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FORMATION OF THE PHASE COMPOSITION, STRUCTURE, AND PROPERTIES OF EUTECTIC Al–Si ALLOYS IN PRESSURE CASTING

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Eutectic silumins are widely used industrial alloys. In traditional casting into sand or chill molds the regular features of the structure formation in silumins have been studied insufficiently thoroughly. In particular, the mechanism of the formation of numerous fine crystals of silicon that cause rapid wear of the cutting tools when the castings are processed is unclear, and the factors affecting the hardening of the alloys have not been studied in detail. The present paper is devoted to the results of a study of the phase composition, strength, and ductility of silumins hardened under conditions of intense cooling and pressure that are typical for pressure casting.

The structure of an Al–Si alloy with a eutectic composition crystallized in casting under pressure is characterized by the presence of excess crystals of α - and β -phases and a high dispersity of the eutectic (Fig. 1a). The segregations of the α -phase are dendrite colonies with a freely developed structure. The regular faces of the segregations of the β -phase are a sign of unrestricted growth of crystals suspended freely in the mother liquid. It has been established that the volume fraction of the α -phase is equal to 22% and that of the β -phase is 8%. It is obvious that nonequilibrium crystallization in casting under pressure begins with the segregation of primary crystals, and only then does the hardening occur in accordance with the eutectic pattern. Figure 1b presents the microstructure of the same alloy crystallized in a mold under a pressure of 100 N/mm² exerted by a piston. A comparative analysis of the structures in Fig. 1 shows that in order to explain the features of structure formation in casting under pressure the pressure should not be treated as the main factor governing the crystallization process.

Let us consider the conditions for the formation of a nonequilibrium structure in casting under pressure. In the beginning of the crystallization process the cooling rate of the melt attains 100 K/sec. However, as the press-mold heats up, the intensity of the heat removal decreases considerably. After the mold is filled, the pressure on the metal is comparatively low, amounting to about 10 N/mm², but in 0.12–0.14 sec the melt experiences an impact of a hydraulic shock and a pressure of about 100 N/mm². Volume shrinkage develops in the metal of the mold and the temperature decreases, which

decreases the pressure again to 7–9 N/mm². All the changes in the temperature and pressure occur in a time period of several tenths of a second.

The method of casting under pressure is characterized by long-term holds of the melt in the furnace at minimum overheating, low feeding temperatures, and preliminary compression and cooling of the metal in the pressing chamber. These features of the manufacturing process cause the development of microinhomogeneities in the structure and composition of the liquid solution of silicon in aluminum. In accordance with the data of [1, p. 13] and [2, p. 60] heterophase complexes of silicon atoms coexist in slightly overheated Al–Si alloys in equilibrium with a solution characterized by a statistical distribution of the components. The formation of the complexes decreases the silicon concentration in the mother solution.

In an analysis of the crystallization process the graphical model is usually a section of the phase diagram by a vertical line whose position relative to the concentration axis corresponds to the content of the second component. If the melt is obviously heterogeneous, this method does not reflect entirely adequately the course of the crystallization process. The dynamics of the segregation of microregions with a concentration of atoms of one element (associates) and the reduction of the concentration of this element in the remaining liquid is represented better by breaking the vertical line into two branches describing the joint cooling of the associates and the mother solution.

To understand the mechanism of the segregation of primary crystals in a eutectic melt we analyzed the special features of the phase equilibrium and the state of the crystallizing melt in the neighborhood of the eutectic point. Figure

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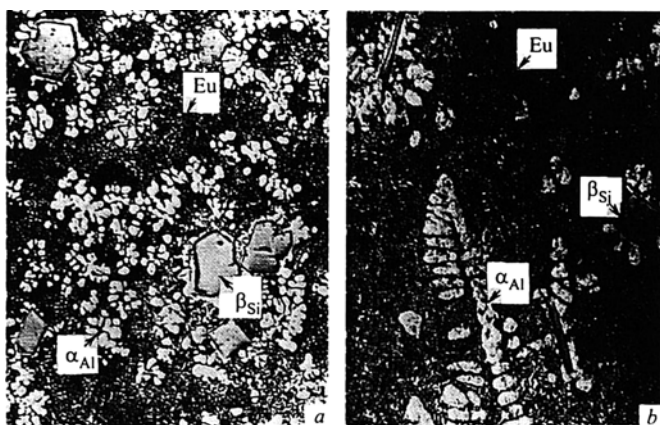


Fig. 1. Microstructure of an Al–11.72% Si alloy crystallized upon casting under pressure (a) and under piston pressure (b): a) $\times 80$ ($\times 2$), b) $\times 80$.

re 2a presents a portion of the Al–Si phase diagram adjoining the region of the eutectic composition (thick lines). Taking into account the supercooling required for nucleation of aluminum and silicon crystals (18 and 25°C, respectively) [2, p. 58] we plotted curves parallel to the lines of the equilibrium liquidus whose intersection corresponds to the position of the nonequilibrium eutectic point I on the eutectic horizontal (thin lines). The initial liquid solution with a concentration of 11.7% Si is in equilibrium with the silicon associates A_{Si} and the microvolumes L' of the liquid from which some of the silicon atoms have passed into the associates, i.e.,

$$L_{11.7} = A_{Si} + L'. \quad (1)$$

Under the conditions of supercooling the equilibrium shifts to the right, causing decomposition of the solution with formation of crystals on the base of the silicon lattice β_{Si} , i.e.,

$$L_{11.7} \rightarrow \beta_{Si} + L'. \quad (2)$$

In Fig. 2a this corresponds to branch A , deviating from the vertical I .

The intersection of branch A with the line of the nonequilibrium liquidus (point K) denotes the beginning of the segregation of β_{Si} crystals. The change in the composition of the liquid surrounding the β_{Si} crystals occurs along the branch L' ; due to the rapid removal of the silicon atoms the curve L' shifts abruptly to the left. The change in the composition of the remainder of the mother melt in this stage is described by the segment KK' of the line of the nonequilibrium liquidus (Fig. 2b).

At the moment when the crystallizing metal receives a high-pressure pulse the point of the eutectic equilibrium shifts to position 3 (the dashed lines in Fig. 2b correspond to the Al–Si phase diagram at a pressure of 100 N/mm² plotted in accordance with data of [3, p. 123]). The compositions of all layers of the liquid surrounding the β_{Si} crystals whose

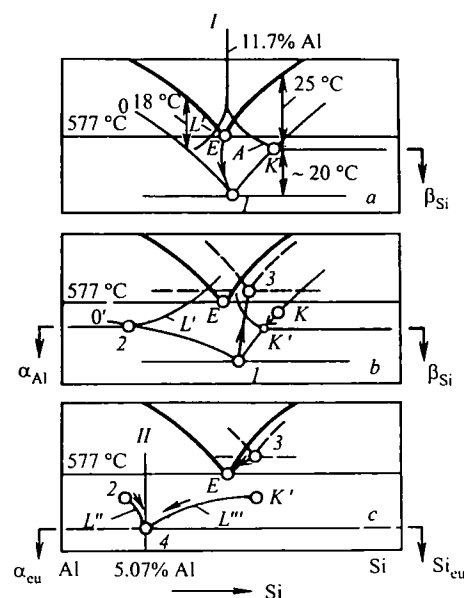


Fig. 2. Change in the position of the eutectic point in the phase diagram of the Al–Si system and composition of the liquid phase in microvolumes of the melt at different crystallization stages under conditions of pressure casting (a diagram).

figurative points lie on the line L' are hypoeutectic. The intersection of the branch L' with the intermediate position of the nonequilibrium liquidus $0' - 1$ at point 2 denotes the beginning of the segregation of numerous fine α_{Al} dendrites in these layers. The second stage of the decomposition can be described by the equation

$$L' \rightarrow \alpha_{Al} + L''. \quad (3)$$

The emission of heat with simultaneous crystallization of α_{Al} and β_{Si} solid solutions decelerates the fall of the temperature, and the further change in the composition of the mother solution occurs over the curve $K' - 4$ (Fig. 2c). The colony-like segregation of the α_{Al} -phase causes isolation of interdendrite spaces from the mother melt, equalizing diffusion occurs incompletely, and the composition of the liquid in the nearest neighborhood of the α_{Al} crystals changes along the line 2–4. The decrease in the pressure in the melt due to the volume shrinkage shifts the eutectic point from position 3 toward the equilibrium point. Therefore, the concentration of silicon in the liquid remainder crystallizing at point 4 with formation of a eutectic structure differs substantially from the equilibrium concentration (Fig. 2c).

By analogy with the considered decomposition of a eutectic melt we can write reactions of stagewise decomposition of alloys of hypo- and hypereutectic compositions (see Table 1).

Thus, the position of the eutectic point in the Al–Si system in crystallization under conditions of casting under pressure is not constant; with change in the pressure, cooling rate, superheating temperature, and casting temperature of the metal the composition and the hardening temperature of the

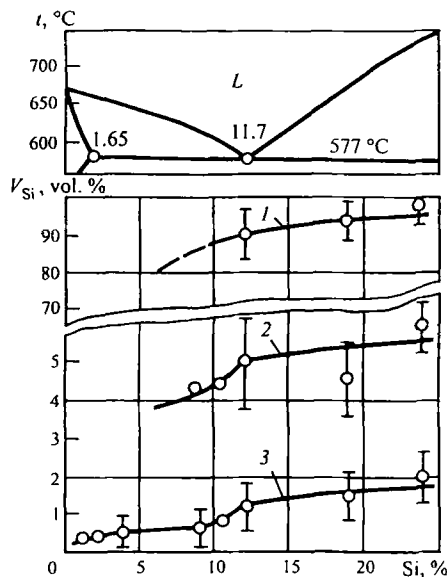


Fig. 3. Distribution of silicon (V_{Si} is the volume fraction) in the structural components of Al–Si alloys in pressure casting: 1) in the β_{Si} -phase; 2) in the eutectic; 3) in the α_{Al} -phase.

eutectic change. An alloy of eutectic composition hardens in a nonequilibrium temperature range of about 20°C (Fig. 2a).

A microscopic x-ray spectral analysis of Al–(1–24)% Si alloys with the help of an MAR-2 device has shown some general features in the distribution of silicon among the structural components (Fig. 3). The content of silicon in the α - and β -solid solutions and in the eutectic of Al–Si alloys cast under pressure does not correspond to the equilibrium concentration. For example, the excess α -phase of a eutectic alloy contains $1.21 \pm 0.32\%$ Si, the eutectic regions contain $5.07 \pm 1.5\%$ Si, and the excess crystals of the silicon phase contain $90.2 \pm 3.3\%$ Si. Let us calculate the mean content of Si taking into account the volume fraction of the structural components (22% α -phase, 70% eutectic, and 8% β -phase) and the concentration of silicon in them, i.e.,

$$0.22 \times 1.21 + 0.7 \times 5.07 + 0.08 \times 90.2 = 11.54\%.$$

The deviation from the data of a chemical analysis is $(11.72 - 11.54) \times 100 / 11.72 = 1.7\%$.

The mean content of silicon calculated in hypoeutectic alloys turned out to be lower than the results of a chemical analysis. This occurred because some of the atoms were spent for formation of fine excess silicon crystals indiscernible under a magnification lower than $\times 960$. At a magnification of $\times 2000$ inclusions of excess crystals of β -phase were determined in alloys containing 10.7 and 8.2% Si.

On the other hand, in hypereutectic alloys a microscopic x-ray spectral analysis showed that the content of silicon in the α -phase exceeded

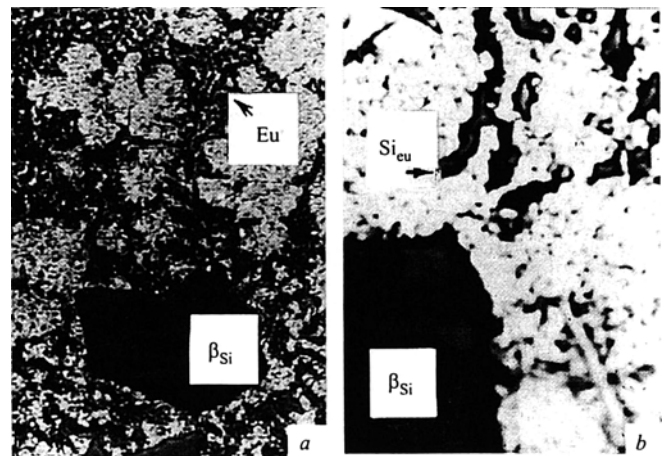


Fig. 4. A crystal of excess silicon in a eutectic alloy (a) and a hypereutectic alloy (b): a) $\times 2000$; b) $\times 2000 (\times 2)$.

the maximum solubility. This was caused by the presence of fine (up to 0.3 μm) inclusions of free silicon in the body of grains of aluminum solid solution.

The concentration of silicon in the composition of the β -phase of eutectic and hypereutectic alloys was much below 100%. Since the solubility of aluminum in the silicon lattice is low, aluminum atoms occur in defects of β -phase crystal formations. A micrograph of a fragment of the structure of a eutectic alloy shows that the body of the silicon crystal contains a considerable number of micropores 0.5–1.5 μm in size (Fig. 4a). It is obvious that microvolumes of the mother solution are captured mechanically by the face of the growing crystal. The surface of the face is not flat and has bulges growing into the liquid at different rates and not strictly in parallel. As the bulges intergrow, the dimples between them turn into pores that are filled with aluminum melt removed from the front of silicon crystallization.

Under 2000-fold magnification we could observe the internal structure of the eutectic regions (Fig. 4). In casting under pressure the silicon phase in the eutectic did not have a well-defined lamellar structure. The silicon inclusions can be classified as vermicular by analogy with free carbon of this shape in gray cast iron [4, p. 315]. The silicon serpents are curved like parentheses and have outgrowths and branches (Fig. 4b). The total length of the silicon serpents is 4–6 μm on the average and the thickness is 0.25–0.4 μm . The shape

TABLE 1

State	Decomposition reactions in crystallization in pressure casting of Al–Si alloys		
	hypoeutectic (8.2% Si)	eutectic (11.7% Si)	hypereutectic (18.3% Si)
Metastable equilibrium	$L_{8.2} = A_{Al} + L'$	$L_{11.7} = A_{Si} + L'$	$L_{18.3} = A_{Si} + L'$
Supercooled liquid solution (decomposition stages)	$L_{8.2} \rightarrow \alpha_{Al} + L'$	$L_{11.7} \rightarrow \beta_{Si} + L' + L''$	$L_{18.3} \rightarrow \beta_{Si} + L'$
	$L' \rightarrow \alpha_{cu} + Si_{cu}$	$L' \rightarrow \alpha_{Al} + L''$ $L'' + L''' \rightarrow \alpha_{cu} + Si_{cu}$	$L' \rightarrow \alpha_{sel} + \beta_{cr} + L''$ $L'' \rightarrow \alpha_{cu} + Si_{cu}$

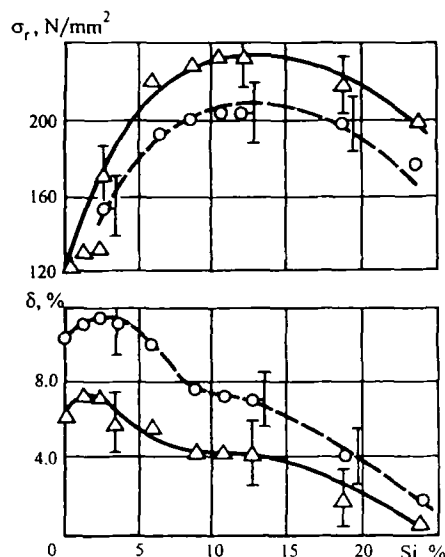


Fig. 5. Mechanical properties of Al-Si alloys as a function of the silicon content: solid lines) casting under pressure; dash lines) crystallization under pressure.

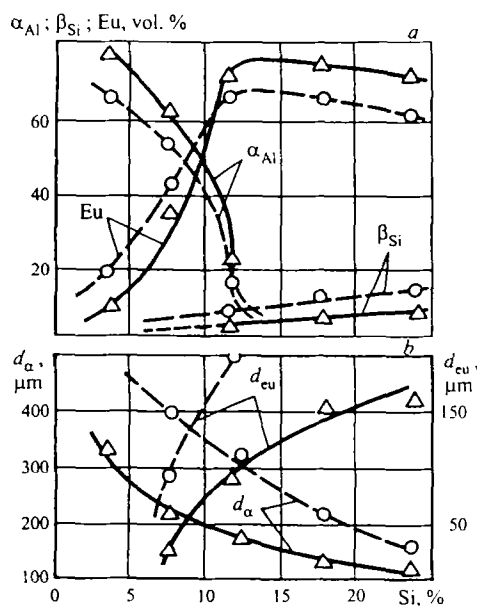


Fig. 6. Dependence of the volume fraction of structural components (a) and the grain size of the solid solution d_α and the eutectic regions d_{eu} (b) in the structure of Al-Si alloys on the silicon content: solid lines) pressure casting; dash lines) crystallization under the pressure of a piston.

coefficient of the silicon serpents calculated as the ratio of their thickness to the length of the rectilinear segments is 0.14–0.22 for eutectic alloys, 0.10–0.17 for hypoeutectic alloys, and 0.06–0.16 for hypereutectic alloys. The eutectic of the alloys of eutectic composition is the most disperse.

It is expedient to treat primary α_{Al} and β_{Si} crystals as independent metastable phases; they are separated by a well-defined boundary and have a special position in the structure. As distinct from the phases of eutectic origin α_{eu} and Si_{eu}

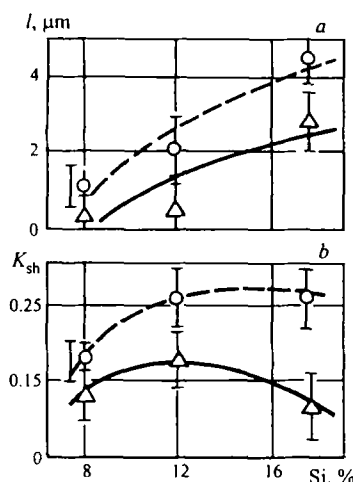


Fig. 7. Dependence of the parameters of silicon segregations (l is the distance between silicon serpents, K_{sh} is the shape coefficient) in the eutectic of Al-Si alloys on the silicon content: solid lines) pressure casting; dash lines) crystallization under the pressure of a piston.

the excess phases dissolve in prolonged heating, whereas in the phases of the nonequilibrium eutectic only the shape and concentration of silicon are changed.

Mechanical properties of binary Al-Si alloys cast under pressure are presented in Fig. 5. Flat tensile specimens were prepared in accordance with GOST 1583-89. For comparison, we tested alloys crystallized under a pressure of 100 N/mm² produced by a piston. The specimens for mechanical tests (type 7k by GOST 1497-84) of alloys crystallized under piston pressure were turned from an ingot 40 mm in diameter and 70 mm high. All the alloys were tested in a cast state, 4–8 specimens at a point.

Solid-phase hardening was virtually absent in the alloys of the studied system. The mechanism of dispersion hardening did not work either, due to rapid coagulation and coarsening of silicon segregations inside the grains of the α -solid solution [5, p. 65]. Beginning with a 3% content of silicon in the alloys, hardening due to the second phase became substantial. Segregations of the silicon phase in the form of chains of a discontinuous or continuous network impeded the translation of strain from grain to grain. For this reason, for example, the ultimate rupture strength of an Al-3.7% Si alloy was 40–50 N/mm² higher than σ_r of pure aluminum and of alloys with 1.2 and 2.1% Si.

When the content of Si exceeded 6%, the alloys acquired a structure typical for cast silumins, namely, dendrites of the solid solution and a eutectic. The concentration range of 6–18% Si is the most interesting for practical purposes because it is used most often for cast alloys. For alloys with this range of silicon concentration the level of the strength and ductility parameters is quite high and changes only in correspondence with the change in the proportion of the structural components (Fig. 6a). The decisive contribution to hardening of these alloys is made by the structural factor, and it is obvious that the optimum proportion of the α -phase and the solid eu-

eutectic corresponds to a eutectic composition. The higher level of strength in alloys cast under pressure relative to the strength of the same alloys crystallized under the pressure of a piston is caused by disintegration of grains of the solid solution (Fig. 6b) and the internal structure of the eutectic component (Fig. 7a). The silicon segregations in the alloy with a eutectic composition have the most favorable shape for the ductility characteristics (Figs. 4a and 7b).

CONCLUSIONS

1. The thermodynamic conditions of the phase equilibrium (the pressure and the temperature) in pressure casting of Al – Si alloys change continuously and rapidly. For this reason, the composition of the solid phase emerging at any moment of the crystallization process is not determined by the equilibrium diagram but rather corresponds to regions of the nonequilibrium diagram that reflects the local metastable equilibria appearing in crystallization in individual microvolumes of the alloy.

2. The kinetics of the decomposition of a microinhomogeneous supercooled melt is characterized by the formation

of metastable phases that have a composition with an inherited distribution of silicon between the mother solution and the associates of the preceding crystallization stage.

3. The high growth rate of silicon crystals makes microvolumes of the second component (aluminum) locate in defects (pores) of the matrix crystals.

4. The disintegration of grains, the predominance of a disperse eutectic in the structure, and the nonlamellar shape of silicon segregations make a decisive contribution to strengthening of industrial Al – Si alloys.

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