ZHF hardness tester (Zwick Roell Ulm, Austria) with a load of 187.5 kg and a steel ball of ∅=2.5 mm for 35 s. Tensile strength tests (UTS), yield strength (YS), elongation (A), and reduction of area after fracture (Z) were performed according to PN-EN ISO 6892-1 on an Instron 3382 machine (Darmstadt, Germany). Eight samples were broken for each overheating temperature (Fig. 1), discarding two extreme results, and the arithmetic mean was calculated from the remaining ones. The obtained results for HB; UTS and YS were rounded to the nearest whole number, while A and Z were rounded to two decimal places and compared with the AlSi17 alloy cast from a temperature of 720°C (without overheating – Fig. 1), which was modified with CuP10 in such an amount that the alloy contained 0.05wt.% P. Metallographic sections were made from the fracture site of the samples for mechanical testing. Microstructure observations were performed on a MeF2 light microscope (LM) and a Hitachi S-3400N scanning electron microscope (SEM) equipped with an energy-dispersive X-ray spectrometer (EDS) Thermo Noran and a wavelength-dispersive spectrometer (WDS) Thermo MagnaRay, as well as a detector for electron backscatter diffraction (EBSD) INCA HKL Nordys II (Hitachi High-Technologies Tokyo, Japan). To better indicate the morphology of primary silicon crystals, the sections were deeply etched in 10% HF acid. Ten images were taken for each overheating temperature and for each casting mould. The presented microstructures represent a representative image of the effect of overheating on the form of primary silicon crystals in the given experiment. The procedure for calculating the stereological parameters of primary silicon crystals β(Si) is described in the literature [24].

a)



b)



$\varnothing_c$ – total diameter of the casting mold, 60 mm
$\varnothing_p$ – diameter of the sample for mechanical testing, 8 mm
h_c – total height of the casting mold, 160 mm
h_p – height of the sample for mechanical testing, 100 mm

Fig. 2. Casting mould: a) diagram; b) dimensions of the sample for mechanical testing (mm)

4. Test results

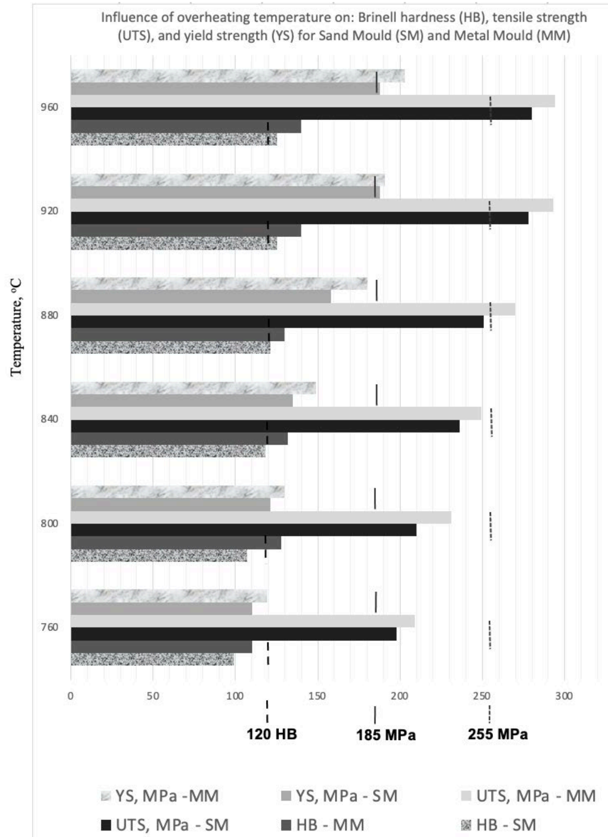
The results of the chemical composition analysis of the AlSi17 alloy are presented in Table 1.

Table 1.
Chemical composition of the AlSi17 cast alloy.

Alloy	Chemical composition, 9 (wt.%)						
	Si	Cu	Fe	Mn	Mg	Ni	Al
AlSi17	16,63	0,07	0,34	0,03	0,04	0,02	rest

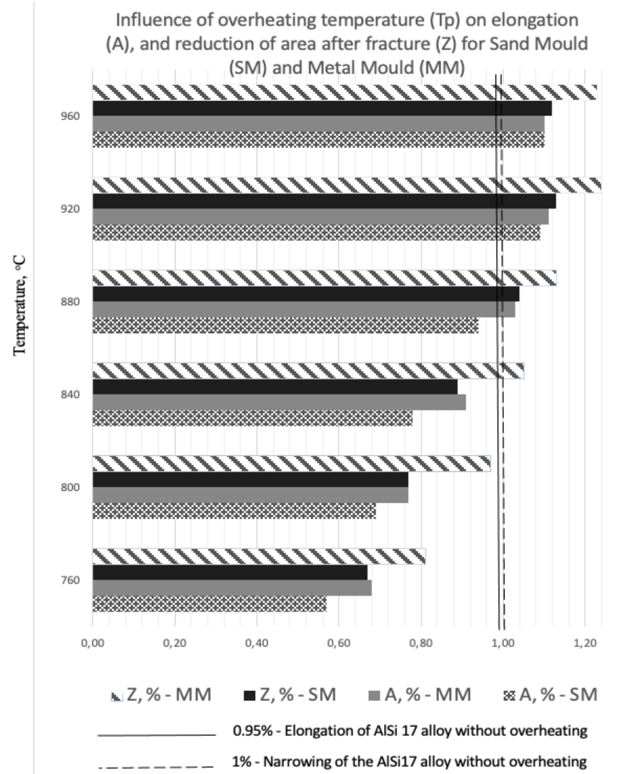
4.1. Results of the Mechanical Properties Tests of the AlSi17 Alloy

The results of the influence of overheating temperature (Tp) on Brinell hardness (HB), tensile strength (UTS), yield strength (YS), elongation (A), and reduction of area after fracture (Z) are presented in Figure 3.



a)

Overheating temperature, °C	HB	SD (HB)	HB	SD (HB)	UTS, MPa	SD (UTS)	UTS, MPa	SD (UTS)	YS, MPa	SD (YS)	YS, MPa	SD (YS)
	SM	SM	MM	MM	SM	SM	MM	MM	SM	SM	MM	MM
760	99	19	110	18	198	33	209	30	110	20	119	19
800	107	17	128	15	210	28	231	27	121	15	130	14
840	118	14	132	13	236	25	249	24	135	14	149	13
880	121	12	130	11	251	24	270	20	158	12	180	10
920	125	11	140	10	278	20	293	18	188	9	191	8
960	125	11	140	10	280	20	294	18	188	9	203	8



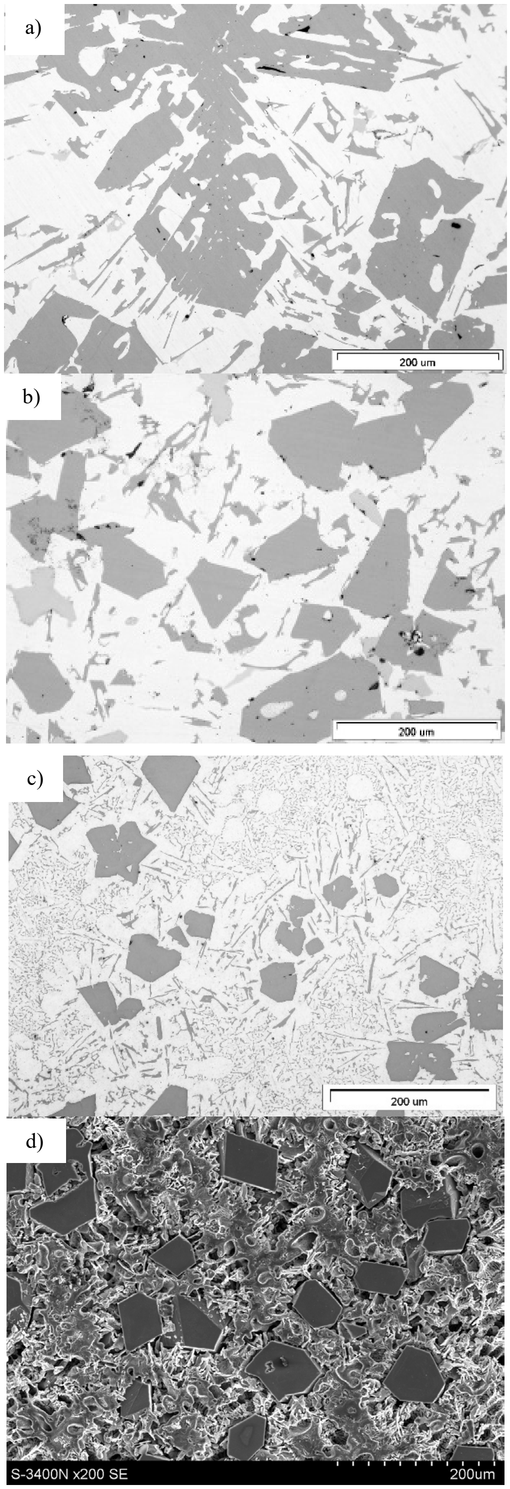
b)

Overheating temperature, °C	A, %	SD(A)	A, %	SD(A)	Z, %	SD(Z)	Z, %	SD(Z)
	SM	SM	MM	MM	SM	SM	MM	MM
760	0.57	0.1	0.68	0.08	0.67	0.1	0.81	0.09
800	0.69	0.08	0.77	0.07	0.77	0.07	0.97	0.06
840	0.78	0.08	0.91	0.04	0.89	0.07	1.05	0.04
880	0.94	0.05	1.03	0.04	1.04	0.05	1.13	0.03
920	1.09	0.02	1.11	0.02	1.13	0.02	1.24	0.02
960	1.1	0.02	1.1	0.02	1.12	0.02	1.23	0.02

Fig. 3. Influence of overheating temperature on: a) Brinell Hardness (HB), tensile strength (UTS), and yield strength (YS); b) elongation (A) and reduction of area after fracture (Z) – average values

4.2. Results of the Microstructure Tests of the AlSi17 Alloy

The influence of overheating temperature on the microstructure of the AlSi17 alloy is shown in Figure 4.



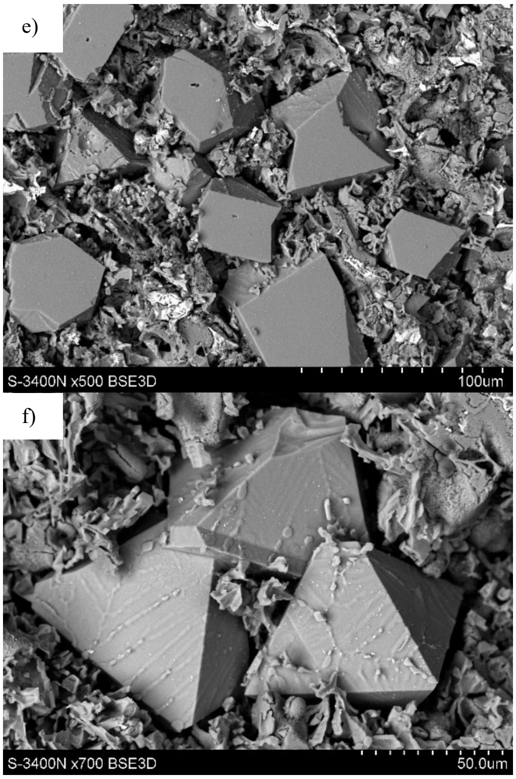


Fig. 4. Microstructure of the AlSi17 alloy: a) without overheating; b) after overheating to 840°C; c-f) after overheating to 920°C; a-c) LM; d-f) SEM; e-f) deeply etched sections

From the SEM microstructures shown in Figure 4, it can be seen that overheating the AlSi17 alloy to approximately 920°C causes the primary silicon crystals to take on the characteristic shape of regular octahedrons (Figure 5b-c), which were not observed in the AlSi17 alloy without overheating (Figure 5a).

Depending on the cross-sectional plane of the metallographic section, primary silicon crystals can take on various "flat" shapes, examples of which are shown in Figure 6.

Overheating the tested alloy significantly above $T_{liq.}$ (Fig. 1) not only changed the shape of the primary silicon crystals but also caused their refinement. The influence of the overheating temperature of the AlSi17 alloy on the reduction of the size of primary silicon crystals, determined by their surface area and the longest diagonal of the surface area, is shown in Figure 7. The averaged values were determined based on the measurement of silicon crystals counted from 10 randomly selected microstructure images.

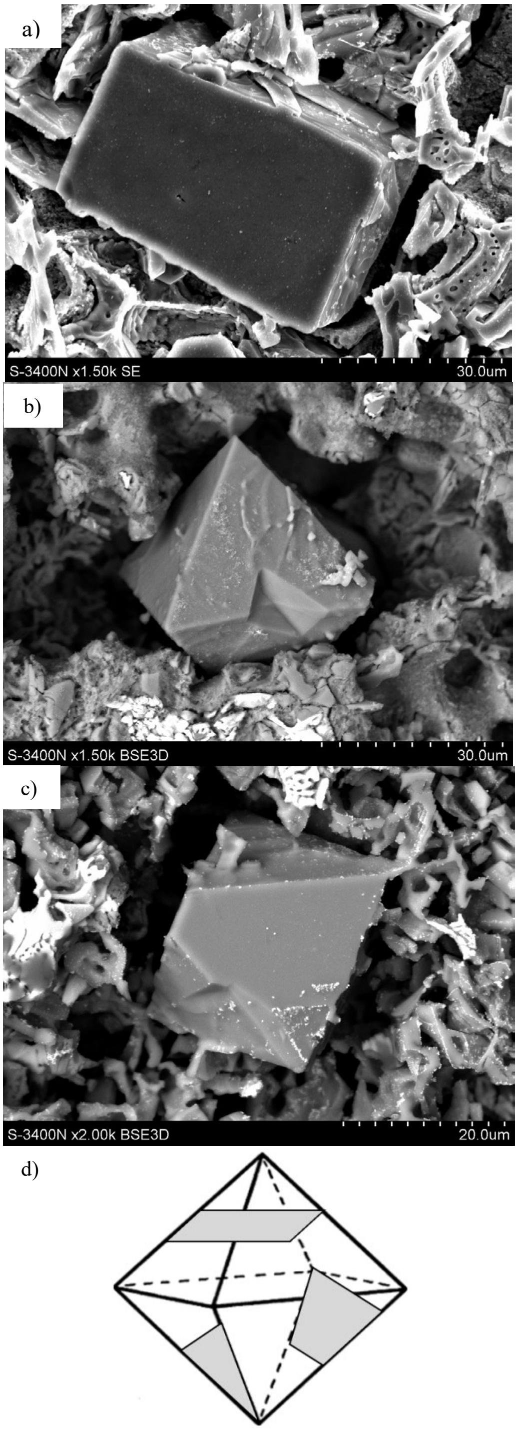


Fig. 5. Microstructure of the AlSi17 alloy with primary silicon crystals: a) without overheating; b-c) after overheating to approximately 920°C; d) diagram of an octahedron with different cross-sectional planes

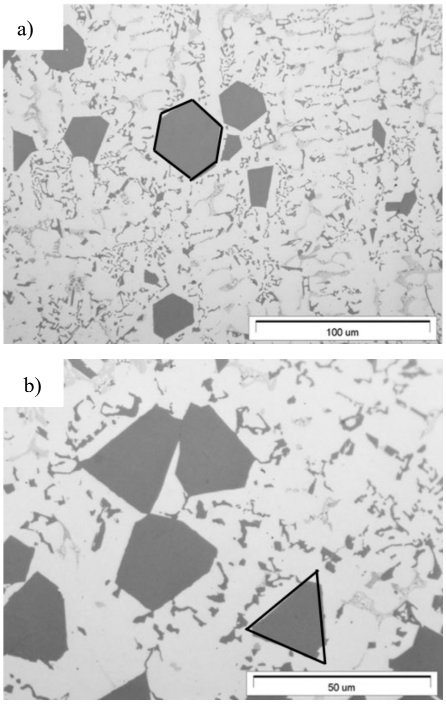


Fig. 6. Microstructure of the AlSi17 alloy after overheating to approximately 920°C with the cross-sectional plane of primary silicon crystals in the shape of: a) hexagon; b) triangle

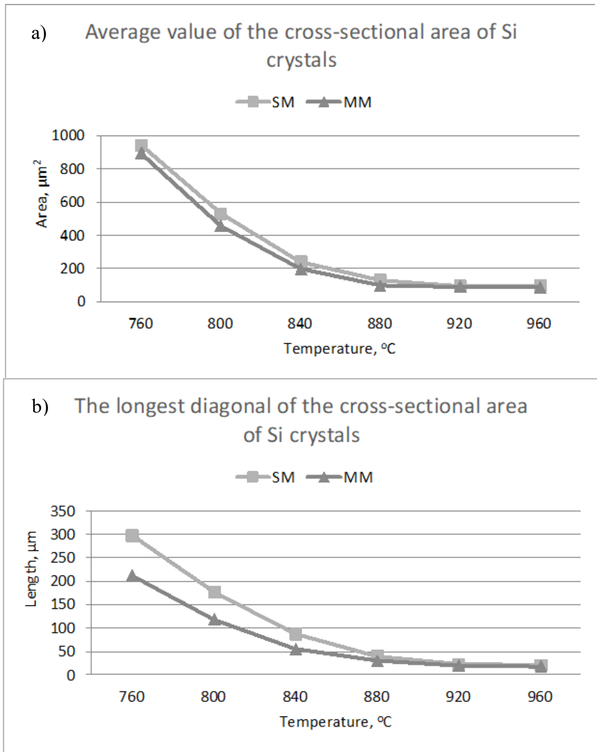


Fig. 7. Influence of overheating temperature on: a) surface area; b) the longest diagonal of the cross-section of primary silicon crystals (average values)

5. Discussion of results

The presented research indicates that overheating the AlSi17 alloy significantly above $T_{liq.}$ substantially affects the microstructure (mainly the morphology of primary silicon crystals) and the related mechanical properties.

The data presented in Figure 3 show that increasing the overheating temperature of the tested alloy cast into a sand mould causes an increase in Brinell hardness (HB) from approximately 100 (for T_p=760°C) to 125 (for T_p=920-960°C), which is about a 25% increase. For the copper chill mould, the increase is from 110 HB to 140 HB – about a 27% increase. It is worth noting that overheating to a temperature between 880 and 960°C (regardless of the type of casting mould) results in higher hardness than the AlSi17 alloy cast from a temperature of 760°C after modification with CuP10 (120 HB).

The tensile strength results indicate that overheating the alloy to 920-960°C increases UTS by approximately 40% (for both SM and MM) compared to T_p of 760°C. This range results in UTS values higher than those for the AlSi17 alloy without overheating and after modification (255 MPa). The yield strength results indicate that overheating the alloy to 920-960°C increases YS by approximately 70% (for both SM and MM) compared to T_p=760°C. Similar to UTS, this overheating range results in YS values higher than those for the AlSi17 alloy without overheating and after modification (185 MPa).

Overheating the AlSi17 alloy to approximately 920-960°C also increased elongation by approximately 89% (for SM) and approximately 61% (for MM) compared to T_p=760°C. This overheating range improves elongation compared to the AlSi17 alloy without overheating and after modification (0.95%). Similar results were obtained for the reduction of area after fracture, with an increase of approximately 67% (for SM) and approximately 51% (for MM). Here too, overheating the AlSi17 alloy to approximately 920-960°C improved the reduction of area compared to the AlSi17 alloy without overheating and after modification (1.0%).

The data also indicate that the most optimal overheating temperature for the AlSi17 alloy, in terms of the tested mechanical properties, is approximately 920°C (200°C above $T_{liq.}$). Further increasing the overheating is not justified in terms of improving the tested material properties. The results of the scatter of properties measured by standard deviation (SD) are also noteworthy. In each case, it was found that increasing Tp of the tested alloy reduces SD. This may indicate better homogeneity of the alloy structure, i.e., a more uniform distribution of primary silicon crystals β(Si) in the solid solution matrix α(Al).

The consequence of the change in mechanical properties was the influence of overheating on the morphology of primary silicon crystals. Figure 4a shows that in the AlSi17 alloy without overheating, the primary silicon crystals have a typical star-shaped structure with large (approximately 250-300μm) plate-like silicon crystals unevenly distributed in the solid solution matrix α(Al). As the overheating temperature increases, the β(Si) crystals become smaller and more evenly distributed in the matrix. After overheating in the temperature range of approximately 920-960°C, these crystals take on the characteristic shape of tetrahedrons and octahedrons with an average cross-sectional area of approximately

95μm² and a side length of approximately from 30 to 60 μm (Figures 5-7).

As suggested by research results [8-11], silicon atom clusters in Al-Si alloys have a tetrahedral shape, which may be beneficial for the formation and growth of primary silicon nuclei. As the overheating temperature of the alloy increases, some bonds in the Si-Si clusters are destroyed, and silicon atoms diffuse towards the liquid aluminium atoms. Therefore, the higher the overheating temperature of the alloy, the smaller the size of the Si-Si clusters due to the destruction of their atomic bonds. Thus, the average size of Si-Si clusters in the liquid alloy in the temperature range of 920-960°C is smaller than in the typical casting temperature of AlSi17 alloy (720°C). Additionally, it is assumed that the higher the cooling rate (resulting, for example, from the type of casting mould), the higher the degree of undercooling ΔT during solidification, which is accompanied by a reduction in the size of primary silicon crystals (Figure 7), due to the increased density of substrates for their heterogeneous nucleation. This is consistent with the findings of studies [8] and the concept that the type and size of Si-Si clusters have a decisive impact on the form of primary silicon crystals. Xu and Jiang [8;9] suggest that large Si-Si clusters can serve as substrates for the nucleation of star-shaped silicon crystals, while smaller Si-Si clusters lead to the formation of more favorable crystals with a compact polyhedral structure.

This is confirmed by Kobayashi and Hogan [14], who suggest, that the nucleation of β(Si) crystals in alloys overheated significantly above $T_{liq.}$ occurs by the addition of successive silicon atoms uniformly in all directions – hence these crystals have the morphology of compact bodies (e.g., tetrahedrons or octahedrons – Figure 5). In alloys without overheating, when nuclei (e.g., impurities, foreign inclusions) of a certain shape are already present in the liquid state, silicon crystals take on a star-plate shape, and only modification can change their shape to a more favourable one.

Overall, it can be assumed that overheating to a temperature of approximately 200-250°C above $T_{liq.}$ may be an alternative to the modification process of hypereutectic Al-Si alloys. This is evidenced by both the changes in microstructure and the increase in mechanical properties, but a fuller explanation of these phenomena requires additional microstructure research, which is in progress.

Further research is planned to investigate the impact of the degree of superheating on the porosity of hypereutectic Al-Si alloys and their technological properties, especially fluidity.

6. Conclusions

Based on the conducted research, the following final conclusions were formulated:

Overheating the AlSi17 alloy above $T_{liq.}$ significantly affects the microstructure (mainly the morphology of primary silicon crystals) and the related mechanical properties.

The most optimal overheating temperature for the AlSi17 alloy (in terms of mechanical properties) is 920-960°C (200-250°C above $T_{liq.}$). Further increasing the overheating is not justified in terms of improving mechanical properties (HB; UTS; YS; A and Z).

Overheating the AlSi17 alloy to 920-960°C does not significantly affect the change in Brinell hardness (HB), but it increases: tensile strength by approximately 40%, yield strength by approximately 70%, elongation by approximately 89% (for SM) and approximately 61% (for MM), and reduction of area by approximately 67% (for SM) and approximately 51% (for MM) compared to the alloy without overheating. This process also reduces the scatter of the tested properties, indicating better homogeneity of the alloy structure.

The application of overheating to the tested alloy also reduces the size of primary silicon crystals (from approximately 250-300μm to approximately 20μm) and changes their morphology from star-plate (typical for hypereutectic silumins without modification) to compact bodies in the shape of tetrahedrons and octahedrons.

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