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THE MICROSTRUCTURE AND MECHANICAL PROPERTIES OF THE AlSi17Cu5 ALLOY AFTER HEAT TREATMENT

MIKROSTRUKTURA I WŁAŚCIWOŚCI MECHANICZNE STOPU AlSi17Cu5 PO OBRÓBCE CIEPLNEJ

In the paper results of the microstructure and mechanical properties (HB, R_m and $R_{0.2}$) of AlSi17Cu5 alloy, subjected by solution heat treatment (500°C /6h/woda) and aging (200°C/16h/piec) are presented. In next step the alloy was modified and heated significantly above the T_{liq} temperature (separately and together). It was found that the increase in the strength properties of the tested alloy after heat treatment compared to alloys without solution heat treatment and aging was due to precipitation hardening. The applied aging treatment of ingots (preceded by solution heat treatment), causes not only increase in concentration in α (Al) solid solution, but also a favorable change of the primary Si crystals morphology. During stereological measurements significant size reduction and change in the morphology of hypereutectic silicon crystals were found. This effects can be further enhanced by overheating the alloy to a temperature of 920°C and rapid cooling before casting of the alloy.

Keywords: casting Al-Si-Me alloys, the solution heat and aging, mechanical properties, microstructure

W pracy przedstawiono wyniki badań mikrostruktury i właściwości mechanicznych (HB, R_m i $R_{0.2}$) odlewów ze stopu AlSi17Cu5 poddanych przesycaaniu (500°C/6h/wrząca woda) i starzeniu (200°C/16h/piec) po procesie modyfikowania i znacznego przegrzania powyżej temperatury T_{liq} (oddzielnie oraz łącznie). Stwierdzono, że podwyższenie właściwości wytrzymałościowych badanego stopu po obróbce cieplnej w stosunku do odlewów bez przesycaania i starzenia nastąpiło na skutek utwardzania wydzieleniowego. Zastosowany zabieg starzenia poprzedzony przesycaaniem, wywołuje nie tylko wzrost stężenia w roztworze stałym α (Al), ale też korzystną zmianę morfologii pierwotnych kryształów krzemu. Na podstawie pomiarów parametrów stereologicznych stwierdzono istotne zmniejszenie i zmianę morfologii nadeutektycznych kryształów krzemu, co dodatkowo można zintensyfikować przegrzaniem stopu do temperatury 920°C i szybkim chłodzeniem przed odlaniem.

1. Introduction

Al-Si alloys are widely used in many branches of industry, especially in transport for the highly loaded parts of pistons and heads of the internal combustion engines. The work environment of combustion engines require that the castings need to have good mechanical, plastic and technological properties, which also allow manufacturing parts with complicated shapes and thin walls. Multicomponent hypereutectic Al-Si alloys with additions such as Cu, Ni, Mg [1-3], after precipitation strengthening meets this requirements. Intermetallic phases, mainly AlSiFe and AlSiCu, form during aluminum solution strengthening, this increases the mechanical properties [4-6], and thus increases the application range of hypereutectic Al-Si-Me alloys. The shape and size of primary silicon crystals are also very important. Size can be reduced by: modification [7-9], mixing, and effects of electromagnetic fields [10]. This change in morphology of Si crystals also positively affects the machinability. Fine crystalline structure can also be obtained by the so-called thermal treatment of the alloy in

the liquid state. It involves overheating of the liquid metal to about 250 ÷ 300°C above the liquidus temperature, holding for some time and quick cooling to pouring temperature just before pouring into the mold [11-15]. This technology results in dissolution of accidental inclusions which can become uncontrolled heterogeneous nucleation sites and also deliberate introduction of other inclusions. It is a viable alternative for the solid state heat treatment of castings.

2. Purpose and scope of research

The aim of the study was to determine the effect of solution heat treatment and aging on the structure and mechanical properties (HB, R_m and $R_{0.2}$) of AlSi17Cu5 alloy. The scope of work included:

- development of the material and technological concept of AlSi17Cu5 alloy heat treatment of in the liquid state,
- selection of technology and research methods adapted to the stage of the test plan,

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- carrying out heat treatment of castings in a solid state,
- measurement of mechanical properties (HB, R_m and $R_{0,2}$),
- structural studies after heat treatment.

3. Materials and research methods

AlSi17Cu5 alloy was melted in an induction furnace (Balzers VSG 02/63) from pure aluminum grade A00 (99.98% Al), technical silicon (99.96% Si) and copper (99.93% Cu) and was cast in the crucible of SiC with a capacity of 600 cm³. To avoid the negative impact of the phenomena associated with gassed liquid metal bath, resulting from a significant overheating of the melt above T_{liq} , was used a protective covering Protecoul-Degasal. This mixture (0.4% wt.) was dipped into the molten under the mirror of liquid metal Rafaglin-3 (0.3 % wt.) was introduced under the formed slag layer preparation for refining the melt. Then alloy was overheated to 920°C for 30 min., than was cooled to a temperature of 800°C. Temperature was registered with NiCr-NiAl thermocouple (K). The modification process was carried out by using phosphorus (CuP10 mortar), when the working chamber of the furnace was closed. Selected alloy was cast into the steel mold, receiving three samples with dimensions of Ø200 × 1600 mm. Samples were machined to the dimensions in accordance with DIN EN 10002-1. Five casts (15 samples) were made for each the following technologies:

1. alloy after modifying with 0.05% wt. P (CuP10), (marked SM)
2. alloy subjected to overcharging at 920°C for 30 min. in the furnace (marked SP)
3. alloy overheated and modified according to the parameters as above (marked SPM)
4. alloy overheated and modified and cast into the mold placed in liquid nitrogen (marked SPMA).

Samples obtained by these technologies were compared with the alloy in the initial state (marked SW).

On the basis of existing technical standards for the recommended heat treatments (mainly on the temperature and time), for the tested AlSi17Cu5 alloy (according to the research methodology), the following heat treatment parameters were used:

- solution heat treatment: 500 ± 5°C / 6 hours / cooling in boiling water,
- artificial aging: 200 ± 5°C / 16 hours / cooling with the furnace.

Brinell hardness test was performed in accordance with DIN EN ISO 6506-1 on the ZHF Zwick hardness tester with a load of 187.5 kg, using steel ball with a diameter of 2.5 mm and measuring time of 35 s. A static tensile test was carried out in accordance with PN-EN ISO 6892-1 on a Instron 3382 machine at a constant ratio 20:1 and a tensile rate of 5 mm / min. From these samples was determined tensile strength (R_m) and a yield strength ($R_{0,2}$).

Samples for structural studies were taken from the middle section of casting. Metallographic samples were prepared according to standard procedure on the Struers grinding and polishing machines, and were etched with a 10% HF acid. Metallographic observations were carried out in the MeF-2 Reichert light microscope.

4. Test results

The chemical composition of AlSi17Cu5 alloy is shown in Table 1.

TABLE 1
Chemical analysis of the AlSi17Cu5 cast alloy, /wt.%

Si	Cu	Fe	Ni	Mg	Mn	Impurities	Al
16,72	4,86	0,29	0,03	0,02	0,02	0,01	rest

To replace the solid state heat treatment it is necessary to overheat the liquid metal above the melting point T_{liq} . Batch of 15 samples have undergone solution heat treatment and aging (according to the parameters as above) and then subjected to static tensile test. The average results of the HB hardness, the tensile strength R_m and yield strength $R_{0,2}$ of the AlSi17Cu5 alloy after solution heat treatment and aging are shown in Figs. 1 to 3

Samples for static tensile test, after heat-treatment (solution heat treatment and aging), and fracture surface of the samples at the macro scale are shown in Fig. 4.

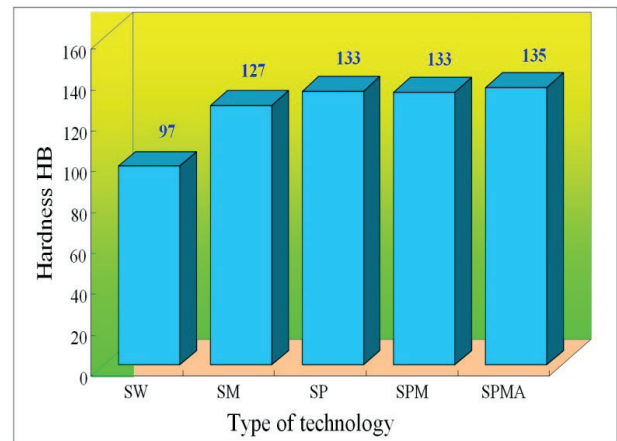


Fig. 1. Hardness HB results of AlSi17Cu5 alloy after solution heat treatment (500°C/6 h/water) and ageing (200°C/16 h/furnace) in function of the technological process applied

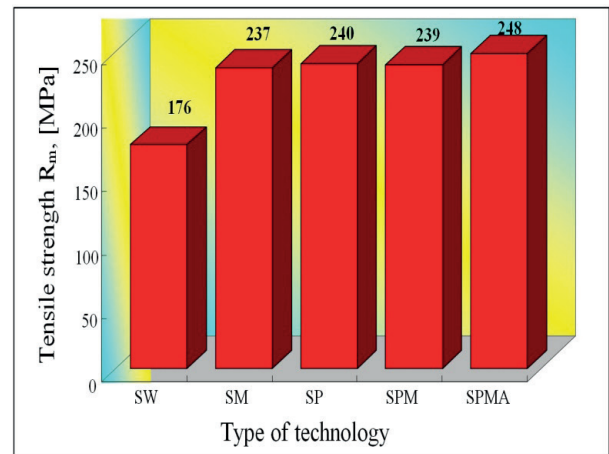


Fig. 2. Tensile strength R_m results of AlSi17Cu5 alloy after solution heat treatment (500°C/6 h/water) and ageing (200°C/16 h/furnace) in function of the technological process applied

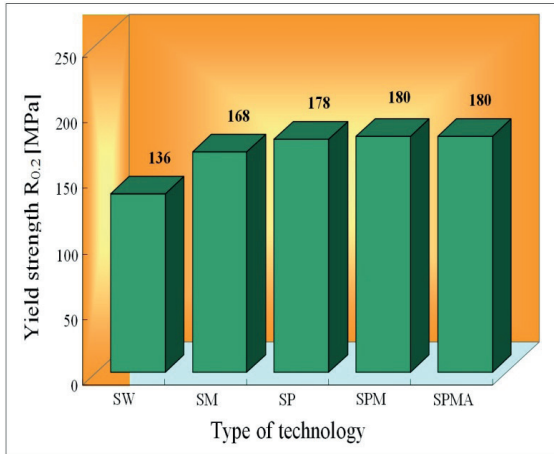


Fig. 3. Yield strength R_{0.2} results of AISi17Cu5 alloy after solution heat treatment (500°C/6 h/water) and ageing (200°C/16 h/furnace) in function of the technological process applied

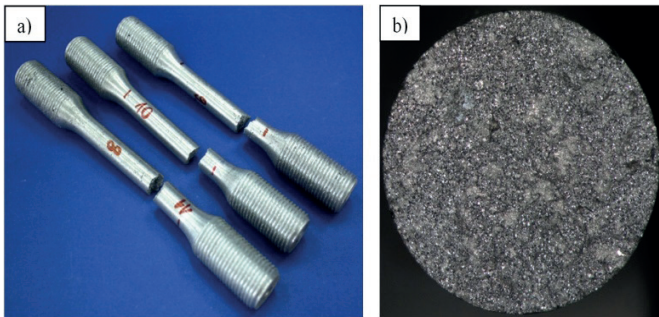


Fig. 4. Casting of the static tensile tests after solution heat treatment (500°C/6 h/water) and ageing (200°C/16 h/furnace): a) after break, b) breakthroughs in the macro scale

The increase of the strength properties of the AISi17Cu5 alloy after heat treatment compared to casting without solution heat treatment and aging was due to precipitation hardening. The applied aging treatment, preceded by solution heat treatment, causes not only increase in concentration of primary silicon crystals in α (Al) solid solution, but also affect on a favorable change in the morphology of Si crystals. An example of microstructure of the AISi17Cu5 after a heat treatment is shown in Fig. 5, while the eutectic form α (Al)- β (Si) and the eutectic phase containing Al₂Cu and Al₉Fe₂Si - are shown in Fig. 6.

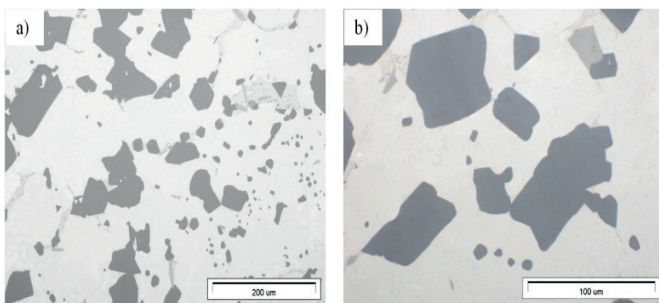


Fig. 5. Microstructure of the AISi17Cu5 alloy after solution heat treatment (500°C/5 h/water) and ageing (200°C/16 h/furnace) (different magnifications)

Due to the noticeable changes in the shape of the primary silicon crystals in castings subjected to a process of solution heat treatment and aging, stereological parameters of silicon crystals in hypereutectic AISi17Cu5 alloy were measured. Just as in studies without heat treatment cross-sectional area, perimeter and diameter of the primary silicon crystals and the aspect ratio and variability index was calculated.

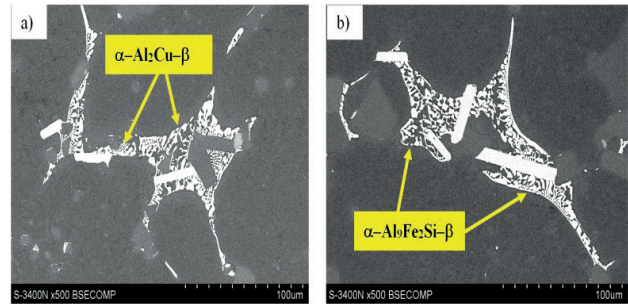


Fig. 6. Microstructure of the AISi17Cu5 alloy after solution heat treatment (500°C/5 h/water) and ageing (200°C/16 h/furnace) with: a) α -Al₂Cu- β eutectic, b) α -Al₉Fe₂Si- β eutectic

The stereological parameters of the primary silicon crystals after solution heat treatment and aging in the alloy overheated to a temperature of 920°C (SP/OC) and fast cooled (SPMA/OC) are shown in Table 2

Even more information on the effect of heat treatment and used technologies on the precipitates' form of the primary silicon crystals were obtained by analyzing the shape factor. shape change and size of the surface area of Si crystals. The values thereof are closer to one, the shape of the crystals is similar to the sphere. Distribution histograms of the shape and surface area of Si crystals in castings after heat-treated are shown in Fig. 7

TABLE 2
Stereological parameters of the Si crystals in the AISi17Cu5 alloy after heat treatment

Stereological parameters	Type of technology	
	SP/OC	SPMA/OC
surface area, μm^2	346,5	204,2
volatility rate	286	383
perimeter, μm	66,01	44,25
volatility rate	157	164
shape factor	0,75	0,75
volatility rate	30	29
maximum diameter, μm	22,05	15,25
volatility rate	126	132
minimum diameter, μm	13,36	9,27
volatility rate	120	125
average diameter, μm	18,2	12,6
volatility rate	1123	128
distance between adjacent particles, μm	26,54	19,76
volatility rate	50,7	46

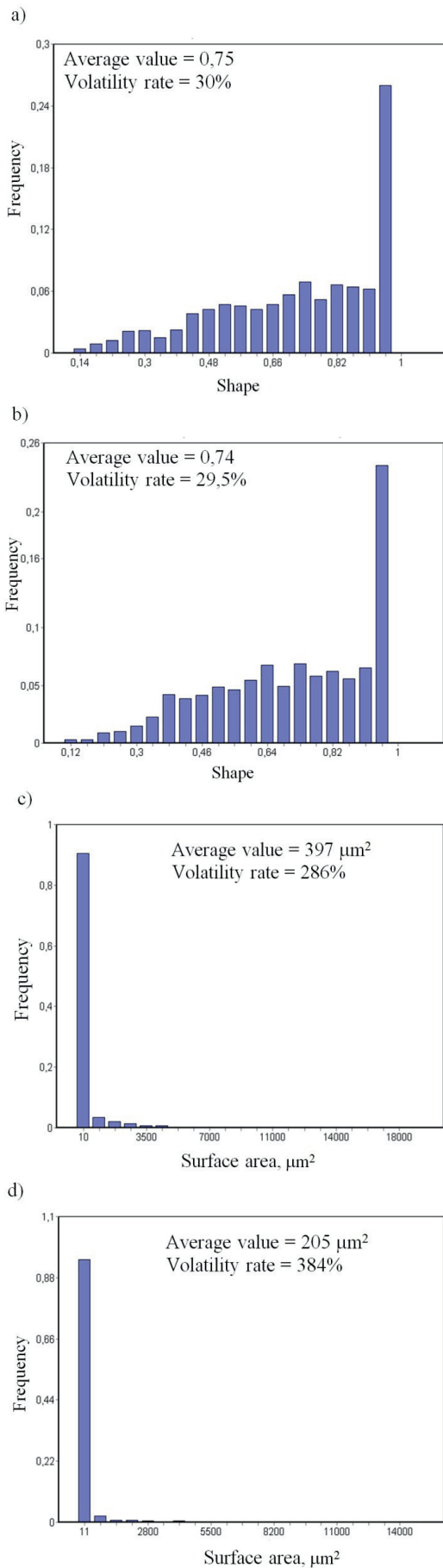


Fig. 7. Histogram showing the distribution of silicon crystal shape and fields in an AlSi17Cu5 alloy after heat treatment: a, c) after overheating, b, d) after overheating and intensive cooling

5. Summary

In accordance with the adopted research methodology, the AlSi17Cu5 alloy castings obtained by selected technologies (SW, SM, SP, SPM, SPMA), were subjected to heat treatment, consisting of the following steps:

- solution heat treatment: $500 \pm 5^\circ\text{C}$ / 6 hours / cooling in boiling water,
- artificial aging: $200 \pm 5^\circ\text{C}$ / 16 hours / cooling with the furnace.

From the study of the mechanical properties (HB R_m , $R_{0.2}$) it appears that the solution heat treatment and artificial aging resulted in a significant increase of the strength properties. The process of overheating (SP) of the AlSi17Cu5 alloy to a temperature 920°C above the T_{liq} have the largest impact.. This process provides a hardness of about 133 HB (Fig. 1), tensile strength R_m of 240 MPa (Fig. 2) and the yield strength $R_{0.2}$ about 176 MPa (Fig. 3). With respect to the alloy in the initial state (unmodified and without overheating - SW), the hardness increase was about 38%, a tensile strength about 36% and a yield strength about 30%. Comparing the obtained results of the mechanical properties of the investigated alloy, after a significant overheating above T_{liq} similarity of the values can be seen. This demonstrates the possibility of the replacement of the solid state heat treatment by the thermal treatment of the alloy in the liquid state. As noted in [16], overheating of the liquid metal indicates a slight increase in primary energy consumption required to withstand the alloy at high temperature (over T_{liq}) and the consumption of refractory materials. However, in the general economic account, the consumption of energy and materials in the proposed technological solution (significant overheating and modification) may be more beneficial than the traditional way of melting, casting and separate solution heat treatment and aging of the cast in solid state.

The applied heat treatment parameters (typical for hypereutectic piston silumins) cause not only an increase in the concentration in the α (Al) solid solution, but also a positive change in the morphology of primary silicon crystals. The microstructures shown in Fig. 5 indicate that partly spheroidization of silicon precipitates (more rounded edges) occurred. Confirmation of changes in the shape of the Si primary crystal in castings subjected to solution heat treatment and aging can be found in the results of stereological parameters measurement (Table 2 and Fig. 7). The significant change in mechanical properties is also influenced by the shape of α (Al)- β (Si) eutectic and ternary eutectic containing phases: Al_2Cu and $\text{Al}_9\text{Fe}_2\text{Si}$ - Fig. 6. It was found that the copper eutectics are fine grained. The size of eutectics containing iron have been significantly reduced by the heat treatment (solution heat treatment and aging).

REFERENCES

- [1] B. Closset, J.E. Gruzleski, Structure and properties of hypoeutectic Al-Si-Mg alloys modified with pure Sr, Metallurgical Transactions A, **13** (6), 945-951 (1982).
- [2] G. Dercz, J. Piątkowski, Rietveld quantitative and structural analysis of the Al-W master alloy for silumina modification,

- Solid State Phenomena, **163**, 161-164 (2010).
- [3] Min Zuo, Kun Jiang: Refinement of hypereutectic Al-Si alloy by a new Al-Zr-P master alloy, *Journal of Alloys and Compounds*, **503** (2), 26-30 (2010).
- [4] J. Piątkowski, F. Binczyk, The alloying effect of the mechanical properties of AlSi17 alloy, *Acta Metallurgica Slovaca* **2** (3/2), 225 (2001).
- [5] C.L. Xu, H.Y. Wang, Effect of Al-P-Ti-TiC-Nd₂O₃ modifier on the microstructure and mechanical properties of hypereutectic AlSi20 alloy, *Materials Science and Engineering* **452-453**, 341-346 (2007).
- [6] N. Natahalla, M. Hafiz, M. Abdulkhalek, Effect of microstructure on the mechanical properties and fracture of commercial hypoeutectic Al-Si alloy modified with Na, Sb and Sr, *Journal of Materials Science* **34** (14), 3555-3564 (1999).
- [7] Z. Qian, L. Xiangfa, D. Hongshand, Re-formation of AlP compound in Al-Si melt, *Journal of Alloys and Compounds* **480** (2), 376-381 (2009).
- [8] T.B. Abbott, B.A. Parker, The origins of primary silicon particles in hypereutectic aluminum-silicon alloys, *Cast Metals* **1** (3), 122-132 (1998).
- [9] F. Binczyk, J. Piątkowski, New opinion on phosphorus interaction In process forming of primary structure of hypereutectic silumins, *Archives of Material Science* **21** (3-4), 199-213 (2000).
- [10] J. Szajnar, T. Wróbel, Inoculation of pure aluminum with an electromagnetic field, *Journal of Manufacturing Processes* **10** (2), 74-78 (2008).
- [11] J. Piątkowski, The effect of Al-17wt.%Si alloy melt overheating on solidification process and microstructure evolution, *Solid State Phenomena*, **176**, 29-34 (2011).
- [12] J. Piątkowski, B. Gajdzik, T. Matuła, Crystallization and structure of cast A390.0 alloy with melt overheating temperature, *Metalurgija* **51**, (3), 321-324 (2012).
- [13] J. Piątkowski, Influence of overheating degree on material reliability of A390.0 alloy, *Solid State Phenomena*, **191**, 23-28 (2012).
- [14] J. Piątkowski, Influence of overheating temperature on the shape of primary silicon crystals in hypereutectic Al-Si cast alloys, *Solid State Phenomena*, **203-204**, 417-422 (2013).
- [15] J. Piątkowski, B. Gajdzik, Testing phase changes in Al-Si cast alloys with application of thermal analysis and differential calorimetric analysis, *Metalurgija* **52** (4), 469-472 (2013).
- [16] J. Piątkowski, Physical and chemical phenomena affecting structure, mechanical properties and technological stability of hypereutectic al-si-me alloys after overheating, *Monography, Silesian Technical University, Gliwice* (2013).

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