Metallurgist, Vol. 42, No. 8, 1998

NEWS OF THE RUSSIAN ACADEMY OF NATURAL SCIENCES

PROSPECTS OF ULTRASONIC (CAVITATIONAL) TREATMENT OF THE MELT IN THE MANUFACTURE OF ALUMINUM ALLOY PRODUCTS

G. I. Éskin

The treatment of melts of aluminum and its alloys by high-intensity ultrasound is an environmentally clean technology and has its broadest range of application in the production of high-quality deformed semifinished products and shaped castings composed of light alloys.

The simplicity of the process of introducing powerful ultrasonic vibrations into a melt as part of existing methods of continuous (vertical and horizontal) casting and mold casting (precision casting, casting in permanent molds, liquid forging, etc.) and the fact that metallurgists have had more than 40 years of experience in the use of high-intensity ultrasound in the casting of light alloys make it possible to accurately gauge the prospects of this active method of regulating the structure and properties of cast and deformed metal [1-3].*

Acoustic Cavitation in a Melt. One of the main prerequisites for the successful treatment of a melt by powerful ultrasound is the realization of acoustic cavitation in the melt. Here, alternating pressure above the cavitation threshold in the liquid metal creates a large number of cavitation cavities in the liquid metal. Some of these cavities pulsate with the frequency of the applied field (usually 18 kHz) without changing the concentration of the gas phase inside each cavity, while other cavities grow rapidly under the influence of tensile stresses and the unidirectional diffusion of dissolved hydrogen in the metal to these cavities. Some of the cavities, unable to be filled completely with gas, merge (collide) under the influence of compressive stresses associated with the sound wave. In this case, "fragments" of cavities are formed near each colliding cavity, and the energy of the collision is converted to pressure pulses of up to 1000 MPa and shaped jets of molten metal with a velocity up to 100 m/sec.

The cavitation process begins anew intensively with the formation of the "fragments" of cavities. It is believed that acoustic cavitation in liquids develops on the chain-reaction principle, whereby isolated cavitation cavities formed on different nuclei have multiplied so greatly after several microseconds that an actively functioning cavitation field forms near the source of the high-intensity ultrasound.

As is known, an actual melt of any metal is not an ideal fluid. Instead, it is a suspension ("plankton") with dispersed particles of oxides of the given metal floating in a melt of that metal. The suspension forms as a result of the existence of a lens of molecular hydrogen on curved sections of the solid phase. Although the fraction of molecular hydrogen on the surface of the dispersed oxides is very small (less than 0.01 vol. %), this amount is sufficient to form cavitation cavities on the unwetted surfaces of the oxides. These cavities are subsequently readily transformed into degassing and crystallization nuclei. Determination of the dependence of the threshold (initial) pressure and the extent of development of acoustic cavitation on the purity of an aluminum melt with respect to its content of solid oxide inclusions and hydrogen concentration (Fig. 1) showed that an increase in the concentration of aluminum oxide plays the deciding role in the development of cavitation processes. The hydrogen dissolved in the melt is less important.

Ultrasonic Degassing of a Melt. Cavitational treatment of a melt ensures anomalously rapid diffusional growth of gas-bubble nuclei (under normal conditions, the gas is dissolved in the liquid). In the presence of cavitational action, dispersed bubbles of hydrogen on the surface of unwetted oxides begin to grow vigorously as a result of the so-called "rectified" diffusion of hydrogen from the melt into the bubbles.

*This article reports results of studies conducted together with V. I. Dobatkin, P. N. Shvetsov, S. I. Borovikova, M. V. Belova, Yu. P. Pimenov, D. G. Éskin, V. I. Tararyshkin, and V. V. Belotserkovets, S. G. Bochvar, and others.

Russian Academy of Natural Sciences. Translated from Metallurg, No. 8, pp. 29-33, August, 1998.

 0026-0894/98/0708-0284$20.00

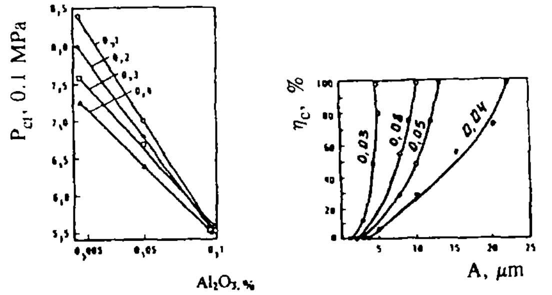

Fig. 1. Dependence of the threshold pressure for acoustic cavitation (P_{ct}) on the purity of an aluminum melt with respect to nonmetallic inclusions and the concentration (the numbers next to the curves are in units of $cm^3/100$ g) of hydrogen (a); effect of the amplitude of vibration A of the source of ultrasound on the extent (η_c) of development of cavitation (b).

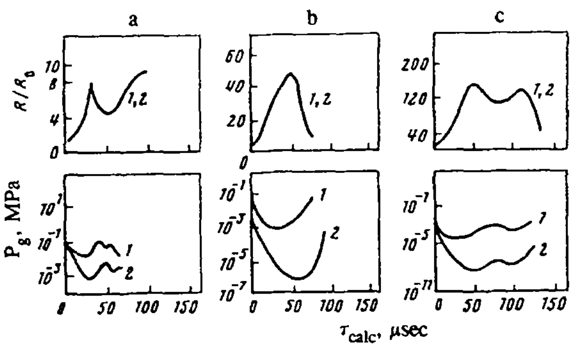

Fig. 2. Dynamic characteristics of a cavitation bubble without (1) and with (2) allowance for diffusion of hydrogen into the bubble from the melt at the beginning (threshold) of cavitation (a) and with different cavitation regimes (b, c): P_g) gas pressure in the bubble; R_0 and R) initial and running radius of the bubble.

An increase in hydrogen pressure in the bubbles by 2-6 orders of magnitude was discovered from the results of calculations of the dynamic characteristics (pulsations) of cavitation cavities with an initial radius $R_0 = 10\ \mu m$, a value of alternating pressure close to the cavitation threshold (Fig. 2a), and two values of alternating pressure (Fig. 2b and c) (allowance was made for the flow of hydrogen into the bubbles during "rectified" diffusion). This increase in hydrogen pressure in the bubbles increases the effect of the ultrasonic treatment on the hydrogen, the bubbles grow more rapidly and easily coalesce, and their dimensions increase to an extent which ensures their evacuation on the surface of the melt.

Thus, the hydrogen content of the metal being treated can be reduced by a factor of two or more, depending on the intensity of the ultrasound. The only other method that can realize such a reduction is prolonged vacuum degassing of the liquid metal.

Commercial trials of a technology for the ultrasonic degassing of a flowing melt, conducted during the continuous casting of large flat ingots of alloy AMg6, showed that it is possible to maximally reduce hydrogen content (to 0.3 $cm^3/100$ g), significantly increase the density of the cast semifinished products, and improve their weldability and their reliability in service. For example, the fatigue life of 10-mm thick plates (at a stress of 160 MPa) increased to $(2\text{-}7)\cdot 10^5$ cycles after ultrasonic degassing (fatigue life for plates prepared by the standard technology is $(0.1\text{-}2.6)\cdot 10^5$ cycles). It is interesting to examine the effect of the ultrasonic degassing of a melt on the quality of welds. The mechanical properties of welds of 10-

TABLE 1. Comparison of Commercial Methods of Degassing Melts of Alloy AL4

Degassing method	H^2, cm³/100 g	Density, g/cm³	Porosity, points	Ultimate strength, MPa	Elongation, %
Ultrasound	0,17	2,706	1-2	245	5,1
Vacuum	0,20	2,681	1-2	228	4,2
Argon	0,26	2,667	2-3	233	4,0
Hexachloroethane	0,30	2,665	2-3	212	4,5
Flux	0,26	2,663	3-4	225	4,0
Initial melt	0,35	2,660	4	200	3,8

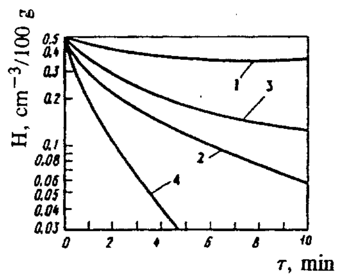

Fig. 3. Dependence of the hydrogen content of a melt of alloy AL9 on the duration and method of degassing: 1) treatment with a universal flux; 2) ultrasonic treatment; 3) vacuum degassing; 4) combination treatment involving ultrasound in a vacuum.

mm thick plates of alloy AMg6 is shown below in relation to the method of degassing (I – with argon, II – in a vacuum, III – ultrasonic):

	I	II	III
Ultimate strength, MPa	300	321	325
Angle of bending, deg	57	65	87
Deflection during bending, mm	0,28	0,32	0,51

The results obtained from the ultrasonic treatment of a melt at the Balashikhinsk Foundry and Machine Shop (Table 1) demonstrated its efficiency compared to vacuum degassing. Ultrasonic degassing can be made even more efficient by combining it with vacuum degassing (Fig. 3).

Fine Filtration in a Field of Ultrasound – Uzfirals Process. Of the simplest and most reliable methods of filtering aluminum melts, the method that has come to be most widely used is filtration with gauze filters made of nonalkaline alumoborosilicate glass. However, relatively coarse filters made of glass cloth with a 1 × 1 mm mesh do not remove dispersed inclusions from melts, while the use of finer filters with a 0.4 × 0.4 mesh or multilayered filters is restricted by the need to have the melt be able to pass through the capillary channels of the filter. Such limitations do not arise if a cavitation field is created in front of the surface of a multilayer filter – the melt smoothly passes through the labyrinth of capillary channels, while the dispersed oxides are deposited in succession on the surface of the filter and the walls of the capillaries.

A commercial trial of the Uzfirals process in the continuous casting of alloys 1973 and 1163 into large ingots 650-830 mm in diameter, combined with vacuum degassing of the melt in a mixer, showed that it is possible to reduce hydrogen concentration to 0.13-0.14 cm³/100 g and alleviate damage from defects connected with the presence of nonmetallic inclusions to 0.005-0.006 mm²/cm² [1-3].

Nondendritic Crystallization. Since D. K. Chernov discovered the dendritic structure of steel ingots, the concept of the grain (dendrite) and the dimensions of dendritic branches (a dendritic structure) have become fundamental to the evaluation of the structure of cast metal. Our studies have shown that the ultrasonic treatment of a melt in the cavitation regime can

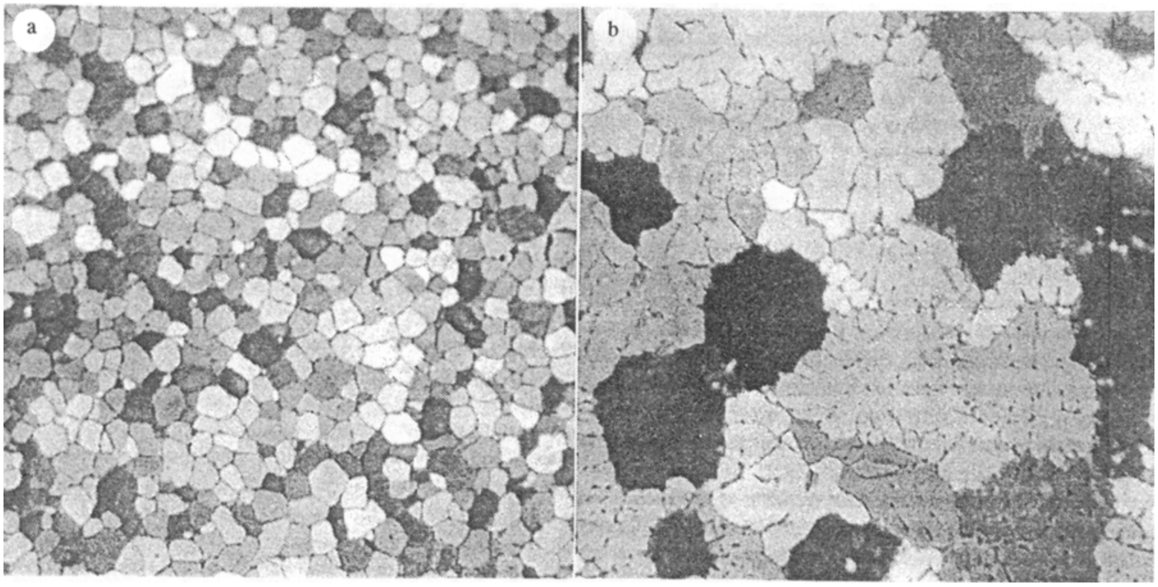

Fig. 4. Microstructure of 830-mm diameter ingots of alloy 1973: a) nondendritic (casting with ultrasonic treatment); b) dendritic (casting without ultrasonic treatment), ×50.

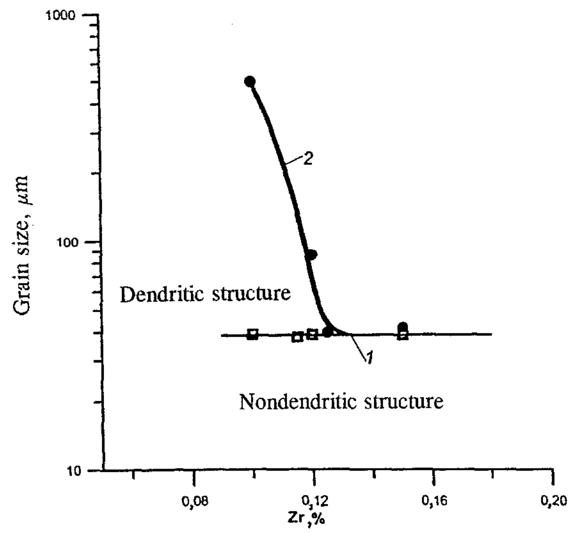

Fig. 5. Dependence of the structure of 178-mm diameter ingots of alloy 1420 on casting conditions (1, with ultrasonic treatment; 2, without ultrasonic treatment) and the zirconium content of the melt.

produce an essentially new structure of a **nondendritic type.** This limitingly refined nondendritic structure consists of globular grains (Fig. 4). The main prerequisite for obtaining the nondendritic structure is intensifying the nucleation and formation of an excess of crystallization centers ahead of the crystallization front. This can be done by means of the catalytic (wetting) action from cavitational treatment of the melt for unregulated nonmetallic impurities. Since the grain serves as a parameter that uniquely characterizes the fragmentation of the matrix structure in sequential nondendritic crystallization, its dimensions – as the dimensions of the branches of dendrites in dendritic crystallization – will depend only on the rate of cooling of the melt. This is a new postulate in the theory of crystallization and was formulated by scientists at the VILS [5].

The main advantage of the nondendritic structure is that it increases the ductility of the metal without decreasing its strength. Thus, thanks to a nearly twofold increase in ductility achieved by nondendritic crystallization in an ultrasonic field, it has become possible to produce large (up to 10 tons) 1200-mm diameter ingots of structural aluminum alloys without

TABLE 2. Effect of the Method of Shaping (Forging or Upsetting) of Products from Cast Semifinished Products of Alloy 1960 on Their Mechanical Properties

Shaping method	Ultimate strength, MPa	Elongation, %
Upsetting of a 280-mm-diam. ingot in the semi-solid state	671/650	10,9/7,8
Forging:		
from a 55-mm-diam. bar	657/657	7,6/6,5
from a 65-mm-diam. ingot	667/664	8,1/7,5

Notes. 1. The numerator and denominator show the characteristics of cast semifinished products with nondendritic and dendritic structures, respectively. 2. The 55-mm diameter bar was obtained from a 280-mm diameter ingot.

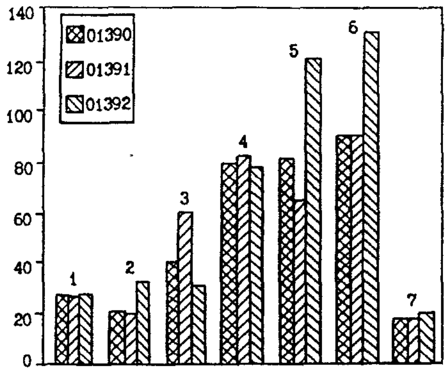

Fig. 6. Physicomechanical properties of deformed hypereutectic silumins 01390, 01391, and 01392: 1) density, g/cm^3 × 10; 2) ultimate strength, MPa × 0.1; 3) elongation, % × 10; 4) elastic modulus, GPa; 5) hardness HB; 6) fatigue limit, MPa; 7) coefficient of thermal expansion, deg$^{-1}\cdot 10^6$ (20-400°C).

cracks. The high ductility of metal with a nondendritic structure persists in the deformed metal, regardless of the method of hot-working.

Reported below is some information on how a nondendritic structure in ingots of high-strength aluminum alloys affects the properties of the semifinished products obtained from the ingots.

Small forgings of alloy 1960 of the "hood" type were obtained from 65-mm diameter ingots with dendritic and nondendritic structures (grain size was 400-500 and 20-30 μm, respectively). Studies showed that the ultimate strength of the forgings obtained from the ingot with the nondendritic grain had increased from 630 to 670 MPa in the height direction and that elongation had increased from 3.3 to 5.5%.

Large forgings of alloy 1973 were made from pressed 460-mm diameter bars obtained from 830-mm diameter ingots with nondendritic (I) and dendritic (II) structures. Tests showed a substantial improvement in the mechanical properties of the metal with the nondendritic structure over the height of the product:

	I	II
Ultimate strength, MPa	463	461
Yield point, MPa	400	405
Elongation, %	8,8	5,6
Reduction of area, %	30	10,1

Long pressed panels of alloy 1973 were made from an upset binocular-shaped ingot 830 mm in diameter. The effect of the nondendritic structure of the ingot was manifest in an improvement in the properties of the metal over the height of the product and a reduction in defects detected by ultrasonic testing. For example, ultimate strength increased from 463 to 478 MPa and elongation increased from 2.6 to 3.5%. The number of defects discovered in ultrasonic testing decreased from 150 to 20 (on one panel).

Rolled Slabs of Alloy 1161. For these studies, we chose flat ingots with nondendritic and dendritic structures and cross sections of 450 × 1200 mm and 165 × 550 mm. Slabs 88-mm thick were rolled from the large ingots, while slabs 40-, 60-, and 80-mm thick were rolled from the small ingots.

Tests of the long slabs showed that the nondendritic structure increases ductility appreciably along with some increase in strength. For example, the ultimate strength of the slabs obtained from the ingots with the nondendritic structure increased from 351-382 to 390-395 MPa (over the height) and elongation increased from 0.8-4.4 to 4.4-4.8%.

The metal with the nondendritic structure was shown to have higher properties in fatigue tests performed by MTsU and MnTsU testing machines on 80-mm thick slabs obtained from 165 × 550-mm ingots. For example, the fatigue limit of the central part of the slabs (in the transverse direction) was 150 and 130 MPa on the MnTsU ($f = 120$ Hz; 10^7 cycles) and 239 and 132 cycles on the MTsU ($f = 3$ Hz; $\sigma = 160$ MPa).

A nondendritic structure in the ingots also helped increase the fracture toughness of rolled slabs of alloy 1161: fracture toughness was 49.05 MPa × $m^{1/2}$ (47.9 MPa × $m^{1/2}$ for the dendritic structure) in the LT direction and 48.4 MPa × $m^{1/2}$ (44.4 MPa × $m^{1/2}$ for the dendritic structure) in the TL direction.

It is known that a nondendritic structure can be obtained in ingots of alloys of the system Al–Mg–Li without ultrasonic treatment of the melt. In this case, additional crystallization centers are nucleated from oxides of lithium and magnesium and from hydrides of lithium. The introduction of a certain quantity of a modifier in the form of zirconium (more than 0.12%) creates even more crystallization nuclei ahead of the solidification front, thereby ensuring the formation of a nondendritic grain. However, a reduction in the concentration of zirconium in ingots of alloys of the given system to 0.08-0.10% results in the formation of a dendritic structure, i.e., the number of crystallization centers near the crystallization front turns out to be insufficient. Ultrasonic treatment is necessary in this case. A study of the crystallization of 178-mm diameter ingots of alloy 1420 in an ultrasonic field showed (Fig. 5) that a stable nondendritic structure is formed at a zirconium content of 0.08-0.14%. The ultrasonic treatment also helps form a homogeneous structure and makes chemical composition more uniform across the ingot (eliminating light spots where the solid solution has a low magnesium content).

Semisolid Deformation. This process is based on the ability of material with a nondendritic structure to be deformed within a temperature range that includes the liquidus and solidus, when the material is highly mobile. Use of the process makes it possible to reduce the deforming force and facilitates filling of the mold by the metal being deformed. The state of the material in this process can be characterized as "quasi-solid" (thixotropic) – the displacements of the grains relative to one another are the same throughout the volume of the specimen, while "apparent" viscosity is higher than the viscosity of the melt and approaches the viscosity of olive oil.

Deformation in the thixotropic state may be considered similar to deformation in the state of superplasticity, when nondendritic grains slide easily in the semi-solid metal and, rotating relatively freely relative to each other, fill the mold while the deforming forces are kept low. The main prerequisite to achieving a thixotropic state in metal is the formation of a globular (nondendritic) structure. Other features of deformation in the semisolid state include rapid heating of the material to the deformation temperature and the relatively high rate of deformation at that temperature, together with the fact that the structure of the metal is not substantially coarsened.

Medium-strength alloys belonging to the systems Al–Si–Mg and Al–Mg–Si (alloys of types A357 and 6061 under U.S. standards) are usually used for semisolid deformation. A nondendritic structure is generally formed in two stages in these alloys: a fine dendritic structure (I) is formed during electromagnetic mixing of the liquid bath of an ingot being continuously cast; while the ingot is held in the semisolid state, the dendritic branches are gradually dissolved and replaced by coarse nondendritic grains more than twice as large as the initial dendritic grains.

In [6-8] we studied the process of semisolid in high-strength alloys 1973 and 1960 of the system Al–Zn–Mg–Cu–Zr (7075, 7050, and 7055 under U.S. standards). Products made of these alloys are usually very strong but not very ductile, which makes it difficult to obtain forgings of complex shape with thin walls.

As is known, a nondendritic structure is characterized by the grain size. Its grain size is roughly equal to the average cross section a branch of a dendrite for a given ingot size or a given rate of cooling of the melt during crystallization. The resulting structure is the most refined structure that can be obtained for the given ingot cross section.

We established in [1-4] that a nondendritic structure can be obtained in nearly all of the light alloys of a number of transition metals if modifying additions are used and ultrasonic (cavitational) treatment of the melt is employed in the crystallization process. It is apparent from Fig. 4 that the nondendritic structure consists of polyhedral grains without branches, in contrast to the dendritic structure in the form of grains with second- and third-order branches. The size of the nondendritic grain is roughly equal to the average cross section of a branch of one of the dendrites, i.e., the structure has been refined to the maximum extent possible.

The use of ingots with the finest possible structure in semi-solid forging opens up new possibilities for simplifying the technology and improving the quality of forgings. In accordance with the information we reported in [6-8], the use of a semifinished product with a limitingly refined nondendritic structure maximizes the filling of the thin sections of the forging and reduces the deforming force to the point where that force is almost independent of forging (upsetting) speed.

An analysis of the results of a study of the mechanical properties of forgings of alloy 1960 after hot-working and of upset semifinished products of the same material after semi-solid deformation shows that the new technology makes it possible to obtain a relatively high level of mechanical properties comparable to those of metal obtained by the serial technology (Table 2).

Research is now being performed on a technology that involves the forging of wheels from cast semifinished products in the semi-solid state (the material is alloy AV). The forged wheels have a nondendritic structure. The proposed technology is designed to replace the standard technology involving the hot-forging of ingots in the solid state.

Bulk Crystallization in an Ultrasonic Field and the Production of Natural Composites Based on Aluminum. The cavitational treatment of a melt and activation (wetting) of the "plankton" of ultrafine nonmetallic inclusions in the melt affect the conditions of bulk crystallization of the excess phases in the liquid bath of an ingot.

Studies [1-5, 10-11] of the formation of the structure of aluminides [of the types Al_3Zr and Al_3Ti) in structural aluminum alloys and of the primary crystallizing phases in hypereutectic Al–Mn and Al–Si alloys in a field of high-intensity ultrasound showed the significant effect that ultrasound has on the refinement of these excess phases.

Ultrasonic treatment of hypereutectic silumins with 14-25% silicon, combined with the use of agents that strongly modify primary silicon, resulted in the formation of fine crystals of primary silicon and thus increased the ductility of the product, which in turn made it possible to use the classical scheme for the production of deformed semifinished products from ingots (due to the presence of coarse inclusions of primary crystals of silicon, hypereutectic silumins can usually be obtained by a scheme that involves formation from a melt by mold casting or liquid forging).

The high elastic modulus, low coefficient of thermal expansion, high corrosion resistance at moderate values of strength and ductility, and excellent weldability of alloys of the above type allow their use in the form of pressed and drop-forged semifinished products and mold castings in different sectors of industry, including construction, oil and gas production, and engine manufacturing. Several grades of deformable hypereutectic silumins (Fig. 6) have now been developed [12-13] for the production of pressed and drop-forged semifinished products of different types. Research is also actively being conducted on reducing the production cost of these alloys by using carbothermal silumin as the initial charge material.

REFERENCES

1. G. I. Éskin, Ultrasonic Treatment of Molten Aluminum [in Russian], Metallurgiya, Moscow (1988).
2. G. I. Éskin, Treatment and Quality Control of Nonferrous Metals with Ultrasound [in Russian], Metallurgiya, Moscow (1992).
3. G. I. Éskin, Ultrasonic Treatment of Light Alloy Melts, Gordon & Breach Publishers, Amsterdam (1998).
4. V. I. Dobatkin and G. I. Éskin, "Nondendritic structure in ingots of light alloys," Tsvet. Met., No. 12, 61-64 (1991).

5. V. I. Dobatkin, A. F. Belov, G. I. Éskin, et al., "Pattern of crystallization of metallic materials. Discovery No. 271," Otkr. Izobret., No. 37, 1 (1983).
6. V. I. Dobatkin and G. I. Éskin, "Ingots with a nondendritic structure for deformation in the semi-solid state," Tsvet. Met., No. 2, 68-70 (1996).
7. V. I. Dobatkin and G. I. Éskin, "Ingots of Aluminum Alloys with Nondendritic Structure Produced by Ultrasonic Treatment for Deformation in the Semi-Solid State," in: Proc. 5th Intern. Conf. on Semisolid Proc. of Alloys and Composites. June, 1996. UK: The University of Sheffield, pp. 193-196.
8. G. I. Éskin, V. V. Belotserkovets, and S. S. Bochvar, "Effect of the structure of a cast semifinished product on the forging of high-strength aluminum alloys of the system Al–Zn–Mg–Cu–Zr in the semisolid state," Tekhnologiya Legkikh Splavov, No. 3, 23-28 (1998).
9. G. I. Éskin, "New aspects of the plastic deformation of light alloys in the thixotropic state," Metallurg, No. 4, 18-20 (1998).
10. V. I. Dobatkin and G. I. Éskin, "Primary crystallization of intermetallic compounds in ingots of light alloys with ultrasonic treatment of the melt," in: Physical Metallurgy of Aluminum Alloys [in Russian], Nauka, Moscow (1985), pp. 163-172.
11. G. I. Éskin, "Principle of ultrasonic treatment: application for light alloys," Advanced Performance Materials, No. 4, 223-232 (1997).
12. Yu. P. Pimenov, V. I. Tararyshkin, and G. I. Éskin, "Optimization of a technology for melting and modifying hypereutectic silumins," Tekhnologiya Legkikh Splavov, No. 3, 17-23 (1997).
13. G. I. Éskin, "Inexpensive aluminum alloys for the building and oil-and-gas industries," Metallosnabzhenie i Sbyt, No. 1, 62-63 (1998).