

The Mechanical Properties of AlSi17Cu5 Cast Alloy after Overheating and Modification of CuP Master Alloy

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Abstract

The paper presents the results of studies on the effect of the AlSi17Cu5 alloy overheating to a temperature of 920°C and modification with phosphorus (CuP10) on the resulting mechanical (HB, R_m, R_{0.2}) and plastic (A₅ and Z) properties. It has been shown that, so-called, "time-thermal treatment" (TTT) of an alloy in the liquid state, consisting in overheating the metal to about 250°C above T_{liq}, holding at this temperature by 30 minutes improves the mechanical properties. It has also been found that overheating of alloy above T_{liq} enhances the process of modification, resulting in the formation of fine-grain structure. The primary silicon crystals uniformly distributed in the eutectic and characteristics of the α(Al) solution supersaturated with alloying elements present in the starting alloy composition (Cu, Fe) provide not only an increase of strength at ambient temperature but also at elevated temperature (250°C).

Keywords: Hypereutectic Al-Si alloys, Overheating, Modification with CuP10 master alloy, Mechanical and plastic properties

1. Introduction

As a result of the solidification process, hypereutectic Al-Si alloys develop the structure composed of a soft dendritic Al matrix with large primary silicon crystals of a non-uniform distribution. A structure of this type has very disadvantageous effect on the mechanical properties and machinability of castings, and therefore the key issue in the application of Al-Si alloys is to reduce the size of primary Si crystals and ensure their uniform distribution. This goal can be achieved through for example modification and refining [1-5] of cast alloys, and also through overheating of melt before casting [6-9].

The results of recent studies suggest that superheating of liquid alloy above the T_{liq}, holding at that temperature and cooling can also cause the refinement of primary silicon crystals and their uniform distribution of the α-β eutectic [10-14].

2. Scope and purpose of research

The aim of the study is to demonstrate what impact the overheating degree and modification process (considered separately or jointly) can have on the change in mechanical (HB, R_m, R_{0.2}) and plastic (A₅, Z) properties of the casting AlSi17Cu5 cast alloy.

To achieve this aim, the scope of work includes:

- choice of alloy and development of a technological concept of its modification through strong overheating,
- overheating the liquid alloy to a temperature of 920°C, holding at this temperature for 30÷40 minutes in the furnace and casting to a metal mould,
- measurement of mechanical properties (HB, R_m, R_{0.2}),
- measurement of plastic properties (A₅ and Z) – at ambient temperature (20°C) and at elevated temperature (250°C),
- study of microstructure.

3. Research method and materials

Casting of specimens for testing of mechanical and plastic properties was carried out in the chamber of a Balzers VSG 02/631 vacuum induction furnace. Alloys were melted in an SiC crucible of 800 cm³ capacity and cast into a steel mould producing simultaneously three Ø200×1600 mm specimens, which were next machined to the dimensions complying with PN EN10002-1. To avoid the negative impact of various phenomena related with the presence of gas in liquid metal bath, resulting from the high-degree overheating of alloy above the T_{liq} point, a Protacol-Degasal protective coating was applied. The mixture (0.4 wt.%) was introduced by immersion under the surface of the molten metal bath, and under the layer of produced slag, 0.2 wt.% of the Rafglin-3 alloy refiner was added. Then the alloy was overheated at 920°C for 30÷40 minutes. With the working chamber of the furnace kept closed, 0.05 wt.% of P in the form of a CuP10 master alloy was added, and after 10 minutes, the bath was deslagged and the alloy was cast to a steel mould in four different conditions:

1. Unmodified (designated by the symbol SN),
2. Modified with 0.05 wt.% P in the form of a CuP10 master alloy (designated by the symbol SM),
3. Overheated at 920°C for 30÷40 minutes in the furnace (designated by the symbol SP),
4. Overheated and modified according to the parameters as stated above (designated by the symbol SPM).

Brinell hardness test was performed in accordance with PN-EN ISO 6506-1 on a Zwick ZHF hardness tester under a load of 187.5 kg using a 2.5 mm diameter steel ball applied for a time of 35 seconds. Static tensile test at room temperature (20°C) was carried out in accordance with PN EN ISO 6892-1 on a 3382 Instron machine, using a 20:1 ratio and a constant tensile speed of 5 mm/min. The following parameters were determined: tensile strength (R_m), yield strength ($R_{0.2}$), elongation (A_5), and reduction of area after specimen fracture (Z). Applying the same parameters, the mechanical tests were carried out at a temperature of 250°C, selected as a value reflecting the actual operating conditions of AlSi17Cu5 alloy. Twelve measurements were taken, discarding the two extreme values, and calculating an arithmetic mean from the remaining values.

4. The results of investigations

4.1. Mechanical properties

Tests were carried out on an AlSi17Cu5 alloy whose chemical composition is given in Table 1.

Table 1.

Chemical analysis of the examined cast alloy (wt.%)

Alloy	Chemical composition of AlSi17Cu5 alloy						
	Si	Cu	Fe	Mn	Mg	Ni	Al
AlSi17 Cu5	16,81	0,17	0,54	0,03	0,04	0,13	rest

The results of Brinell hardness measurements obtained for the aforementioned four technological variants is shown in Figure 1a. The results of static tensile test to determine the tensile strength R_m of AlSi17Cu5 cast alloy at ambient temperature and at elevated temperature (250°C) are shown in Figure 1b; Figure 1c shows the same results obtained for the yield strength. Average values of the reduction of area after specimen fracture (Z) and of elongation (A_5), plotted in function of the technological variant selected, are shown in Figures 2a and 2b, respectively.

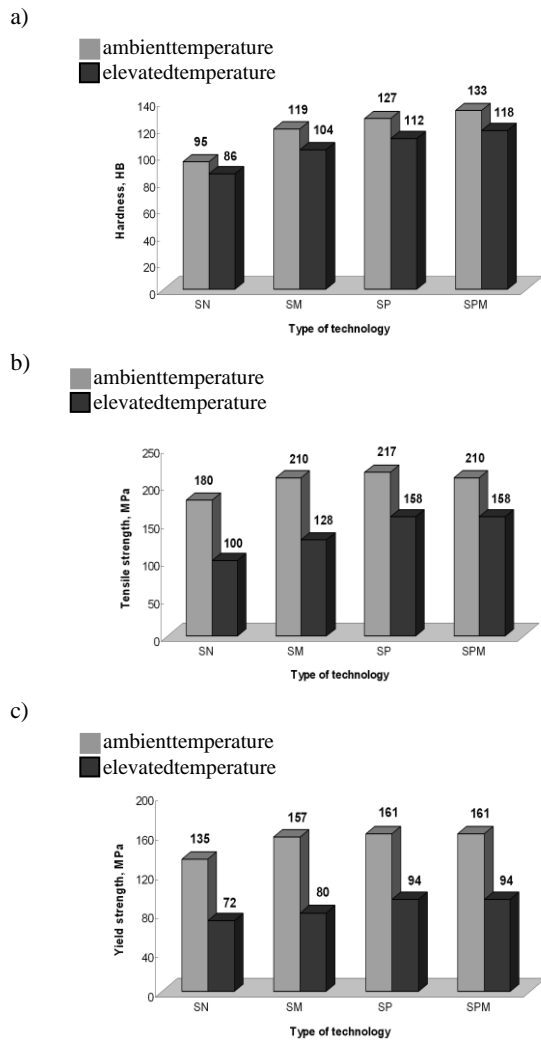
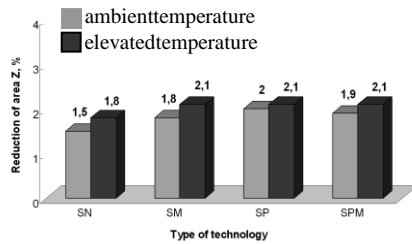


Fig. 1. Mechanical properties of AlSi17Cu5 cast alloy at ambient temperature (20°C) and at elevated temperature (250°C): a) Brinell hardness, b) the tensile strength R_m , c) the yield strength $R_{0.2}$ by four variants of the technology

a)



b)

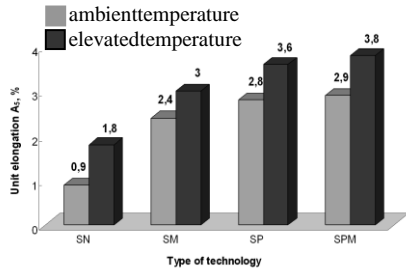


Fig. 2. Plastic properties of AlSi17Cu5 cast alloy at ambient temperature (20°C) and at elevated temperature (250°C): a) reduction of area Z, b) the unit elongation A_5 by four variants of the technology

4.2. Study of microstructure

A complementary research to the solidification process was study of microstructure. Microstructures of AlSi17Cu5 alloy unmodified and modified with 0.05 wt.% P in the form of a CuP10 master alloy are shown in Figure 3. Microstructures of AlSi17Cu5 alloy overheated to 920°C and overheated to 920°C and modified with 0.05 wt.% phosphorus is shown in Figure 4.

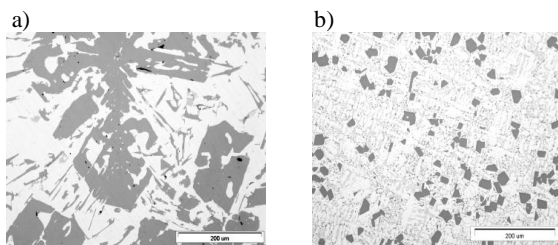


Fig. 3. Microstructure of AlSi17Cu5 alloy: a) unmodified, b) modified with 0.05 wt.% phosphorus (CuP10)

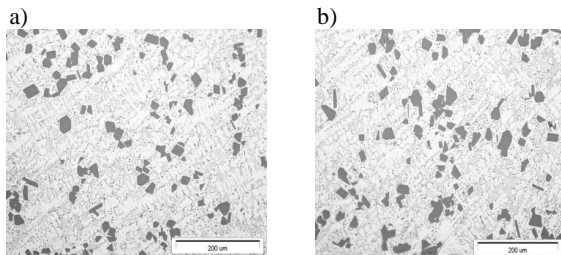


Fig. 4. Microstructure of AlSi17Cu5 alloy: a) overheated to 920°C, b) overheated to 920°C and modified with 0.05 wt.% phosphorus (CuP10 master alloy)

5. Summary of the results

As follows from the studies, each time the application of:

- ✓ modification with 0.05 wt.% P (CuP10) – SM,
- ✓ overheating for 30÷40 min. to a temperature of 920°C – SP,
- ✓ overheating and modification – SPM.

increased the alloy hardness HB by 21% respectively, while the combined process of strong overheating and modification resulted in a 29% increase as compared to the AlSi17Cu5 alloy in an unmodified condition (SN).

So it can be concluded that alloy overheating above T_{liq} produces similar effects of hardness increase as the process of modification or modification combined with strong overheating. This is related with the degree of under cooling, the value of which may reach even $106 \text{ K}\cdot\text{s}^{-1}$, corresponding to the phase growth rate of approximately $200 \text{ m}\cdot\text{s}^{-1}$ [15]. Pouring the alloy into a steel mould speeds up the solidification process, and is one of the casting techniques used to produce metastable and amorphous alloys. Additionally, rapid heat transfer refines alloy structure, raising the number of potential substrates for heterogeneous nucleation of silicon. Another advantage of rapid solidification is the possibility to produce a more homogeneous melt, owing to the reduced heterogeneity of chemical composition and increased solubility limit of alloying elements in the solid phase. This can explain, among others, the increase of mechanical properties as compared to the properties of alloys cast by conventional techniques.

The remaining part of studies concerning the effect of technological process on the mechanical and plastic properties of the investigated alloy mainly focussed on the results of static tensile test. Since alloys tested for automotive applications are usually cast into metal moulds, a die was used in these tests and in this die, twelve samples were cast using each of the four technological variants developed. The obtained values of the tensile strength (R_m) and yield strength ($R_{0.2}$) were analysed and showed in each case an increase in the properties of the examined material as compared to the alloy in base condition – see Figures 1b and 1c, respectively. Modification with phosphorus or strong overheating of the alloy increased the tensile strength by 16÷18% compared to the alloy in base condition, i.e. unmodified and without overheating, while the combined process of overheating and modification with phosphorus increased this property by 28% (at ambient temperature).

Modification or overheating above T_{liq} , as well as a combination of these two methods finally gave $R_{0.2}=161 \text{ MPa}$, which means about 20% increase (at ambient temperature) compared to the alloy unmodified and without overheating.

Compared to the unmodified condition, the applied technological variants also changed the alloy plastic properties. All variants gave the reduction of area after fracture $Z=2\%$ and elongation $A_5=3\%$, which means a considerable improvement of plastic properties in respect of the alloy in base condition – see Figures 2a and 2b, respectively.

As mentioned previously, practical application of the examined alloy mainly focussed on cast pistons and heads of IC engines. Typically, the piston crown holds an appropriately shaped combustion chamber, in which nearly all of the heat supplied together with the fuel is evolved. These conditions increase the thermal load under which the piston is operating, making it,

in some extreme cases, heated to a temperature of 310°C, with a change of 12°C in one operating cycle. On this information were based the mechanical tests carried out at elevated temperature. From Figure 1 it follows that at this temperature, the tensile strength R_m suffers a drop of 55% when the alloy is not modified. Hence, it can be concluded that modification (or any other treatment that refines the alloy structure) is necessary, particularly when the Al-Si-Me alloys are used for parts operating at elevated temperatures (in the engine working chamber). Due to the developed technological variants of alloy treatment, the drop of R_m at the temperature of 250°C was less sharp and amounted to:

- 40% for alloy modified with phosphorus (SM),
- 28% for alloy overheated to a temperature of 920°C (SP),
- 25% for alloy overheated and modified (SPM).

From the above it follows that after the process of strong overheating of the AlSi17Cu5 alloy above T_{liq} , the tensile strength R_m at a temperature of 250°C will drop from 210 MPa (at ambient temperature) to 128 MPa after the modification with phosphorus and to 158 MPa after strong overheating. Data on the mechanical and thermal loads under which pistons are operating show that piston crown must withstand the stresses of approximately 80 MPa at the moment of the maximum load application. Current trends in designing of pistons for engines of the new generation are rather focussed on reduction of the overall piston height by about 20÷40% to increase the engine power and improve fuel efficiency. This change causes further increase in both mechanical and thermal loads up to even 120 MPa. The results shown in Figures 1 and 2 indicate that each of the technological variants applied meets this criterion.

Studies of the yield strength $R_{0.2}$ at elevated temperatures showed a decrease of this parameter by:

- 47% for alloy in base condition (from 135 to 72 MPa),
- 49% for alloy after modification with P (from 157 to 80 MPa),
- 42% for alloy overheated to a temperature of 920°C (from 161 to 94 MPa),
- 42% for alloy overheated and modified according to the parameters as stated above (from 161 to 94 MPa).

These data indicate that overheating the alloy to a temperature of 920°C and holding at this temperature for 30÷40 minutes (SP) as well as a combined process of overheating and modification with phosphorus (SPM) result in the smallest drop of the yield strength $R_{0.2}$ at elevated temperatures (42%). At 250°C, the yield strength $R_{0.2}$ suffers the most severe drop of 49% in alloy subjected to the sole process of modification with phosphorus and of 47% in alloy in the base condition (SW), compared with the results obtained at ambient temperature. On the other hand, a growing tendency has been observed in the reduction of area and unit elongation after fracture.

The final conclusion is that the increase of mechanical (HB, $R_{0.2}$, R_m) and plastic (Z , A_5) properties is the result of a modification with phosphorus and strong overheating above T_{liq} with subsequent rapid cooling. This is consistent with the assumptions made in the thesis of this study about the manufacture of light hypereutectic Al-Si-Me alloys subjected in the liquid state to a time-thermal treatment conferring to them in as-cast state the

required high mechanical properties, combined with the satisfactory plastic properties. This favourable relationship of material characteristics is expected to contribute to the fact that in some applications, the cast hypereutectic Al-Si-Me alloys will gain an advantage over their hypoeutectic and wrought counterparts.

The results of the studies of mechanical and plastic properties were confirmed with microstructure examinations. In the unmodified AlSi17Cu5 cast alloy the crystals of silicon assumed a large, star-like shape (Fig. 3a). Modification with phosphorus (CuP) causes fragmentation of the microstructure – Figure 3b.

Overheating to 920°C temperature (Fig. 4a), causes high degree of structure refinement was observed. Silicon crystals reduced their size, became more compact and more evenly distributed in the matrix of $\alpha(\text{Al})$ – $\beta(\text{Si})$ eutectic.

Acknowledgements

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