The modification of hypereutectic high-alloy silumins — prospects for the development of technology for producing materials with a low linear expansion coefficient

S G Bochvar¹, P Yu Predko², V Yu Konkevich³ and I V Kostin⁴

¹ Baikov Institute of metallurgy and materials sciences of the Russian Academy of Sciences, 49 Leninsky pr., 119334, Moscow, Russia
² All-Russian Institute of light alloys, 2 Gorbunova st., 121596, Moscow, Russia
³ Moscow aviation institute, 4 Volokolamskoe shosse, 125993, Moscow, Russia
⁴ Unated company RUSAL, 37/1 Pogranichnikov st., 660111 Krasnoyarsk, Russia

E-mail: sgbochvar@yandex.ru

Abstract. This article discusses the possibilities of using hypereutectic silumins and the problems that impede their wider distribution. The known methods of manufacturing products from hypereutectic silumins of high quality are shown. A method for producing casting blocks from hypereutectic silumins by direct chill casting is considered. The possibility of milling primary silicon crystals by introducing modifiers and master alloys of Al-Si-P, Al-Cu-P systems, inorganic carbon and phosphorus compounds is shown. The tendency of copper-doped silumins to hot shortness is shown. The technology of impact on the melt of ultrasonic cavitation is considered together with the introduction of additional active modifiers made of master alloy rods to obtain casting blocks from hypereutectic high-alloy silumins using the method of direct chill casting with a primary silicon crystal size of no more than 10 µm. Technological principles for reducing the grain size of α-solid solution, uniformly distributed over the ingot cross-section, are proposed.

1. Introduction

Among the variety of aluminum structural alloys used in various branches of mechanical engineering, there are alloys based on the Al-Si system with a silicon content higher than the eutectic concentration (12%) — hypereutectic silumins.

Of particular interest are hypereutectic silumins containing 18-25% Si and alloying elements that strengthen the alloy such as Cu, Mg, Fe, Ni, Ti, etc. Hypereutectic silumins attract consumer attention due to the following properties — their low density with satisfactory strength, high corrosion resistance, weldability, ability to preserve strength at low temperatures, etc. Hypereutectic silumins in contrast to other aluminum alloys are characterized by a high elastic modulus, a low linear expansion coefficient, a high wear resistance in rubbing pairs, and other properties important for practice.

Currently, Al-Si based hypereutectic alloys are widely used for the production of diesel engine pistons with rather high demands with respect to thermal conductivity, dynamic and fatigue strength, wear resistance, specific gravity and the thermal expansion coefficient. In addition, materials with a low linear expansion coefficient are used in instrument engineering, for example, in lenses, gyroscopes, and other components of navigation and control systems; therefore, ensuring their satisfactory structural properties is of great importance.
A characteristic structural element of such alloys is primary silicon crystals. Their size, usually 50-150 \( \mu m \), depends on the size of the casting (respectively, the cooling rate during solidification), and on the casting technology, on the method of alloy modification. The large size of silicon crystals not only makes the alloy more brittle, it can also contribute to chipping and, consequently, to the reduction of product life. Line arrangement of silicon crystals is very dangerous for the performance characteristics of the pistons. It seriously weakens the alloy and often causes destruction of the piston in the pin area, as well as in the groove of the first compression ring. There is a danger of the piston being destroyed at the “cold” start.

Without performing a special modification of the structure of hypereutectic silumins, the manufacture of these products is possible only by the methods of shaped casting or liquid stamping. High-quality plastic strain of casting blocks from hypereutectic silumins is possible after modification of the structure with the use of new modifiers and new methods of controlling the process of milling the excess phases during casting.

In recent years, new approaches to modifying the structure of ingots of aluminum alloys using master alloy rods have been applied in industry. Dissolving in the melt, they introduce insoluble ready solidification nuclei into the liquid metal in the form of dispersed compounds of various high-melting elements. In this case, the bulk of dispersed nuclei are involved in the solidification process, creating an excess of them at the solidification front, thereby forming and grinding the grain structure of the ingot.

In this regard, the relevance of the work is to obtain casting blocks from hypereutectic silumin-based alloys suitable for subsequent deformation and the production of high-quality parts with a satisfactory combination of strength and plastic characteristics.

2. High-speed solidification of 1379p pelletized hypereutectic silumin

To improve the structural characteristics of hypereutectic silumins during casting, various technological methods are applied, one of the most effective of which is high-speed solidification technology during casting (pellet metallurgy) \[1,2\].

Production of high-alloy 1379p hypereutectic silumin in the form of pellets was performed with a cooling rate during solidification, \(~1 \cdot 10^3-1 \cdot 10^4\) K/s \[3\]. This made it possible to provide a pseudo-eutectic structure without primary silicon crystals (figure 1a) or an eutectic structure with small (5-10 \( \mu m \)) uniformly distributed silicon crystals (figure 1b) due to solidification according to a metastable diagram. The chemical composition of the 1379p alloy ingot is as follows (wt.\%): 17.2 Si, 4.2 Cu, 1.0 Mg, 0.6 Mn, 1.1 Ni, 1.2 Fe, 0.3 Ti, 0.27 Zr, the rest is Al.

![Figure 1. Microstructure of 1379p alloy pellets.](image)

The 1379p alloy contains, in addition to aluminum and silicon, a number of other components — copper, magnesium, manganese. Moreover, it is doped with low-soluble transition metals, such as iron, nickel, titanium, zirconium, which can interact with aluminum, silicon and other elements, forming various simple and complex phases.

In addition to suppressing the formation of primary silicon crystals (or their substantial milling) during casting with high solidification rates, the Fe-containing phases are dispersed, which makes it possible to use aluminum products with a high iron content for the production of alloys. Moreover, with increased doping of Ti and Zr, due to subsequent technological heating and, accordingly, the
decomposition of the anomalously supersaturated solid solution, dispersion strengthening Al\textsubscript{13}Zr and Al\textsubscript{13}Ti phases are formed.

1379p alloy pistons made of pellets with such a structure have a high level of hardness and wear resistance, which contributes to an increase in the characteristic life. The low linear thermal expansion coefficient also provides an increase in engine power by reducing the gap between the piston and the cylinder. Improving environmental performance — reducing noise, reducing exhaust emissions — is very important because it makes it possible to operate the diesel engines in confined spaces.

The process flow diagram of piston fabrication includes the following operations [2]:

- the centrifugal casting of pellets;
- the drying and separation of pellets;
- the vacuum degassing of pellets in sealed capsules;
- the compaction of pellets in a hydraulic press;
- the facing of compact casting blocks and rod extrusion;
- isothermal stamping;
- heat treatment;
- machining.

Analysis of the microstructure of pistons made of 1379p alloy pellets showed that the structure of the pistons is dispersed, uniform (figure 2).

**Figure 2.** Microstructure of the 1379p alloy piston: scanning electron microscopy (a) with micro X-ray analysis: b — large white phases (FeMn)\textsubscript{3}Si\textsubscript{2}Al\textsubscript{15}; c — grey phases of primary silicon.

The structure contains primary silicon dispersion crystals 3-7 µm in size and dispersion complex phases containing aluminum, silicon, iron and manganese, probably Al\textsubscript{13}Si\textsubscript{2}(FeMn)\textsubscript{3} 0.5-2 µm in size. There are also phases formed by other alloying components (Mg\textsubscript{2}Si, Al\textsubscript{2}Cu, Al\textsubscript{13}Zr, Al\textsubscript{13}Ti, etc.).

Figure 3 shows the typical structure of the high-alloy 1379p hypereutectic alloy. It is apparent that the characteristic structural elements of the alloy are primary crystals of silicon 50-150 µm in size, there are Mg\textsubscript{2}Si phases, a complex phase, apparently Al\textsubscript{13}Si\textsubscript{2}(FeMn)\textsubscript{3}, Al-, Cu-, Ni-containing phases, and the presence of Ti and Zr coarse intermetallic phases of transition metals is also possible.
Figure 3. Microstructure of the 1379p cast alloy: a — scanning electron microscopy with micro X-ray spectral analysis; b — large white phases \((\text{FeMn})_3\text{Si}_2\text{Al}_{15}\); c — black phases \(\text{Mg}_2\text{Si}\); d — large grey phases of primary silicon.

However, the high doping degree of piston alloys and the associated high level of hardness and low level of ductility predetermine the processibility of these alloys in the manufacture of pistons. In particular, serious difficulties arise during extrusion (alloys are prone to the formation of “barbed” defects), stamping, and machining. The high content of silicon, the particles of which act as an abrasive, predetermines the need to use a special tool.

It should be added that the granulation technology, as noted above, requires special equipment and complexity of the process, which significantly increases the cost of the resulting products. It is possible to replace the granulation technology with a less costly continuous casting technology to obtain wrought casting blocks from hypereutectic, high-alloy silumins with primary silicon size not exceeding 40 µm by developing new approaches to modifying silumin.

3. Modification of high-alloy hypereutectic silumins in the continuous casting of ingots

As applied to silumins, the modification is aimed at solving a number of problems, the priority of which depends on the purpose of casting or the wrought part, on the loading conditions (static, dynamic, etc.), on the operating conditions, on the silicon doping level. Among these problems, it is possible to distinguish the following [4]:

- macrograin milling;
- milling, changing the morphology of the eutectic component of Si;
- milling of primary Si crystals formed in the process of the solidification of hypereutectic alloys, etc.

However, it is not always advisable to solve all these problems at the same time. For example, in the fabrication of cast pistons of ICE from hypoeutectic or eutectic silumins, excessive milling of the silicon eutectic component can lead to a decrease in wear resistance, while the fabrication of strength components from these alloys requires milling and spheroidising the silicon eutectic phase to improve ductility and, respectively, performance [4].

For milling the grain structure (macrograin milling), the Al-Ti-B-based master alloy in the form of a rod containing finely dispersed \(\text{TiB}_2\) crystals with a size of 1-3 µm which are effective centers of solidification has become the most common. At the same time, it was noted in [5] that in ingots cast from alloys having a wide solidification interval, the introduction of such master alloy rods can lead to the development of shrinkage porosity, and for alloys having low plasticity at temperatures close to the melting point, there is a probability of the ingot being destroyed.
In the fabrication of products from hypereutectic silumins, the main problem is achieving the controlled milling of the primary silicon crystals, which under normal conditions of casting reach 100 \( \mu m \) or more in size. The development of technology for modifying hypereutectic silumins allows proposing new modifier compositions and improving the modification process itself. In this case, the achieved milling of the structure of hypereutectic silumins will be somewhat less than in the case of pellets, but the manufacturing process itself is cheaper and more attractive for practice.

To modify the primary silicon, phosphorus-containing master alloys such as Cu-P, Fe-P, Al-Cu-P, various salts (chemical compounds of phosphorus pentachloride, preparations containing red phosphorus and hexachloroethane, sodium- and phosphorus-based phosphorus-containing salts, etc.) are mainly applied [6,7]. P-Na and Al-Si-P additives, inorganic carbon and phosphorus compounds, mixtures of phosphorous copper, boric acid as well as iron and nickel oxides are also applied [8,9].

3.1. Experimental melting of the 1379s alloy in the direct chill pit

Hypereutectic silumins of the 1379s alloy were cast in pilot-industrial conditions by continuous casting into a casting mold 92 mm in diameter [10]. The chemical composition of the 1379s alloy ingot is as follows (wt.\%): 16.2 Si, 4.34 Cu, 1.0 Mg, 0.51 Mn, 0.9 Ni, 0.35 Fe, 0.16 Ti, 0.11 Zr, 0.007 P, the rest is Al.

Degassing and finishing was carried out with argon and hexachloroethane. As the modifier of the structure, the AlCuP rod master alloy and PRM-9 tablets (manufactured by ODO Evtektika, Minsk) containing non-sodium salts of Mg, K polyphosphates (dipolyphosphates, tripolyphosphates) were used. The modification was carried out both in the furnace and on the way to the casting mold.

The appearance and the typical structure of the ingots are shown in figure 4a-c. The macrostructure analysis showed that in the process of casting a dense structure is formed without shrinkage pores, shells, nonmetallic inclusions. A quantitative analysis of the structure carried out using the Axiovert (Carl Zeiss) microscope showed that the applied scheme of PRM9 furnace modification + out-of-furnace modification with Al-Cu-P rod made it possible to obtain an average size of silicon crystals about 20 \( \mu m \) (Table 1).

![Figure 4. The appearance of 1379s alloy ingots of a 92 mm diameter (a, b), a typical structure (c) and template with crack (d).](image)

![Table 1. Quantitative analysis of the structure of the 1379s alloy ingot 92 mm in diameter](table)

| Parameter | Sum       | Average | Deviation | Minimum | Maximum |
|-----------|-----------|---------|-----------|---------|---------|
| Length, \( \mu m \) | 1215.19   | 20.95   | 1.13      | 9.53    | 43.20   |

However, it was also found that in most cases the ingots had a longitudinal crack in the centre passing through the diameter (figure 4d).

The formation of cracks as judged by the characteristic click occurred at different times — at the beginning of casting in the middle during the final stage because of the tendency of the 1379s alloy to hot shortness (the copper content in the 1379s alloy is critical from the point of view of the tendency to hot cracking) [11].

The most well-known method of eliminating hot crack defects is grain milling while the relative elongation increases and the linear shrinkage reduces, the alloy plasticity margin in the solid-liquid
state increases and thereby the hot shortness reduces \cite{11}. Therefore, to prevent the cracking of ingots during casting, an additional modification of the melt by the Al-Ti-B master alloy was carried out which made it possible for the most part to reduce the tendency to crack occurrence and thereby significantly increase the casting yield ratio. However, the structure of such milled grains still remains dendritic.

In the integrated modification of aluminum alloys including of hypereutectic silumin with the use of melt flow ultrasound treatment (UST) it will be possible to reach the ultimate milling of the grain structure and to avoid the occurrence of casting cracks. This is due to the fact that the non-dendritic structure is characterized by a significantly more uniform grain size distribution than the dendritic grain structure, i.e. the non-dendritic grain ingot structure in addition to its substantial grinding is even more homogeneous than the structure of a similar dendritic grain ingot \cite{12}.

However, it is known that TiB\textsubscript{2} particles being the active centers of grain nucleation, in the Al-Ti-B master alloy are mainly in the agglomerated state in the form of clusters up to 30 \(\mu\)m in size and, when introduced into the melt, they create a minimal modifying effect since most of them are retained in the filtering and refining devices. In \cite{13-15} it was proved that the use of ultrasonic melt treatment enhances the effect of modification by eliminating the agglomeration of modifying particles and accordingly increasing the active centers of grain nucleation which leads to the achievement of the ultimate milling of the grain structure up to the formation of a non-dendritic structure. For example, \cite{15} shows the effect of ultrasound on the rod modifier during the casting of sheet ingots made from the 5052 alloy based on the aluminum-magnesium system under industrial production conditions. In addition, the melt UST during the casting of hypereutectic silumin makes an additional contribution to the grinding of primary and eutectic silicon crystals and their uniform distribution over the ingot cross-section.

Stamped 1379s alloy piston casting blocks 90 mm in diameter were obtained in the press by a force of 2.45 MN from casting blocks faced to a diameter of 88-89 mm. Assessment studies of 1379s alloy stamped casting blocks conducted at NPP Avtotekhnologiya-MAMI LLC showed a high level of properties. TCLE studies were performed with the use of a Netvsch dilatometer (model VIL-402ac). The results are presented in Table 2.

| Temperature range, °C | 1379s sample (ingot) 10^{-6} K^{-1} | 1379p sample (pellets) 10^{-6} K^{-1} |
|------------------------|------------------------------------|-----------------------------------|
| 30-100                 | 18.66                              | 16.49                             |
| 30-150                 | 19.70                              | 17.99                             |
| 30-200                 | 18.89                              | 18.41                             |
| 30-250                 | 20.27                              | 18.89                             |
| 30-300                 | 20.81                              | 19.17                             |
| 30-350                 | 20.53                              | 19.30                             |
| 30-400                 | 20.50                              | 19.51                             |
| 30-450                 | 20.58                              | 19.70                             |
| 30-500                 | 20.36                              | 19.79                             |

The thermal coefficient of linear expansion of the 1379s alloy was slightly higher than that of the 1379p pelletised alloy (samples were cut from the piston skirt in the vertical direction).

The properties of the stamped 1379s alloy casting blocks in comparison with the properties of the 1379p pelletised alloy and the AK18 off-the-shelf alloy \cite{16} are shown in Table 3. It is apparent that although the properties of the stamped casting blocks obtained according to the ingot technology are somewhat inferior to the properties of the stamped casting blocks obtained according to the granulation technology, they fully meet the requirements imposed by customers on these products (\(HB > 120, \sigma_U \geq 350\) MPa), while significantly exceeding properties of the AK18 alloy casting blocks.
Table 3. Comparative mechanical properties of stamped casting blocks

| Alloy grade | \(\sigma_{U}, \text{MPa}\) | \(\sigma_{0.2}, \text{MPa}\) | \(d, \%\) | \(HB\) | TCLE \((\alpha_{0-100\text{C}} \times 10^{-6}\) deg) |
|-------------|-----------------|-----------------|-----|------|------------------|
| AK18        | 250-270         | —               | 0.6-0.8 | 100-120 | 19.5 |
| 1379p       | 380-430         | 320-360         | 2-4  | 150-170 | 17.5-18.0 |
| 1379s       | 370-390         | 360-385         | 2.5-2.7 | 130-150 | 18.0 |

3.2. Modification of hypereutectic silumin during the continuous casting of ingots with melt flow ultrasound treatment

As mentioned above, the modification of hypereutectic silumin is one of the main operations of the process of fabricating products from them. It was shown that the use of a complex modification with a combination of such modifiers as AlCuP, AlTiB and PRM-9 makes it possible to significantly mill the primary silicon crystals and reduce the tendency to hot cracking. It is possible to enhance the effects of modification as well as to use aluminum waste products with a high iron content due to the dispersion of Fe-containing phases similar to casting with high solidification rates due to the effect of intensive cavitation on the melt flow in the process of the continuous casting of ingots. Such work was carried out under the leadership of Dr.Sc. in Engineering G.I. Eskin.

In [17,18] a significant size reduction of the primary silicon crystals and an increase in the uniformity of their distribution were achieved, with a complex modification method when after the introduction into the melt of a chemical reagent, for example FeP, an additional effect was exerted on the liquid metal by superimposing ultrasonic vibrations under conditions of developed cavitation.

In the studies carried out in experimental-industrial conditions according to the continuous casting method, ingots of 01392 hypereutectic silumin [19] with a diameter of 114 mm were cast. Prior to casting, the melt in the furnace was thoroughly degassed using hexochloroethane tablets. A rod AlCuP-based master alloy was used as a modifier. The chemical composition of the 01392 alloy ingot is as follows (wt.%): 18.0 Si, 3.2 Cu, 0.4 Mg, 0.25 Mn, 0.5 Fe, 0.1 Ti, 0.007 P, the rest is Al.

It has been shown that with the introduction of the AlCuP ternary master alloy in the form of a master alloy rod off-the-shelf \(\text{Cu}_3\text{P}\) modifying particles with sizes <10 \(\mu\text{m}\) are fed into the alloy. In the process of complex modification during the hypereutectic silumin treatment, the \(\text{Cu}_3\text{P}\) particles dissolve in the melt with the formation of dispersion particles of \(\text{Al}_3\text{P}\) which ensures the participation of almost all the introduced phosphorus in the modification process.

Figures 5a, b show a typical microstructure of unmodified hypereutectic silumin with primary silicon crystals of 100-200 \(\mu\text{m}\). Modification with the AlCuP master alloy made it possible to significantly reduce the size of the primary silicon crystals (figure 5c), however they are unevenly arranged in clusters and there is also a line pattern in their distribution. Such a structure negatively affects the performance characteristics of the pistons since large silicon crystals are concentrators in the destruction of the pistons. For a more uniform distribution of silicon crystals the melt flow from the tap hole to the casting mold was subjected to ultrasonic treatment in the pouring spout. The structure of the ingot after the melt UST is shown in figure 5d.

![Figure 5](image_url)

**Figure 5.** Microstructure of the modified 01392 alloy ingot: a, b — unmodified; c — modified AlCuP; d — modified AlCuP and UST.
The study of the distribution of primary silicon crystals before and after the application of UST showed that the size of crystals decreased by more than 2 times, on average to 30 µm and in [17] it was shown that further milling of primary silicon crystals in ingots and semi-finished products (≤20 µm) leads to a sharp increase in ductility, increased wear resistance and fatigue life at elevated temperatures.

The studies [18] on the modification of the hypereutectic silumin of the 01392 alloy under conditions of developed cavitation and the subsequent deformation of the obtained casting blocks showed that after cross rolling (CR) the additional milling of primary silicon crystals occurs 2-3 times. It was shown that the morphology and size of secondary silicon crystals in the eutectics also undergo changes (Table 4). Structural changes after CR made it possible to increase the strength from 160 to 180 MPa and the plasticity from 3.7 to 4.0% in the wrought state.

In [20] it was shown that with UST of a crystallizing ingot from an Al-3% Mn alloy prone to primary solidification of Al₆Mn intermetallic compounds, dispersion crystals are formed instead of developed crystals. Similar results were obtained when studying the effect of UST on the structure of remelts of AK9M2CX secondary silumin (figure 6) with a high iron content (up to 1.5%) and a number of alloyed elements such as Cu, Mn, Zn, Mg, Ni, Ti, Cr.

It is shown that primary intermetallic compounds of Al₅FeSi type (figure 6a, b) and the structure of the eutectics (figure 6c, d) are milled under the action of the melt cavitation treatment. Table 5 gives the quantitative characteristics of this milling, and Table 6 presents the changes in the mechanical properties after UST.

**Table 4.** The effect of CR on the efficiency of the milling of primary and eutectic silicon crystals in the 01392 alloy

| Product Type of crystals | Crystal shape | Crystal size, µm |
|--------------------------|---------------|-----------------|
| Primary                  | faceted       | range medium    |
| ingot                    | 30-80         | 50              |
| rod                      | 10-20         | 15              |
| Eutectic                 | plates        | up to 10       |
| ingot                    | 8             |                 |
| rod                      | less than 1   |                 |

**Figure 6.** The structure of primary intermetallic compounds Al-Fe-Si (a, b) and Al-Fe-Si eutectics (c, d) in AK9M2SH alloy ingots cast without UST (a, c) and with UST (b, d).

**Table 5.** The effect of the melt cavitation treatment on the milling of the structural components in the AK9M2SH remelted alloy ingots

| UST | Siliceous component, µm | Fe-containing component, µm |
|-----|-------------------------|-----------------------------|
|     | length width            | length width                |
| −   | 20-40 2-4               | 30-95 4-5                   |
| +   | 15-20 2-3               | 5-20 2-3                    |
### Table 6. The effect of the melt cavitation treatment on the mechanical properties in the AK9M2SH remelted alloy ingots

| UST | Tensile strength, MPa | Yield strength, MPa | Relative elongation, % | Relative narrowing, % |
|-----|-----------------------|--------------------|------------------------|------------------------|
| -   | 160–234               | 147–156            | 1.2–2.0                | 2.0–2.4                |
| +   | 200–237               | 156–164            | 2.8–3.2                | 2.4–4.0                |

### 4. Conclusions

As a result of the research, it was determined that the hardness of the 1979s alloy ingots produced according to ingot technology and the mechanical properties under static stretching of forging made of the same alloy met the requirements for the 1379p pelletised alloy — $HB > 120$, $\sigma_U \geq 350$ MPa.

Compared with the 1379p alloy, the 1379s alloy has a higher thermal coefficient of linear expansion (TCLE) although it is quite close, especially in the temperature range of 30-200°C: $18.41 \times 10^{-6}$ K$^{-1}$ and $18.89 \times 10^{-6}$ K$^{-1}$ respectively. It may be assumed that, with the improvement of the modification technology, in terms of combining in-furnace and out-of-furnace modification with the melt flow UST it will be possible to further achieve milling $\leq 10$ μm of silicon crystals in ingots and their uniform cross-section distribution as well as to achieve an additional effect on reducing the grain size of the $\alpha$-solid solution. This makes it possible, if necessary, to further reduce the TCLE values, to dope the alloy cast according to ingot technology, closer to the upper limit.

Thus, the casting technology of complex modification with additional out-of-furnace ultrasonic melt processing of high-alloy hypereutectic silumin is promising making it possible, in certain cases, to replace high-cost technology for producing casting blocks from pellets for manufacturing pistons of diesel engines and other products requiring low TCLE and high dimensional stability.

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