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THE PROCESS OF NANOMODIFYING CAST ALUMINUM ALLOY INGOTS FOR COMPONENTS OF AEROSPACE VEHICLES

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Currently, increasing attention has been paid to such a class of materials as nanopowders (NP) of chemical compounds, which are ultra-thin formations of not more than 100 nm in size. Such attitude to these materials is explained by the fact that they have unique physical, chemical and mechanical properties significantly different from the properties of materials of the same chemical composition in a massive state, and these properties can be transferred to some extent from them or with their participation to the products.

The existing methods of introducing NP into metal melts could not be used due to their special properties in comparison with coarse powders, and therefore a new method of their introduction into the melt was developed, excluding direct contact of NP particles with oxygen and unhindered penetration of particles into the melt through the oxide layer. The essence of the method was as follows. In the aluminum container filled up with aluminum particles or deformable aluminum alloys D1 or D16 and various NP (nitrides, carbides, oxides, etc.), and this composition was pressed into the rod, with its help NP was introduced into the melt during casting of aluminum ingots and deformable aluminum alloys.

The results of the study showed that this excludes the appearance of cracks in the ingots, as well as improves their technological and mechanical properties.

Keywords: aluminum alloys, ingots, nanopowders, improvement of technological and mechanical properties.

НАНОМОДИФИЦИРОВАНИЕ АЛЮМИНИЕВЫХ СПЛАВОВ ПРИ ЛИТЬЕ СЛИТКОВ, ДЕФОРМИРУЕМЫХ В АЭРОКОСМИЧЕСКИЕ ИЗДЕЛИЯ

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В последнее время все большее внимание уделяется такому классу материалов, как нанопорошки (НП) химических соединений, которые представляют собой сверхтонкие образования размерами не более 100 нм. Такое отношение к этим материалам объясняется тем, что они обладают уникальными физико-химическими и механическими свойствами, существенно отличающимися от свойств материалов одного и того же химического состава в массивном состоянии, и эти свойства могут быть в определенной степени переданы от них или с их участием продуктам.

Существующие способы введения НП в металлические расплавы не могли быть использованы вследствие наличия у них особых свойств по сравнению с более крупными порошками, в связи с чем был разработан новый способ их введения в расплав, исключающий прямой контакт частиц НП с кислородом и беспрепятственное их *проникновение в расплав через окисную пленку. Суть способа заключалась в следующем. В алюминиевый контейнер засыпали частицы алюминия или алюминиевых деформируемых сплавов Д1 или Д16 и различные НП (нитриды, карбиды, оксиды и др.) и подвергали эту композицию прессованию в пруток, с помощью которого НП и вводили в расплав при литье слитков из алюминия и алюминиевых деформируемых сплавов.*

Результаты исследования показали, что при этом исключается появление в слитках трещин, а также повышаются их технологические и механические свойства.

Ключевые слова: алюминиевые сплавы, слитки, нанопорошки, повышение технологических и механических свойств.

Introduction. In recent years, more attention has been paid to such a class of materials as nanopowders (NP) of chemical compounds, which are ultrafine crystalline or amorphous formations with 100 nm in size (1 nm = $= 10^{-9}$ m) [1]. Such an attitude to these materials is explained by the fact that they have unique physicochemical and mechanical properties that differ significantly from the material properties of the same chemical composition in a massive state, and these properties can be transferred to the products obtained from them or with their help [2].

History. There is various information regarding the proposal of the term “nanotechnology” [3]. Thus, according to [4], the first who not only proposed (in 1950) a new term – molecular engineering, but also predicted the creation of nanomolecular devices, was an electrical engineer at the Massachusetts Institute of Technology A. R. von Hippel). In 1959, the Nobel Prize laureate, physicist Richard Feynman, in his famous lecture published in 1960 [5], pointed to the possible significant prospects for designing at the scale of atoms and molecules that can be achieved as a result of obtaining materials and devices molecular scale (atomic-molecular scale) and noted that to control the properties of these small nanostructures (“nano” – structures), it will be necessary to create a new class of miniature tools.

In the early 1980s, an engineer at the Massachusetts Institute of Technology, K.E. Drexler proposed approaches, physical principles for obtaining complex nanoscale structures [6]. Later on this topic, he published several monographs, including [7], in which he outlined the prospects for the application of molecular technology (molecular manufacturing technology) opportunities in a number of industries. In this monograph, he used the term “nanotechnology” (nanotechnology) to describe the vision of the subject by R. Feynman and the technologies for implementing his idea. It is believed [8] that N. Taniguchi from the University of Tokyo, in a report made in 1974 at a conference of the Japanese Society of Precise Engineering on the coming transition to processing with ultrahigh precision, defined the term “nanotechnology” [9] as a technology that ensures “extra” high precision and “ultra fine” sizes about 1 nm (1 nanometer = 10^{-9} m). He defined the term “nanotechnology” the following way: “nanotechnology mainly consists of the processing of separation, consolidation, and deformation of materials the size of one atom or one molecule” [10].

Today publications on the use of NPs in the creation of products, both on a metal and an elastomer basis appear [11–13]. The first author's certificate on the invention on the use of NP for grinding the structure of aluminum alloys [14] was obtained in 1981 (priority from 10.17.79). According to the results of the technologies developed on the use of NP for improving the quality of metal products manufactured in various ways from various metals and alloys, 25 USSR author certificates and patents of the Russian Federation for inventions were obtained. Most of the work was done to crush the structure and, as a result, increase the level of mechanical properties of products from aluminum cast alloys (shaped casting and liquid stamping) and cast iron (shaped casting), aluminum and deformable aluminum alloys during casting of ingots in a semi-continuous manner. The process of grinding the structural components of the alloys at the macro and micro levels is called modifying. The result of the modification of metal compositions is the improvement of the technological properties at the stage of obtaining products, as well as improvement of the strength and plastic characteristics of the finished products, especially in the case of using NP for this purpose.

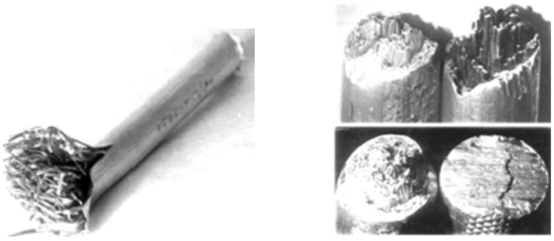
The method of introducing nanopowders into metal melts. Existing methods of introducing powdered additives into metal melts could not be taken using NP due to their special properties as compared to coarse powders, and therefore a fundamentally new method of their introduction into the melt was developed [14], which excluded direct contact of powder particles with oxygen in the process of their introduction, penetration of particles through the oxide layer, exclusion of aggregation and controlled dosing by weight.

The essence of the method was as follows. In a thin-walled aluminum container (diameter 165 mm, height 235 mm, wall thickness 2 mm) pellets of aluminum or aluminum deformable alloys D1 or D16 with a diameter of 1.5–3.0 mm, obtained by centrifugal spraying, were poured. The same container was filled up to 3.0 wt. % NP by weight of the granules. Nitrides, carbonitrides, oxides, carbides, and other high-strength refractory chemical compounds with particle sizes up to 100 nanometers were used as NP.

The opening in the container was closed with a lid, installed in an installation with an eccentric axis of rotation, and it was rotated, as a result the surface of the granules was clad with nanopowder particles.

Then this container was heated, placed in a container of a hydraulic press and with a pressing force of 100–120 ton-force the rods were pressed with a speed of 3.5 cm/sThe rods obtained in this way had a thin-walled surface (tenths of mm), the quality of which (roughness) was almost the same as the surface of profiles pressed from compact aluminum billets made from ingots.

And their volume consisted of densely pressed fibers (see the figure). This is explained by the fact that, due to the presence of NP particles on the granule surface during the extrusion process, the granules were deformed separately from each other, which is confirmed by the results of a microscopic study of the surface of clad aluminum particles and fibers. It turned out that the fibers are completely covered with NP particles firmly embedded in their surface. At the same time, the purity of the surface of such a bar was the same with a rod extruded from a compact aluminum billet obtained from an ingot. In rods ∅9.5 mm there were from 1100 to 1200 densely compacted fibers with a cross section of 0.005–0.075 mm^2, the length of which, depending on the size of the aluminum particles, is in the range of 400–3200 mm.



A typical type of modifying rod ∅ 9.5 mm, pressed from the composition of aluminum granules + NP

Типичный вид модифицирующего прутка ∅ 9,5 мм, отпрессованного из композиции алюминиевые гранулы + НП

In the process of conducting experiments under production conditions, it was found that regardless of the chemical composition of the NP, their crystal system and class, symmetry elements, space group, structural type, lattice period, density, melting temperature and other parameters considered, they all had a similar modifying effect.

Modification of aluminum and aluminum alloys with nanopowders during casting of ingots in a semi-continuous manner. A rather common defect of ingots cast in a semicontinuous method from aluminum and wrought aluminum alloys is the occurrence of cracks in the process of crystallization – crystallized or hot cracks, and after complete solidification of the metal – cold cracks. According to [15], on flat ingots, cracks are located on the surface of both the bottom part and the bottom part with a transition to wide faces, where their direction coincides with the direction of the casting. These cracks are formed as a result of violations of the speed and temperature of the casting due to uneven cooling around the perimeter of the ingot. On round ingots, cracks are classified as follows: a) central (due to rapid cooling of the peripheral layers with a sufficiently strong core that resists shrinkage of the outer layers); b) radial – located in the middle part of the ingot and develop from the periphery to the center (they appear only at the initial moment of cooling of the ingot with water, when the bottom of the well is above the belt of direct cooling of the ingot with water; upon subsequent cooling these cracks are tightly compressed); c) circular cracks – occur in the zone of change in the character of the grain structure and more often on ingots with a columnar structure (the reason is a big difference in the cooling rates of the crust near the wall of the mold and the metal in the middle of the ingot from the direct effect of cooling water). The occurrence of cracks is associated [16] with the occurrence of internal stresses during solidification of the ingot, due to the presence of a temperature gradient in the cross section and height of the ingot, which leads to non-simultaneous crystallization of the outer and inner volumes of the metal and as a result of difficult shrinkage of the first peripheral and then the inner layers. It is believed that hot cracks appear due to the low ductility of the alloy in the solid-liquid state, and cold – due to low elongation in the hardened state. It has been noted that hot cracks do not occur if the elongation in the solid-liquid state is more than 0.3 %, and cold – if its value is more than 1.5 %. The magnitude of the stresses in this case is determined by the elastic and plastic deformations that occur in the considered volume of the metal under the influence of adjacent layers, which are cooled with a different speed. This phenomenon is aggravated by a significant heterogeneity of the structure over the section of the ingot, characterized by three zones: a thin peripheral layer of the ingot that forms at the surface of the water-cooled crystallizer, has the smallest structure, then comes a layer of large columnar crystals directed to the center of the ingot, and the central zone consisting of coarse disoriented crystals. Such a structure is a characteristic of large-sized ingots, during casting of which cracks often occur. Most of the defect in the continuous casting of steel ingots also refers to cracks [17]. To a greater degree, the occurance of cracking increases [18] when aluminum liquid charge, delivered to the mixtures of casting section directly from the electrolyzers, is used for casting ingots (economically more advantageous technological scheme due to the exclusion of the operation of preparing alloys by melting solid charge). The reason for this is the formation of a coarse-crystalline structure of ingots, which is associated with the deactivation of nucleating agents at high temperature (1173–1223 K) of electrolysis aluminum supplied directly to the mixer It has been established that with an increase in the grade (purity) of aluminum, the ingot rejects for cracks increase, which is associated with the formation of a coarse-crystalline structure.

In order to identify the causes of cracks and establish optimal casting conditions that reduce the risk of this defect by the method of multidimensional correlation analysis [19], the ingot defects were calculated for cracks cast from A6 aluminum [20]. For active control of the technological process, a mathematical model of the connection of the number of ingots (optimization parameter, U, %) of two standard sizes was investigated: I – 347 × 1325 mm and II – 347 × 1630 rejected on cracks along a wider face, with controlled molding parameters (X_1 – casting speed, mm / min and X_2 – casting temperature), with the ratio of impurities of Fe: Si (X_3) and including the element-modifier (X_4, %). Digital expressions of all factors were fixed in 264 heats. As a result of the calculations, linear regression equations were obtained, which relate the number of ingot defects for cracks to the factors influencing its appearance.

For an ingot of type I, an equation was obtained:

$$U = -791.4 + 0.376X_1 + 1.152\,X_2 - 0.11X_3 - 130X_4. \quad (1).$$

For ingot type II:

$$U = -961.0 + 2.38X_1 + 1.25\,X_2 - 0.09X_3 - 1390X_4. \quad (2).$$

The coefficient of multiple correlation for equation (1) was 0.71 and 0.869 for equation (2), which indicates a significant proportion of the studied factors in the volume of active factors. The close dependence of the level of defect on cracks on the studied factors turned out to be much more than its dependence on each of them separately and on the close connection of factors with each other. The magnitudes of the coefficients in the equations and the sign in front of them indicates the relative magnitude and direction of the influence of the effect of the corresponding factor on the optimization parameter (reduction or increase in the defect). The values of the pair correlation coefficients between Y and X_1, X_2 and X_4 are close, which indicates that these factors have approximately the same effect on the ingot defect on cracks. So, for an ingot, the cross section of 347 × 1325 mm, the bond between Y and X_3 is weak ($ryx_3 = -0{,}027$), which is explained by the compliance with the required value (> 1) of the ratio Fe: Si – average 1.24, and for an ingot with a cross section of 347 × 1630 mm, this relationship was much closer ($ryx_3 = -0.0476$) which, when casting such ingots, requires a stricter respect for the ratio Fe:Si. Using the obtained equations, nomograms were calculated and constructed, which allow us to predict the expected level of defect on cracks during the smelting process and adjust the casting technological parameters (casting speed and temperature, Fe: Si ratio, titanium content), respectively, to reduce the ingot defect for cracks [20]. Experimental verification gives a very satisfactory convergence of the estimated number of defects with the actual. Good convergence is also observed in the case of introducing into the calculation the water pressure in the cooling system of ingots with dimensions of 295 × 1230 × 2400 mm made from A7 aluminum. Analysis of the initial information showed that when casting ingots of type I, the content of titanium in different heats varies in the range of 0.01–0.028 %, for type II – in the range of 0.014–0.027 %. The calculation of defects for cracks using the regression equations found for the lower and upper titanium contents with the stability of the other factors showed a significant influence of this factor. So, for ingot I, at the lower level of titanium, a defect for cracks is predicted to 24.9 %, at the top – it decreases to 1.45 %, for II, respectively, 21.16 and 3.09 %.

When working with commonly used ligatures, obtained in the form of relatively massive ingots containing titanium modifying element, or with a titanium sponge, which dissolve for quite a long time, incommensurable with the casting speed of the ingot, it is not possible to change this factor (X_4 – titanium, %) affect the reduction of defects for cracks. In the case of the use of rod modifying ligatures that can be made with any desired diameter, their dissolution occurs at a rate commensurate with any of the ingot casting speed adopted by the technology (from 60 to 90 mm/min), while ensuring stable and equal content of modifying element in any volume of metal in the ingot.

The negative consequences of the use of the liquid charge are prevented by the introduction of modifiers into the melt, in particular, titanium, less often in its pure form, more often in the volume of aluminum-titanium master alloys. When titanium interacts with liquid aluminum in the melt, nucleating particles of $TiAl_3$ compound appear, which leads to a refinement of the structure, and, consequently, to an increase in the plasticity of the hardened and hardening metal, and as a result – to a decrease in the ingot defect due to cracks. Analysis of 9857 ingots cast at Krasnoyarsk Aluminum Smelter 347 × 1325 mm and 347 × 1630 mm and weighing up to five tons showed that the smallest number of defects on cracks (2.0–4.5 %) provides a titanium content in the range of 0.030–0.035 %. Moreover, it is also known that the occurrence of cracks in ingots is also influenced by the ratio of Fe and Si impurities present in aluminum. Without going into a hypothesis explaining this phenomenon, it can be noted that in order to reduce defects on cracks, it is recommended that the iron content be higher than the silicon content by 0.02–0.05 %. On the same number of ingots, we found that the smallest number of them is with cracks (1.1–1.3 %) with the same titanium content is characterized by the ratio Fe: Si in the range 1.0 : 1.2. Due to the fact that cutting of large-sized ingots at the plant for studying their structure was not possible, it was studied on sample tests simultaneously cast with ingots with an estimate of the size of the macro grain detected on thin sections according to a developed scale. So, for the smallest grain (area of about 0.5 mm^2) I point was taken, and for grain with an area of about 100 mm^2, V point was taken. Comparison of the obtained data showed that the number of ingots with cracks correlates with the grain size on samples: with an increase in the grain size, the number of ingots with cracks increases. So, if with a structure characterized by II point, the defect does not exceed 2.2 %, then with V point, the defect reaches 21.0 %. It should be noted that not all ingots are finally rejected for this type of defect, some types of cracks, especially shallow ones, are cut down and the cutting site is cleaned. Nevertheless, there is a danger of production of ingots with cracks undetected on the surface for further processing by pressure, where this defect at the technological stages is not always detected and can get into the finished product, and lead to negative consequences in operation.

Despite the relatively high efficiency of titanium for grinding the structure and reducing the likelihood of cracks in the ingots, this method has a significant disadvantage, that titanium is introduced either as a titanium sponge or as a pig ligature into a liquid metal in a mixer-forehearth or in the distributing mixer, where these components, firstly, dissolve for quite a long time (hours), secondly, despite the mixing of the melt, titanium is unevenly distributed over the volume of the bath, which is reflected in its distribution over the height of the ingot, and, consequently, on the degree of grinding of the grain and further – on the technological properties of the ingot and on the mechanical and operational characteristics obtained from these products (sheet, profile, forgings).

Modifying technology. We applied a technology implemented under production conditions, firstly, eliminating the long standing of the melt in the mixer, and, secondly, ensuring the same content of the modifying agent throughout the entire ingot. As mentioned earlier, from the composition consisting of aluminum and NP particles, rods were pressed, which were wound onto a bobbin, and their continuous dosed introduction, coordinated with the volumetric flow rate of the poured metal, was carried out either into the chute or into the junction box in automatic mode using designed installation, consisting of: reel, which serves for winding the rod, electric motor, gearbox, feeding unit of rod and guide tube. The feed speed of the rod into the melt was consistent with the volume flow rate of the metal and was adjusted by changing the number of revolutions of the drive shaft on which the reel was mounted, using an autotransformer. At the same time, the number of NP injected did not exceed 0.05 mass. %, and the consumption of the rod was 20–25 kg per ton of metal. In order to determine the algorithm for automatic control of the rate of introduction of a modifying rod into the melt during ingot casting, which provides the required amount of modifier (NP) in the alloy, such factors as casting temperature (X_2) and Fe: Si ratio (X_3), which are usually not subject to significant fluctuations ingot casting process, taken as stable. Building on the coordinate plane a system of points M_i (X_i, Y_i, where X_i is the mass flow rate of aluminum when casting an ingot, Q, kg; Y_i – titanium content, Ti, kg) showed that the points are located on a line very close to a straight line. Therefore, we can assume that between X_i, (T_i, kg) and U_i, (Q, kg) there is a linear relationship like $Y = a + bX$, where a and b are constant. Based on this assumption, a calculation was made by which an empirical relationship was obtained: $Y = –0.2304 + 0.00055X$, the value of the correlation coefficient for which ($r = 0.9996$) confirms the existence of a close, straightforward relationship of the required titanium content in aluminum with volume flow of the latter. The coefficient of determination in this case was $d = r^2 \times 100\ \% = 99.92\ \%$. As an example, the established linear dependence of the melt flow rate and the titanium content in it was transformed into the operating parameters of the casting process of an ingot with a cross section of 400 × 1560 mm, respectively, into the casting speed and the feed speed of the rod alloy. This largest ingot produced by the company was chosen as the object of testing the technology of introducing bar ligatures due to the largest amount of defect on cracks in its bottom part and reaching a wide edge, which is associated with a relatively slow crystallization rate of the metal, contributing to the formation of a large cristal structure. In order to test the installation's ability to provide a high bar feed rate, a ligature with a low content of – Al – 1.95 % Ti modifier was used, commensurate with the content of NP in rods. At the adopted ingot casting speed (70 mm/min), the volume flow rate of aluminum was 135 kg / min, which required, in order to ensure the content of titanium in aluminum A7 provided for by technical documentation, to introduce a rod with a diameter of 8 mm (the weight of the one running meter is 0.144 kg) at a speed of 4 m/min (4.27 kg per 1 ton of aluminum). Such a rod feed rate ensured introduction of about 0.008 % Ti into the melt in addition to the titanium sponge previously injected into the mixer (about 0.018 % Ti), which in total turned out to be close to the required titanium content, which was determined by chemical analysis – 0.027 % Ti. It is easy to obtain a similar empirical dependence of the feed speed of a rod with different content of the modifying agent on the volume flow rate of aluminum. On thin chargesof the bottom part of the samples with a diameter of 75 mm and a height of 40 mm, cast simultaneously with the casting of the ingot, it was found that the average area of the macrograin of the original aluminum A7 containing 0.018 % Ti is 1.24 mm^2, and the additional introduction is 0.008 % Ti rod ligature reduces it to 0.082 mm^2 (15.1 times). The fact that such an effect of grinding grain was obtained precisely due to the additionally introduced modifier –titanium is evidenced by the fact that when introduced into the same melt when casting the same ingot, a 10 mm diameter rod made of aluminum of the AD0 brand with the same volume feed with a titanium-containing rod, the area grain decreases only 2.4 times (to 0.051 mm^2). At the same time, the depth of the peripheral zone of the columnar crystals of the sample of the original aluminum is 3.5 mm (9.3 % of the sample diameter); when introducing the aluminum rod AD0, it decreases to 2.0 mm (1.75 times) and when modifying with a titanium rod, it is completely absent.

The influence of the type of modifier on the grinding of grain and the mechanical properties of aluminum alloys. Preliminary experiments were carried out under production conditions when pouring from 973 K into metal form samples with a diameter of 60 mm and a height of 300 mm of an aluminum wrought alloy D16 prepared in a liquid charge and taken from a pre-chamber 20-ton mixer from a temperature of 1003 K to a filling bucket with a capacity of 4 kg the subsequent introduction into the melt of various NP in the volume of modifying rods with a diameter of 8 mm, pressed from the granules of the alloy D16 and various NP. The study of charges prepared on the cross-sections of the cast samples showed the effect of grinding grain when using all types of modifying substances, but to a greater degree this effect is observed when modifying the NP. So, if, when a sample rod is brought into the melt, pressed only from granules, the grain is crushed 1.3 times, and the rod pressed out of REM – 1.7 times, then all used NP grind the grain 2–3 times. The effect of the modifying additive on the size of the macrograin in the cross section of a chill sample with a diameter of 60 mm, 300 mm high, cast in a chill mold of alloy D16: 1 – without modification; modifying rod pressed from granules: 2 – alloy D16; 3 – rare-earth metals (Al + 11,0 % La; Al + 11,0 % Ce); modifying bar is pressed out of granules of alloy D16 and nanopowder: 4 – Si_3N_4; 5 – SiC; 6 – $V_{0,75}N_{0,25}$ (with an impurityV_2O_3); 7 – SiC (with an impurity SiO_2);8 – B_4C (with an impurity BN); 9 – $Cr_3C_{1,6}N_{0,4}$ (with an impurity Cr_2O_3 + C); 10 – B_4C; 11 – TaN; 12 – SiC (with an impurity SiO_2 + Si). The effectiveness of the modifying impact of the NP was confirmed under production conditions when casting ingots on a continuous casting installation when they were introduced into the melt in the automatic mode in the amount of modifying rods.

Thus, when casting ingots with a diameter of 420 mm from AMg6 alloy at a speed of 60 mm / min at 968 K with the adding of a rod into the mold under a metal stream, it was found that if the standard modifying additive (Al-Ti ingot) the average grain size makes up 0,322 мм^2, then when modifying the NP BN it decreases to 0.146 mm^2 (2.2 times), NP SiC – to 0.123 mm^2 (2.6 times), and NP TaN – to 0.078 mm^2 (4.1 times).

When casting ingots with a diameter of 190 mm from alloy D16, a modifying rod with a diameter of 6 mm was pressed from the granules of the alloy D16 and NP SiC. Rods with a diameter of 12 mm were pressed from homogenized ingots (holding for 6 hours at 753–773 K, air cooling), and after quenching (holding for 15 minutes at 763...773 K, cooling in water), standard cylindrical specimens were carved from them. Analysis of the test results showed that the SiC NP crushes the macrograin over the ingot cross section on average 1.7 times (from 0.35 for the alloy modified by the factory technology to 0.20 mm^2), and by c of the ingot radius – 2.3 times (from 0.35 to 0.15 mm^2). The temporal resistance $\sigma_в$ in the samples of the modified NP SiC alloy increased by 2.3 %, the yield strength $\sigma_в$ – by 11.0 %, and the relative elongation δ by 31.6 %. The microstructure did not show significant differences from the usual alloy. During casting of ingots with a diameter of 480 mm from D1 alloy, the effect of introducing into the melt NP SiC, B_4C and $V_xC_yN_z$ was investigated. Modifying rods with a diameter of 10 mm were pressed from both D1 alloy granules and from these granules and NP on a rod-shaped horizontal hydraulic press P8743B with a force of 2000 tf at a speed of 2 mm/min. The ingots were cast at 983 K at a speed of 32.36 mm / min, homogenized (the mode is indicated above) and cut into blanks 800 mm long, which were then heated in an IN600 furnace to 653–673 K and on a P4757 press with a force of 700 tf, they were pressed into an intermediate product with a diameter of 100 mm. Of the three sections of this product (loose, medium and tightening blanks with a length of 250 mm were cut, heated them to 633...653 K and on the press P8739 with a force of 800 tf extruded profile 100–59 (corner with a shelf width of 20 mm). Mechanical properties were tested on three corners cut from the above-mentioned hardened corners (as indicated above) in the VZP-1 vertical tempering furnace. Comparison of the results of testing the mechanical properties of different parts of the profile (output, medium and tightening), pressed from similar parts of the intermediate product, showed that modifying with all the above mentioned NPs in all cases gives mechanical properties higher than conventional technology provides. The study of the structure of the transverse templates of ingots showed that the highest degree of grinding grain provides NP $V_xC_yN_z$. At the same time, there were no significant differences in the microstructure of the alloy modified by various NPs.

Due to the fact that the filtering used at the enterprise to remove non-metallic inclusions from the melt leads to the enlargement of the macrograin ingots, work was carried out to eliminate this undesirable phenomenon using NP. At the same time, ingots of 280 mm in diameter were cast from the AMg6 alloy at 983–993 K at a speed of 6 mm/min with the filtration of the melt in an upward flow, ingots with a diameter of 280 mm were cast through successively installed meshes from glass fabric SSF-4 and SFF-0.06. Modifying bar with a diameter of 10 mm, containing NP SiC or B_4C, or $V_xC_yN_z$, injected into the mold under a stream of metal coming from the transfer case. For comparison, ingots were cast with the introduction of a rod pressed only from pellets into the mold. The cast ingots were homogenized (holding for 6 hours at 753–773 K; cooling in air), after which they were cut into blanks 700 mm long, heated to 673–683 K and pressed on a horizontal press into profile PC13820-2. Of the three sections of the profile (output, medium and tightening) cut samples for testing mechanical properties. The macrostructure was studied on the ingot transverse templates. The results of tests of mechanical properties showed that, in general, NPs lead to an increase in the relative elongation. So, if δ for ingots cast from filtered metal by factory technology is 19.1 %, then NP B_4C increases it to the greatest extent до 29.4 % (by 24,6 %), NP $V_xC_yN_z$ – to 22.6 % (by 23.4 %) and NP SiC – to 21.8 % (by 14.1 %), then a rod of granules – to 21.6 % (13.2 %). There is also an increase in yield strength $\sigma_{0,2}$. So, if for an ingot cast with filtration according to factory technology, its value is 230 MPa, then NP SiC increases $\sigma_в$ to 247 MPa (by 5.2 %), NP $V_xC_yN_z$ – for 250 MPa (by 8.5 %), granulated rod is up to 233 MPa (by 1.3 %), and NP B_4C does not change this characteristic. Temporary resistance $\sigma_в$ does not change in all types of NP and with the introduction of the rod of granules. The study of the structure of the ingots showed that the filtration of the alloy enlarges the macrograin, whereas the introduction of the NPs studied into the melt after filtration leads to its sharp grinding and to the formation of a homogeneous structure over the section.

Modification of the structure of ingots for forgings. The obtained positive results with the introduction of NP into the melt during the casting of ingots, from which further extrusion methods were used to extrude a profile of different cross sections, served as the basis for testing this technology during the casting of ingots intended for the manufacture of forgings from them. For this purpose, when casting ingots of ∅420 mm from AMg6 alloy, the melt was modified with a rod of 10 mm containing one of NP – SiC, BN or TaN. The ingots were cast at 973 K at a speed of 60 mm / min with the introduction of the rod into the transfer case. Cast ingots were homogenized (holding for 6 hours at 753–773 K; air cooling), then they were cut into workpieces 750 mm long, turned to ∅380 mm and, after preheating to 703 K, forgings were obtained with a force of 1250 tf deformation $\xi = 62$ % according to the scheme: upsetting the workpiece in a disc coil → forging disc coil on a rod → secondary sedimentation of a rod in a disc coil KP-10-27. The structure was studied on templates cut from an ingot and from a disc coil. Metal contamination by nonmetallic inclusions was estimated from fractures of technological samples (40 × 40 × 120 mm) cut from transverse templates, as a result of which it was found that the least contamination is characteristic of serial ingots – $\Sigma F_{inc} = 10$ mm^2, whereas with the introduction of rods containing NP BN, SiC, TaN, this characteristic significantly increases – to 23.5; 24.0 and up to 38 mm^2, which exceeds the requirements of technical documentation. When analyzing the macro-structure of cross-section templates, it was found that ingots cast by serial technology with the introduction of a rod of granules are characterized by a heterogeneous structure: fine grain around the periphery, then a columnar structure (width 50–90 mm) follows, and behind it – fine-grained structure. The introduction of any of the NPs prevents the formation of a columnar structure, and according to the degree of impact, the most effective of them was NP TaN grain refinement 4.1 times as compared to serial ingots (from 0.322 to 0.073 mm^2), then NP SiC – 2.6 times (up to 0.123 mm^2) and NP BN – 2.2 times (up to 0.146 mm^2). Analysis of the microstructure did not reveal any special differences in the internal structure of the grain of serial ingots and ingots of a metal modified by NP. At the same time, in all ingots, close microporosity is observed. The study of macrosections and kinks of templates of forgings made of modified NP alloy showed the presence of non-metallic inclusions (total area ΣF_{inc}, mm^2) and stroke bundles associated with the presence of oxide layers in the metal (total length, mm), respectively, on charges – from 4 up to 9 mm^2 and from 10 to 24 mm, at fractures – from 5 to 6.5 mm^2 and from 18 to 28 mm, which meets the requirements of technical documentation, but at the same time exceeds the number of defects for a serial forging, on the macrosections of which no defects were found, there is a part of fan structure with an area of 25 mm^2; at fractures, the area of nonmetallic inclusions ΣF_{inc} is only 2 mm^2. The mechanical properties of specimens cut from forgings according to the required documentation of the scheme in the fractional, transverse and altitudinal directions turned out to be quite close to the properties of serial forgings, and in some cases even exceeded them, especially the relative elongation. Macrograin forgings made from ingots modified by NPs turned out to be smaller than forgings made from serial ingots and from ingots cast from an alloy into which a bar of granules was introduced. Thus, as a result of the research described above, it was found that as a result of the introduction of various refractory materials into the liquid alloy AMg6, the grain size of the nonmetallic inclusions increases, as well as the number of laminations (in forgings). A possible reason for their existence can be considered the use of modifying rods of granules as a basis, which contribute to the volume of this product a large amount of aluminum oxide Al2O3, which is present on their surface, and gases, present (hydrogen) on the surface. It should be noted that in all our studies, non-metallic inclusions and delaminations were not observed on the products pressed from ingots cast from alloys modified by various NPs. By the way, this fact does not at all indicate in favor of the absence of non-metallic inclusions (aluminum oxide particles Al_2O_3) in the volume of compacts – their number, both in the original ingots modified by NP, and in the compacts or forgings obtained from them, remains almost the same but in the process of obtaining products from ingots, these oxides are crushed and evenly distributed over the volume of the deformed metal.

Conclusion. As a result of the use of a new type of modifiers – nanopowders of refractory chemical compounds, and the developed method of their introduction into metal melts in the volume of rods pressed from the composition "aluminum particles + nanopowders", the mechanical properties of the products obtained by the pressure treatment of ingots cast with the semicontinuous method from aluminum and aluminum alloys were improved.

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