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Deformation, heat treatment and properties of piston hypereutectic silumins

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Abstract. A series of piston hypereutectic silumins based on Al – (15 ÷ 20) % Si alloyed with copper, magnesium, nickel, and chromium was studied. The alloys were modified with phosphorus and hydrogen-containing reagents to increase the deformability and mechanical properties. The experimental ingots, cast in the steel mold, had dimensions: diameter 190 mm, height 500-550 mm, weight 32-40 kg. The mechanical properties and temperature coefficient of linear expansion (TCLE) of the experimental ingots and forgings made from them are determined. Temporary tensile strength and relative elongation of deformed ingots from hypereutectic silumins were 227-306 MPa and 5.7-7.5%, respectively. The optimal heat treatment of deformed silumins was determined: quenching with step heating and aging, which allows the strength of forgings to be increased up to 370-470 MPa. Moreover, the ductility indicators remain at a high level, and the average TCLE of the alloys is (18.0 ÷ 19.2) $\cdot 10^{-6}$ K^{-1} in the range of 50 ÷ 200 °C.

1. Introduction

The analysis of the working conditions of pistons in modern heavily loaded engines [1-3] shows that in the process of operation they perceive significant dynamic loads that change during one cycle in sign and direction. Moreover, the gas pressure on the piston can reach 800 MPa. Another feature of the piston operating conditions is the high temperature of fuel combustion products (~ up to 2000 °C). This determines the heating of the piston bottom under certain engine operating conditions to 350-400 °C. Given the piston operating conditions, hypereutectic alloyed silumins are currently one of the most promising materials for the manufacture of pistons for internal combustion engines. This is determined by the favorable combination of low specific gravity, low temperature coefficient of linear expansion (TCLE) with good mechanical and technological properties. However, the presence of coarse crystals of primary silicon in the structure of hypereutectic silumins reduces their ductility and does not allow pistons to be produced by the pressure treatment in the industrial conditions [2-7].

To ensure the necessary complex of physicomechanical characteristics of workpieces from piston alloys, the final heat treatment is applied [3, 8-10]. Therefore, the study of the tendency of experimental high-silicon deformable silumins to hardening heat treatment and to TCLE change is of practical interest and is the aim of this work.

2. Materials and methods of research

A series of experimental ingots from hypereutectic silumins based on Al – (15÷20) % Si alloyed with copper, magnesium, nickel, chromium and other elements was made. In order to ensure good deformability and a high complex of mechanical properties, the alloys were modified with phosphorus and hydrogen-containing reagents [2,3]. The diameter of the experimental ingots was 190 mm, the height was 500-550 mm, and the weight was 32-40 kg. The chemical composition of the alloys is given in table 1.

Table 1. The chemical composition of the experimental piston hypereutectic silumins.

Alloy No.	Alloy components, weight. %								
	Si	Cu	Mg	Ni	Mn	Cr	Ti	P	H	Al
1	15	3	0.2	-	-	-	-	0.01	0.00008	res.
2	15	3	0.2	1.0	-	-	-	0.01	0.0001	res.
3	15	5	1.1	1.0	-	-	-	0.01	0.0003	res.
4	18	4	0.6	-	-	-	-	0.02	0.0003	res.
5	18	4	0.6	1.0	-	-	-	0.02	0.0006	res.
6	20	5	1.1	-	-	-	-	0.03	0.0006	res.
7	20	1	0.4	-	0.8	0.3	0.1	0.01	0.00008	res.

After removing the cast surface and cutting the ingots into billets, they were hot forged. The total degree of deformation was ε = 94%, and the total forging coefficient was $K_{tot} = 28$. Forging of blanks was carried out on a pneumatic forging hammer MV 412 with a hammer mass of 160 kg. Before forging, the ingots were annealed to obtain an equilibrium structure in them. The annealing temperature and the holding time were 450-470 °C and 1.5–3 h. During the forging process, intermediate annealings were performed at a temperature of 450±10 °C for 0.5–1 h [11-14].

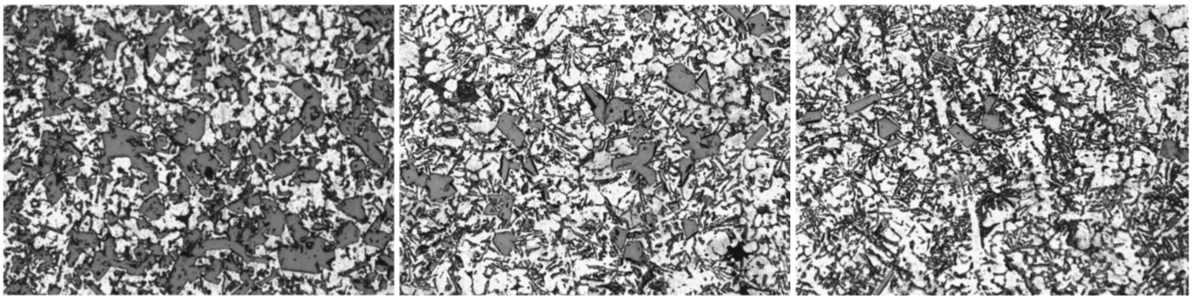
The heat treatment of the forgings was carried out in resistance furnaces of SNOL type. For metallographic analysis of ingots and forgings, an OLYMPUS GX-51F optical microscope was used. The microstructure of the ingots was studied on microsections prepared from transverse templates cut at the same height from the bottom of the ingot. The TCLE of the alloys was determined using a high-temperature differential dilatometer. The error in determining the TCLE was $0.1 \cdot 10^{-6}$ K^{-1}.

3. Results and discussion

The microstructure of the experimental ingot of doped hypereutectic silumin based on Al-18% Si is shown in aigure 1. It is established that the microstructure of the alloys in the cast state is inhomogeneous over the cross section of the ingot. According to its cross section, three characteristic zones can be distinguished:

- surface zone – is a coarse-crystalline rim 3 ÷ 5 mm wide with the largest volume fraction of primary silicon crystals;
- intermediate zone – consisting of needle-type eutectics, sections of α-solid solution and primary silicon crystals. Dark desorption phase of Mg_2Si and light rounded ones of $CuAl_2$ are also clearly visible.
- central zone – the microstructure consists of double and more complex eutectics, sections of an α-solid solution of complex composition and crystals of primary silicon (CPS). Moreover, the volume fraction of CPS in the ingot central zone is much less than in the intermediate.

Table 2 shows the mechanical properties and temperature coefficient of linear expansion of alloys in the cast state. It can be seen that despite the structural differences between the edge (intermediate zone) and the central parts of the ingots, their hardness differs slightly and amounts to 840-1020 and 813-1006 MPa, respectively. Temporary tear resistance of ingots from experimental hypereutectic silumins is in the range of 80-153 MPa. Their average value of the coefficient of linear expansion, determined in the range of 50-200 °C, is (17.2÷19.5) $\cdot 10^{-6}$ K^{-1}, and in the range of 200-450 °C – (17.7÷21.4) $\cdot 10^{-6}$ K^{-1} respectively.



(a) (b) (c)

Figure 1. The ingot microstructure from an experimental alloyed silumin Al-18 % Si-4 % Cu-0.6 % Mg: a – surface zone; b – intermediate zone; c – central zone; ×100.

Before forging, the ingots were annealed at 450–470 °C for 1.5–3 h to eliminate the heterogeneity of the structure and composition of the alloys. The mechanical properties of the experimental forgings from silumin are σ_r = 227÷306 MPa, δ = 5.7÷7.5 %.

Heat treatment of forgings from alloyed hypereutectic silumins included hardening and aging. Hardening in this case is achieved by fixing the maximum supersaturated α-solid aluminum solution during quenching and its decomposition during subsequent aging due to the decrease in the solubility of the alloying components with decreasing temperature.

Table 2. Physico-mechanical properties of ingots from alloyed hypereutectic silumins.

Alloy No.	Hardness, HB, MPa		σ_r, MPa	Average TCLE, $\alpha \cdot 10^{-6}$ K^{-1} in the range of temperatures, °C	
	edge	centre		50-200	200-450
1	873	853	153	19.1	20.8
2	840	813	148	18.9	19.7
3	1020	1006	125	19.2	20.6
4	986	928	138	19.5	21.4
5	980	876	124	16.7	17.7
6	943	941	86	18.7	19.9
7	958	950	80	19.0	20.5

The analysis of the state diagram of the Al-Si-Cu-Mg system, to which these alloys belong, shows that they have a complex phase composition. Seven phases can be in equilibrium with the aluminum solid solution: Si, θ ($CuAl_2$), β (Al_2Mg_3) or (Al_8Mg_5), Mg_2Si, S (Al_2CuMg), T (Al_6Cu Mg), W ($Cu_2Mg_8Si_6Al_5$) [4]. The main hardeners are the phases $CuAl_2$, Mg_2Si, S (Al_2CuMg) and partially W ($Cu_2Mg_8Si_6Al_5$). The complex phase composition of the alloys makes it possible to carry out a large number of invariant reactions in a wide temperature range of 444–577 °C [15] and, consequently, the formation of complex fusible eutectics, the melting temperature of which determines the quenching heating conditions, is possible. To ensure the complete dissolution of the alloying elements and prevent the possibility of burnout, it is recommended to use step heating for hardening. The need for such heating for these alloys is confirmed by the results of experiments on the influence of the heating temperature for quenching in cold water and the exposure time on the mechanical properties of alloys (aging mode – 150 °C, 5 h), shown in table 4 for alloy composition No. 4 (see table 1).

The analysis of the data in table 3 shows that the satisfactory combination of strength and ductility is achieved after quenching in modes 2 and 3, providing for step-by-step heating under quenching at temperatures of 480 ± 10 °C (first stage) and 490 and 500 ± 10 °C (second stage) with holding at these temperatures 0.5-1 h and subsequent aging. After carrying out the indicated heat treatment regimes, the temporary resistance of the forgings is 450-460 MPa, the elongation is 4%, the relative narrowing is 5.8-8.3%.

Table 3. Mechanical properties of forgings from alloys Al-18 % Si-4 % Cu-0.6 % Mg, depending on quenching conditions (aging 150 °C, 5 h).

No.	Quenching temperature and holding time	Mechanical alloys		
		σ_r, MPa	δ, %	Ψ, %
1	Without treatment	306	7.2	13.4
2	480±10 °C, 2 h → 490±10 °C, 2 h	450	4.0	5.8
3	480±10 °C, 2 h → 500±10 °C, 0.5 h	460	3.8	8.3
4	480±10 °C, 2 h → 500±10 °C, 1 h	425	1.0	0
5	490±10 °C, 1 h	437	1.2	0
6	490±10 °C, 3 h	437	1.0	0

After quenching according to regimes 5 and 6, which do not provide for the use of step heating, burnout processes occur in the alloys, which leads to a sharp decrease in ductility to 1-1.2%.

Thus, the following was adopted as the optimal heat treatment regime for piston alloys: quenching – stepwise heating 480 ± 10 °C → (490-500)±10 °C, with a holding 2 and 1 h, respectively, at the lower and upper stages, cooling in cold water and subsequent artificial aging at 150 °C for 5 hours. Table 4 shows the physicomechanical properties of the studied deformable alloys after heat treatment according to the specified mode.

Table 4. Physico-mechanical properties of forgings after quenching and aging.

Alloy No.	Mechanical properties			Average TCLE, $\alpha \cdot 10^{-6}$ K^{-1} in the range of temperatures, °C	
	σ_r, MPa	δ, %	Ψ, %	50-200	200-450
1	425	6.4	9.9	18.6	22.4
2	372	4.6	7.4	19.0	22.1
4	450	4.0	5.8	18.0	20.6
5	400	2.8	6.1	19.2	21.5
6	470	5.0	5.2	18.8	22.0
7	400	3.5	-	19.0	22.7

From these tables it can be seen that as a result of quenching and aging, the tensile strength of the deformed hypereutectic aluminum-silicon alloys significantly increases to 370-470 MPa. Moreover, the ductility indicators remain at a high level for piston silumins, and the average TCLE of the alloys after heat treatment is $(18.0\div19.2)\cdot10^{-6}$ K^{-1} in the range 50÷200 °C and $(20.6\div22.7)$ 10^{-6} K^{-1} in the range of 200 ÷ 450 °C.

Metallographic studies of deformable doped hypereutectic silumins after quenching and aging showed that in the microstructure of heat-treated forgings, particles of primary and eutectic silicon take a more round and spheroidized shape. The phases Mg_2Si and $CuAl_2$, which did not completely dissolve upon heating and deformation of the workpieces, after quenching dissolve in the α-solid solution of aluminum

4. Conclusion

The mechanical characteristics and TCLE of ingots and forgings from experimental hypereutectic silumins based on Al – (15 ÷ 20) % Si alloyed with copper, magnesium, nickel, chromium, modified with phosphorus and hydrogen-containing reagents are studied.

Through the use of optimal heat treatment modes (hardening and aging), the possibility of improving the complex of physico-mechanical properties of deformed piston hypereutectic silumins is shown. A significant increase in strength for such alloys was obtained while maintaining high ductility in comparison with cast piston silumin and a low TCLE in relation to deformed alloys.

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