https://doi.org/10.46813/2026-161-076

UDC 620.175.2:669.715

INCREASE OF THE MECHANICAL PROPERTIES OF HIGH-STRENGTH ALUMINUM ALLOYS

T.V. Nosova, S.T. Mamchur
Oles Honchar Dnipro National University, Dnipro, Ukraine
E-mail: amaretanya0512@gmail.com

The work substantiates the choice of scandium for microalloying and modification of high-strength aluminum alloys. The research material is a high-strength aluminum alloy V96Ts1 (Cyrillic: В96Ц1) of the Al-Zn-Mg-Cu system. Scandium was chosen as the microregulating and modifying element. The state diagram of Al-Sc, physical and mechanical properties of scandium were studied. Modes of heat treatment of the V96Ts1 alloy have been developed. The influence of the microstructure on the mechanical properties of the modified alloy was investigated. The work substantiates the choice of scandium for microalloying and modification of high-strength aluminum with a dispersed structure and a high complex of mechanical properties of the V96Ts1 alloy, which represents the practical value of the work. The complex of research conducted confirmed the microalloying and modifying effect of scandium in the aluminum melt, the proven technology of introducing scandium into the melt, the amount of Sc was optimized. It was established that the technology of introducing scandium into the melt and the temperature-time parameters of the heat treatment of the blanks made it possible to obtain a dispersed structure and a high complex of mechanical properties of the В96Ц1 alloy, which represents the practical value of the work.

INTRODUCTION

Innovations in metalworking are a key element in the ability of metallurgy to compete on the modern world market. Competence to meet market requirements by timely production of high-quality metal products is the main condition for effective development of the industry at the global, national and regional levels. Improvements in processing technologies and modern materials demonstrate that the future of the metallurgical industry will be significantly different from current processes [1, 2]. Modern trends in mechanical engineering, shipbuilding, rocket, space and aviation engineering are the reduction of the mass of the elements of responsible mechanisms and structures and the simultaneous increase of their operational properties. This combination makes it possible to increase functional characteristics, increase the durability of equipment units and reduce energy consumption. One of the important areas is the study of methods of modification of light structural alloys based on aluminum and magnesium. They have a high potential to increase specific strength indicators. This can be achieved by modifying the internal structure of materials. Methods of dispersion strengthening with intermetallic phases, such as aluminum scandium, aluminum-zirconium, aluminum-copper are used. Artificial aging of aluminum and magnesium is used to obtain high mechanical properties. An alternative scheme is deformation methods, which lead to the grinding of grains to sub-micron sizes using intensive plastic deformation. In this case, ultra-fine-grained alloys of aluminum and magnesium are obtained with improved physical and mechanical properties compared to their coarse-grained counterparts. In this case, several strengthening methods are activated. An additional contribution to the improvement of properties is made by dispersion strengthening with intermetallic nano-sized inclusions, which are formed from a solid solution during the processing process.

After numerous theoretical and experimental works devoted to aluminum alloys and the development of high-strength alloys of the Al-Zn-Mg-Cu system, it was believed for a long time that further improvement of the strength properties of aluminum alloys is impossible [3]. However, in the last two decades, successes have been achieved due to alloying of alloys with scandium [1, 2]. In this connection, it became possible to further improve the complex properties of aluminum alloys and obtain dispersed structures with strengthening phases.

MATERIALS AND METHODS

The research material is a high-strength aluminum alloy V96Ts1 of the Al-Zn-Mg-Cu system. Scandium was chosen as a microalloying and modifying element. The state diagram of Al-Sc, physical and mechanical properties of scandium were studied. Modes of heat treatment of the V96Ts1 alloy with 0.3% scandium have been developed. The structure and mechanical properties of the modified alloy were studied. The complex of research conducted confirmed the microalloying and modifying effect of scandium in the Al melt, the proven technology of introducing scandium into the melt, and the amount of Sc was optimized. In the modified blanks, grain grinding was achieved by 2.5 times and the characteristics of the strength limit and yield limit of the alloy were increased while maintaining plasticity. Establishing the technology of introducing scandium into the melt and the temperature-time parameters of the heat treatment of the blanks made it possible to obtain a dispersed structure and a high complex of mechanical properties of the B96C1 alloy, which represents the practical value of the work [1, 3, 4, 8]. Aluminum is easily processed in various ways – forging, stamping, rolling, etc. Aluminum alloys are conventionally divided into foundry (for the production of castings) and deformed (for the production of rolled products and forgings).

In the works of Kutsova V.Z., Bolshakova V.I. and other prominent scientists, data on the structure and properties of aluminum alloys are given [4, 6]. But in well-known works, the modification of alloys with low-melting salts of the NaCl type was studied, these methods are not ecological and provide an insufficient complex of alloy properties, therefore, works on the modification of melts with refractory nanocompositions are relevant and have wide prospects [5]. A satisfactory structure of the ingot is a fine-grained and homogeneous structure in its cross-section [7]. This can be achieved by introducing dispersed intermeta-ice particles into the melt, which are potential substrates for the crystallization of alloys and the creation of conditions for their formation in the melt.

The problem of creating non-deficit dispersion-strengthened aluminum alloys for mass use in modern technology remains relevant. At present, there are main directions: strengthening of the material due to alloying; force action on the melt, which crystallizes; introduction of nano-sized strengthening particles. Also, the tendency to reduce the number of alloying elements and strengthening current-current remains relevant.

Among the existing methods of strengthening alloys and obtaining a fine grain, the most well-known are recrystallization, heat treatment, and modification [4]. A number of problems arise during crystallization: liquation, shrink shells, cracks, microchemical and microphysical inhomogeneities, large grains, dendrites. The main method of combating these defects is the modification of the melt, but it is associated with significant changes in the initial composition and properties. It is theoretically possible to combat casting defects by changing the cooling rate of the liquid metal but these methods require complex hardware design and are time-consuming.

The addition of nano-sized reinforcing particles allows to obtain a special structure and unique mechanical properties. Considering the difficulties that arise when trying to achieve a uniform distribution of nano-sized particles that have a high surface energy in the melt due to the formation of agglomerates, the technology of introducing nanoparticles into the melt for mass production needs significant improvement.

Thus, the aim of this work was the theoretical justification of the choice of scandium as a microalloying and modifying element to improve the strength properties of aluminum alloys. In the work, the liquid flowability of alloys was determined using the spiral test method.

The scientific novelty of this research work is the theoretical justification of the use of nanodisperse compositions of SiC and ZrC up to 100 nm in size as modifiers of cast aluminum alloys of the Al-Si system.

Correspondence of the crystal-geometric structure of nanomodifiers of the carbide class with respect to the aluminum matrix of alloys was established. To test the effect of the complex modifier and optimize its composition, experimental melting of cast aluminum alloys was carried out under industrial conditions. The research material was a deformed aluminum alloy V96Ts1 of the Al-Zn-Mg-Cu system with a chemical composition, mass %: 6.8 – Zn; 2.5 – Mg; 1.8 – Cu; 0.4 – Mn; 0.7 – Zr; 0.4 – Si; 0.1 – Ti. Scandium was added in the form of a ligature at the rate of 0.2...0.3% by weight. After melting the charge and cooling the castings, they were deformed and heat-strengthened. The microstructure and mechanical properties of the alloy were studied using standard methods.

RESULTS AND DISCUSSIONS

The ecological method is obtained by modification with nanodisperse compositions. The alloys of the Al-Zn-Mg-Cu system have the greatest strength. However, hidden reserves of increasing the strength of aluminum alloys are laid in microalloying with scandium and transition metals [9, 10]. Scandium microalloying made it possible to increase the strength and plasticity of alloys, as well as to improve technological properties: weldability and machinability, and even corrosion properties [11].

Industrial aluminum alloys are multi-component systems, so scandium alloying has features due to the interaction of scandium with the alloying elements that make up the alloys. Scandium is a chemical element of group III of the periodic table, melting point is 1540 °C, density is 3020 kg/m^3, polymorphic metal. The electronic configuration of a scandium atom corresponds to 3d1 4s2. The solubility of scandium in aluminum is 0.3% by weight, and the ligature contains the intermetallic Al_3Sc, the size of which should not exceed 20 nm in order to dissolve in the melt. The analysis of the state diagram of Al-Sc [2] made it possible to establish that, an insignificant temperature interval of crystallization (5 °C); noticeable limit solubility of 0.4% by weight; gentle liquidus of near-eutectic alloys.

All this gives reason to assume the possibility of formation of supersaturated solid solutions of scandium in aluminum at relatively low crystallization rates close to industrial conditions. The significant solubility limit at the eutectic temperature sharply decreases with a decrease in temperature, which indicates the possibility of strengthening alloys due to heat treatment. As a result of quenching of Al-Sc system alloys containing 0.3% scandium, from a temperature of 620 °C, sharp cooling at a rate of 100 °C/s and higher does not cause the solid solution to disintegrate with the release of $_{AlSc}$ intermetalide particles. In the aging process of hardened metals, secondary Al_3Sc precipitates are formed. The optimal aging temperature is 300 °C. Since the melting temperature of complex aluminum alloys is below 600 °C, quenching at pre-melting temperatures does not lead to the transfer of scandium into a solid solution in these alloys. The formation of secondary Al_3Sc precipitates is possible by aging of the metal after rapid crystallization, as well as by deformational aging. The special effect of scandium on aluminum metals is explained by the electronic structure of scandium. The significantly greater solubility of scandium in most elements of the periodic table is associated with a much smaller value of the atomic radius of scandium, due to its electronic structure. In [7], it was established that alloys of the Al-Sc system have a high effect of artificial aging. The study of the kinetics of the decay process showed the supersaturation of the solid solution obtained during crystallization similar to the aging of the metal after hardening. During the decomposition of a solid solution of scandium in aluminum, particles of the stable Al_3Sc phase are released. They originate homogeneously, are released in a dispersed form and are completely coherent matrices. The main effect of scandium is to increase strength properties due to the formation of dispersed products of the breakdown of a solid solution of scandium in aluminum and preservation of a stable structure with small subgrains in heat-treated semi-finished products.

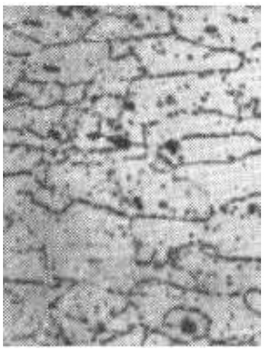
To obtain the maximum effect when alloying aluminum alloys with scandium, it is necessary to take into account the peculiarities of the interaction of scandium with aluminum, alloying elements and impurities, as well as the kinetics of phase and structural transformations in aluminum alloys containing scandium. The content of scandium should be such that during the casting of ingots, its main part is fixed in a supersaturated solid solution, which then disintegrates during further technological heating of ingots and semi-finished products with the formation of dispersed phases, which ensure the formation of a fine subgranular structure with high resistance against recrystallization of the matrix with the help of dispersion hardening. At a high cooling rate, a solid solution of scandium in aluminum is prone to anomalous supersaturation with a concentration of scandium in aluminum of about 0.6% [2].

Therefore, the maximum strengthening effect in deformed semi-finished products is achieved with a content of 0.6% Sc in aluminum and its alloys. However, this is true only for semi-finished products in laboratory conditions, when it is possible to limit the decomposition and coagulation of the decomposition products of a supersaturated solid solution of scandium in aluminum. In production conditions, ingots and semi-finished products are subjected to long-term high-temperature heating, while the decomposition of the supersaturated solid solution takes place completely, and the decomposition products strongly coagulate.

As a result, the effect of the introduction of 0.6% Sc is lost. This is due to the fact that the solid solution of scandium in aluminum is unstable, and its decay rate is several orders of magnitude higher than the decay rate of solid solutions of other transition metals in aluminum. To reduce the degree of decomposition of the solid solution and limit the coagulation of decomposition products, it is advisable to limit the content of scandium to 0.25…0.5%. After crystallization, ingots were homogenized at 470 °C for 8 h, which significantly affected the formation of a homogeneous structure and stabilization of properties. In the process of homogenization of the B96 alloy modified with scandium, in addition to the dissolution of excess phases and equalization of the concentration of the solid solution of the main components in aluminum, the solid solution of Sc in aluminum disintegrates at a high rate.

The temperature-time conditions of homogenization were chosen based on the data of differential thermal analysis and statistical processing of the results of mechanical tests. To study the microstructure, sections were made after deformation (Figure). Etching was carried out in the reagent of concentrated hydrofluoric acid HF. Microstructure research was carried out on grindings using a Neophot 2 optical microscope at magnifications of 50, 100, 200. Micro-X-ray genospectral analysis was carried out in order to determine the chemical composition at points (at the boundaries of grains and phases), the distribution of the microalloying element – scandium. The tests were performed on a JSM-6360LA multipurpose raster microscope equipped with a JED 2200 X-ray spectral energy dispersive microanalysis system.

The microstructure of the alloy in the deformed state is shown in Figure After deformation, the microstructure of the alloy is characterized by the presence of grains of α-solid solution of aluminum stretched along the direction of deformation, that is, during deformation, the microstructure of the alloy acquires the orientation of the grains in the direction of deformation. After hot deformation, inhomogeneity of grains is observed in the initial alloy. A homogeneous fine-grained dispersed structure of α-Al solid solution was obtained in the modified alloy after deformation. The microstructure of the alloys in the equilibrium state consists of an α-solid solution of aluminum and intermetalide Al_3 (Schx, Zrx-1). The main microalloying elements in the alloy are scandium and zirconium. The distribution of these elements along the cross-section of the sample is uniform: scandium and zirconium are present both in the core of the matrix alloy and along the grain boundaries. In modified samples, silicon is concentrated in inclusions, forming SiO_2 oxide, increasing the strength of the material (see Figure).



a

b

Microstructure of the deformed V96Ts1 alloy:
a – after deformation of the unmodified alloy, x200;
b – after deformation of the modified alloy, x200

The study of the micro- and macrostructure of serial and modified ingots of the V96Ts1 alloy showed a more homogeneous structure of the modified ingots and grain grinding from 140 to 50...60 μm. The modified in ingots had almost zero porosity in the form of small shiny areas (<0.02 mm^2) in the fractures of the technological samples. An increase in the quality of the cast modified metal was indicated by an increase in the mechanical properties of the deformed blanks (Table 1).

The mechanical properties of the alloy samples were determined in the state of quenching and artificial aging (110 °C, 4 h + 160 °C, 8 h). The microstructure of non-homogenized ingots of V96Ts1 alloy had a coarse dendritic structure – a solid solution with large allocations of intermetallic phases along the boundaries of dendritic cells. After homogenization, the dispersion of dendrites increased, the size of the dendritic cell was comparable to the size of the grain, i.e. 40...50 µm.

Intermetallic phases (Al_3Sc, $FeAl_3$, Al_3CuMg, $MgZn_2$) are dispersed and uniformly distributed in the grain volume. The deformation resulted in a fibrous structure; moreover, non-homogeneous large phases of the original metal formed rows of increased grass-bridge, and the grains of the aluminum solid solution had reduced digestibility. This heterogeneity led to anisotropy of the strength properties of the original alloy. As a result of the scandium modification of the bands, the differences were not observed and the anitropy according to the strength characteristics decreased.

Table 1

Mechanical properties of the V96Ts1 alloy

State	$\sigma_в$, MPa	$\sigma_{0.2}$, MPa	δ, %
Output ingot	280	240	12.5
Modified ingot	340	290	11.0
Output profile	560	490	8.0
Modified profile	620	570	7.5

The test results are presented in the Table 2.

Table 2

Yield strength of samples of alloy 1545 with different contents of Mg_2Si, SiC

№ melting	Contents Mg_2Si, SiC, %	$\sigma_{0,2}$, MPa	$\sigma_в$, MPa
1	initial state	344	384
2	0.05	376	415
3	0.10	408	446
4	0.15	360	402

It was found that the maximum values of $\sigma_{0.2}$ and σ_v correspond to the optimal content of the powder composition: 0.10% with a further increase of the modifier, the strength properties decrease, while the increase in the strength properties of the modified alloy is 29% compared to the initial state . According to the data in Table 2, the dependence of the yield strength of the modified alloy 1545 on the content of the modifier is plotted.

In the course of research and industrial experiments, mechanical tests were conducted to determine the tensile properties of samples with different contents of a complex modifier.

According to the data in Table 2, the dependence of the yield strength of the modified alloy 1545 on the content of the complex modifier is the state after heat treatment and before heat treatment.

Heat-strengthening treatment consisted of quenching and artificial aging [1, 8]. The maximum values of the yield strength are obtained by the content of the complex modifier of 0.1% by mass. At the same time, the yield strength of the modified 1545 alloy was increased to 446 MPa, which is 29% compared to the original state.

To obtain comparative data on the corrosion resistance of alloys, general corrosion tests were conducted according to the standard method. To simulate operating conditions, the test method was chosen in conditions of 100% relative humidity, as well as the method of periodic exposure to a 3% NaCl solution at room temperature. The corrosion resistance of aluminum alloys was evaluated by the metallographic method and by changing the mass of the samples. Intercrystallite, well corrosion (MKK) was determined according to the standard method [4, 6, 8].

The results of general corrosion tests showed that modification with SiC powder leads to an increase in the corrosion resistance of alloys due to a 29% reduction in the corrosion rate. The increase in corrosion resistance can be explained by a change in the alloy structure. During modification, the length of interphase boundaries increases. Intermetallics and impurity atoms, which were located at the interphase boundaries in alloys before modification, are distributed over a larger area after modification.

Therefore, impurities will have a less negative effect on the corrosion resistance of alloys. The stress state of the modified structure also plays an important role [11]. When Mg_2Si+SiC dispersed particles are introduced, the microvolumes of the alloys become more energetically stressed, which increases the corrosion resistance of the system. The sensitivity of alloys to MCC appearsas a result of structural inhomogeneity of grain boundaries, separation of secondary phases, impoverishment or enrichment of adjacent areas of the α-Al solid solution with alloying elements.

In the modified deformed alloy, no susceptibility to MCC was detected. According to the results of tests for corrosion cracking of the V96Ts1 alloy before and after modification for different periods of time (45 and more than 55 days), the following data were obtained: during the test duration of 45 days, the alloy in its initial state had a stress of 0.8 MPA, test duration of more than 55 days after modification, the stress was 0.9 MPa.

CONCLUSIONS

The choice of scandium as a microalloying and modifying element of high-strength aluminum alloys is justified on the basis of domestic and foreign research and analysis of the physicochemical properties of the elements. The main criteria of the modifying ability of scandium and its advantages over transition metals are given. The technology of introduction of Al-Sc-ligature into aluminum melt has been developed. The amount of scandium 0.2...0.3 wt.% is optimized. For effective modification, the temperature parameters of the heat-strengthening treatment of the V96Ts1 alloy are proposed.

A homogeneous dispersed structure of blanks with a high complex of mechanical properties was achieved. Scandium is proposed as a microalloying and modifying element of the hgh-strength aluminum alloy V96Ts1. The nature and physical and mechanical properties of Sc were analyzed. The criteria for the properties of Sc as a modifier of Al-alloys have been determined. An analysis of the Al-Sc phase diagram was carried out, on the basis of which the tempering and aging temperatures of the metal were adjusted. Experimental melting of the V96Ts1 alloy in its original state and with the addition of Sc-ligatures was carried out. The modified samples obtained a dispersed structure and an increased level of strength properties.

REFERENCES

1. Ю.В. Мильман, Н.А. Ефимов, Н.П. Захарова, Н.И. Даниленко, А.О. Шаровский. Структура и прочностные характеристики деформируемых сплавов Al-5Mg, легированных скандием, цирконием и ниобием // *Электронная микроскопия и прочность материалов. Серия «Физическое материаловедение, структура и свойства материалов»*. 2015, в. 21, с. 23-29.
2. Y. Oikawa, T. Minami, H. Mayama, K. Tsujii. Preparation of self-organized porous anodic niobium oxide microcones and their surface wettability // *Acta Materialia*. 2009, v. 57, p. 3941-3946.
3. Н.Е. Калинина, А.Е. Калиновская, В.Т. Калинин. Технологические особенности наномодифицирования литейных жаропрочных никелевых сплавов // *Компрессорное и энергетическое машиностроение*. 2003, №1(31), с. 54-56.
4. Патент України на корисну модель №82163, МПК C22C 19/03. *Комплексний модифікатор нікелевих сплавів* / Н.Є. Калініна, А.Є. Калиновська, В.Т. Калінін, З.В. Віліщук, Т.В. Носова. №201300612, Заявл. 17.01.2013; Опубл. 25.07.2013, Бюл. №14.
5. О.Я. Качан, Н.Є. Калініна. *Авіаційно-космічні матеріали і технології.* Запоріжжя: «Мотор Січ», 2009, 385 с.
6. *Диаграммы равновесия двойных металлических систем*: Справочник / Под ред. Н.П. Лякишева. М.: «Машиностроение», 1997, 56 с.
7. N. Saunders, S.Y. Fahrmann. *The Application of CALPHAD Calculations to Ni-based Superalloys. Small In "Superalloys 2000" /* Eds. K.A. Green, T.M. Pollock, and R.D. Kissinger. TMS, Warrendate, 2000, 803 p.; https://www.researchgate.net/publication/271491796_The_application_of_CALPHAD_calculations_to_Ni-based_superalloys
8. N. Kalinina, D. Glushkova, A. Voronkov, A. Sanin, A. Kalinin, T. Nosova, O. Bondarenko. Special features of the phase composition and structure of aluminum alloys modified by refractory nanocompositions // *Functional materials*. 2020, v. 27, N 3, p. 508-512; http://functmaterials.org.ua/contents/27-3/fm273-508.pdf
9. N.E. Kalinina, D.B. Hlushkova, O.D. Hrinchenko, V.T. Kalinin, A.I. Voronkov, L.L. Kostina, I.N. Nikitchenko, T.V. Nosova, A.A. Reznikov. Hardening the input edges of the turbine blades by electricospark alloying // *Problems of Atomic Science and Technology*. 2019, N 2, p. 151-154.
10. K.G. Cooper, J.L. Lydon, M.D. Corre, Z.C. Jones. *Three-Dimensional Printing GRCop-42* (p. 1-9) (Unites States, NASA, Marshall Space Flight Center). Huntsville, AL. NASA/TM-2018-22012, 2019, p. 388-393; https://ntrs.nasa.gov/api/citations/20190001243/downloads/20190001243.pdf
11. P. Gradl, C. Protz, K. Cooper, C. Garcia, D. Ellis, L. Evans. *GRCop-42 Development and Hot-fire Testing using Additive Manufacturing Powder Bed Fusion for Channel-Cooled Combustion Chambers*. Paper presented at 55nd AIAA/SAE/ASEE Joint Propulsion Conference, August 2019. Indianapolis, IN, p. 445-452; https://ntrs.nasa.gov/api/citations/20190030453/downloads/20190030453.pdf

Article received 02.09.2025

ПІДВИЩЕННЯ МЕХАНІЧНИХ ВЛАСТИВОСТЕЙ ВИСОКОМІЦНИХ АЛЮМІНІЄВИХ СПЛАВІВ

Т.В. Носова, С.І. Мамчур

Обґрунтовано вибір скандію для мікролегування і модифікування високоміцних алюмінієвих сплавів. Матеріалом дослідження є високоміцний алюмінієвий сплав В96Ц1 системи Al-Zn-Mg-Cu. Мікролегуючим і модифікуючим елементом обраний скандій. Вивчено діаграму стану Al-Sc, фізико-механічні властивості скандію. Розроблено режими термічної обробки сплаву В96Ц1. Досліджено вплив мікроструктури на механічні властивості модифікованого сплаву. Проведений комплекс досліджень підтвердив мікролегуючу та модифікуючу дію скандію в алюмінієвому розплаві, відпрацьовано технологію введення скандію у розплав, оптимізовано кількість Sc. Встановлено, що технологія введення скандію у розплав і температурно-часових параметрів термічної обробки заготовок дозволила отримати дисперсну структуру і високий комплекс механічних властивостей сплаву В96Ц1, що являє собою практичну цінність роботи.