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Main Characteristics and Future Development of Aluminum Alloys with High Dispersion Ability of Phase of Alloying Elements

Juri A. Gorbunov*
Engineering and Technology Center «SIAL» Ltd
103 Pogranichnikov, Krasnoyarsk, 660111, Russia

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This article present main characteristics of aluminum alloys with high dispersion ability of phase of alloying elements. Examined future development in the field of obtaining heat-resistant and high-strength aluminium alloys, as well as alloys for special purposes.

Keywords: aluminium, microalloying, continious casting, high-temperature strength, mechanical properties.

For semi-finished aluminum alloys produced by traditional methods of semi-continuous casting billets and pressure treatment, potential for significant improvement of physical and mechanical properties to date largely been exhausted. Therefore, special importance attaches new ways to improve the performance characteristics of structural alloys, in particular, through a combination of alloying using not traditional components and increasing the degree of dispersion of all elements of their structure.

The combination of these two exposure approaches on metals properties can be implemented in various ways, including, for example, increasing the doping level by group of transition metals with simultaneous application of high velocity cooling melts (more than 10^3 K/s) during the crystallization. In this case, along with fundamental morphological changes in the metal structure can observe anomalous supersaturated solid solution of transition metals. This factor provides additional opportunities to obtain materials with unique characteristics

The most significant part of research and pilot works of the last decade to achieve high cooling rates during crystallization of aluminum alloys, based on the dispersion melt in various ways, with the subsequent crystallization of received particles in a gaseous medium, an aqueous medium or on a metal base. Hereafter, these particles were heated in an inert atmosphere or in vacuum then were compacted and processed into various kinds of semi-finished products by traditional methods of metal treatment under pressure. In studies of these semi-finished products was established that high cooling rates during the crystallization of molten aluminum, besides the increasing of many mechanical properties semi-finished products, allowed discovering unique opportunities to obtain materials with exclusive physical properties.

* Corresponding author E-mail address: gja@sial-group.ru

On the basis of a great number of researches in this way performed domestic and foreign scientists, were created a number of new, so-called rapidly solidified alloys (including granular alloys) aluminum-based alloys. Some of these alloys have been widely used in the pilot production number of plants. Analysis of published research data of different organizations linked with the data obtained by the author and his colleagues during the work in “All-Russian Research Institute of Aviation Materials” (“VIAM”) and in Research and Development Center of Krasnoyarsk Metallurgical Plant (“KraMZ”), allows to identify the following main features of these alloys.

High-temperature alloy. At the first stage the efforts of Russian scientists were aimed at the creation of alloys characterized by abnormal supersaturation of solid solution by transition metals. In this direction most actively worked domestic scientific schools in the “VIAM headed by Fridlyander I.N. and in the “All-Russian Institute of Light Alloys” (“VILS”) under the guidance of Dobatkin V.I. and Yelagin V.I. They proceed from the fact that the segregation of anomalously supersaturated solid solutions recorded during casting, in the processing of particles rapidly crystallized alloys in the semi-finished products leads to formation of dispersed intermetallic phases which resistant to coagulation to a defined temperature level. It was found that the higher melting temperature of hard-melting components included into the alloy, the higher the heat resistance of the alloy. Based on this principle have been developed weldable alloys 01419 (Al-Mn-Cr-Zr-Ti-V), 01435 (Al-Cr-Zr) and others. Long-term strength for the alloy 01419, for example, is 65-70 MPa, and for alloy 01435 is 60-65 MPa.

Abroad first generation of heat-resistant alloys were created by heterogenization of cast structure used as insoluble additives iron, nickel, cerium, cobalt and other elements (companies “Alcoa”, “Lockheed”, “Pratt and Whitney”, “Allied Signal Inc”. etc.).

At the next stage, both domestic and foreign metallurgists turned to complex alloying heat-resistant alloys. As a result, metallurgists from “VILS” were created 01489 alloy of system Al-Fe-Cr-Zr-Mo, having short-term strength with of 210-240 MPa and foreign metallurgists were created FVS0812 alloy of system Al-Fe-V-Si and a series of alloys of system Al-Fe-Mo.

Comparative analysis of the characteristics of the developed heat-resistant alloys showed that heterogeneous alloys have an advantage under short term operation, under elevated temperatures; and for prolonged operation, under elevated temperatures (up to 250 °C) are more suitable alloys which form the homogeneous structure during casting.

In domestic practice, heat-resistant alloys - the first of rapidly solidified materials, have found practical applications in engineering (including aeronautical engineering). First pilot production of semi-finished products from these alloys were organized in Moscow in the “Plant of Light Alloys”. Semi-finished productsofalloy01419usedin products continuously operating under elevated temperatures (up to 350-400 °C), for example, in heat exchangers, pipe connections, manholes, plugs; 01435 and 01489 alloys used as body parts, launching racks, compressor blades etc.

Practical applications of these materials has shown that the alloy 01419 possesses complete insensitivity to solidification cracks during welding. The strength of weld joint is close to the strength of the base material, which is a consequence of the high stability of the heterogeneous structure of the material. It should be pointed that the depth of corrosion damage of semi-finished products from alloy 01419 during use in aggressive coastal environments in several times lower than any series of aluminum alloy. According to the developers of the material it is associated with higher than billets alloys; passivation properties caused by the formation of solid solutions of transition metal in the aluminum, as well as partly also due to entering of transition metals into the protective oxide film. Th ealloy01435hassimilarcorrosionproperties.

High-strength alloy. During creation of alloys of this group, as well as the development of high-temperature alloys, in the 70-80s, Russian scientists were originally used principles of anomalous supersaturating by transition metals of solid solution based on aluminum. Dobatkin V.I., Yelagin V.I. and Fedorov V.M. was shown that increased strength rapidly solidified alloys of this group in comparison with traditional alloys, obtained by standard technology, is determined by a combination of the two hardening mechanisms:

- Precipitation hardening connected with the release of solid particle reinforcing phases formed by copper, magnesium, zinc and silicon, as the result of quenching and aging deformed semi-finished;
- Precipitation hardening connected with the formation of anomalously supersaturated solid solutions of transition metals in aluminum at high cooling speed and release of aluminides of transition metals during subsequent thermal and deformation treatments.

Additionally, elevated concentration of the transition metals leads to significant increase the temperature of alloy recrystallization and, accordingly, leads to enhance the effect of structural strengthening.

For the first stage of work based on the research results and based on Al-Zn-Mg and Al-Zn-Mg-Cu systems, specialists from “VILS” and “Russian State Technological University” (“RSTU”) were created 01949, 01995, 01996 alloys and others. For the next stage - production development stage of semi-finished products specialists of “VILS”, basic scientific research laboratory of “VIAM” and “KraMZ” were evaluated behavior of these alloys under thermal desorption of grains and under deformation and heat treatments of semi-finished products. For the first time, during compaction of experienced alloys into semi-finished products relative small size and their following deformation, allowed to obtain and to analyze semi-finished products having inconsistent, until that time, the complex of characteristics.

Alloys 01949 and 01995 are the only high-strength alloy that can be welded by argon arc welding. From these alloys by experimental-industrial method were obtained extruded, stamped and rolled semi-finished products for using in a wide range products of responsible engineering. According to their mechanical properties, these alloys are close to well-known B95 and 7075 alloys, but 01949 and 01995 alloys completely have not a tendency to hot cracking during the welding. Alloys have high corrosion resistance, tensile strength of welded joints from these alloys is superior to all the best weldable alloys (tensile strength is 480-550 MPa). The presence of foreign analogues of these alloys is still not known.

Extruded and forged semi-finished products from alloy 01996T1 possess sufficient tensile strength (700-730 MPa) at the level of the other characteristics that are close to B96цT1, but at the same time the corrosion resistance of the alloy 01996T1much higher than for the B96цT1. Verification nature tests of stamped products from 01996T1 alloy in a range of constructions showed their high functional reliability and wide opportunities of applications.

For the organization of industrial production of semi-finished products made from listed granular alloys, “KraMZ” has been developed and started the technology of degasification and compaction large-sized capsules by vertical hydraulic presses. This is the first time in the practice allowed to produce briquettes with diameter of 470×1100 mm for the followed by extrusion into rods with diameter from 10 to 280 mm and forging these rods into plates with size of 80×1100×3500 mm by vertical presses for the followed by hot rolling into sheets. However, during practical applications of industrial technology of treatment large-sized semi-finished product from alloy 01996 was found insufficient stability of structure during prolonged heating over a range of deformation temperatures and high extension appropriate of production of thin-walled semi-finished products.

At this time, foreign specialist more preferred to use alloying aluminum by hard soluble elements such as cobalt and nickel. Entering of cobalt was the result of the formation of dispersed particles during crystallization. These particles allow to connect together detrimental impurities into complex phase $(Co, Fe)_2Al_9$ and increase the fatigue strength and corrosion resistance of semi-finished products. Using this method Laboratory of company «Alcoa» created 7090 and 7091 alloys, and the Production Base (California) started industrial production of workpieces with the weight of 50-160 kg for the followed by production of semi-products from it. Indicators of fracture toughness, fatigue crack propagation velocity, corrosion resistance and other performance characteristics of these alloys were close to the domestic high-strength alloys, but much inferior to them on the strength characteristics.

Combining alloying methods of aluminum alloys using transition metals, which formed anomalously supersaturated solid solutions, and with difficult soluble elements, domestic specialists with participation of the author of this article was developed a group of alloys of aluminum-zinc-magnesium-copper system. The alloys of this system contain the most positive effects of the alloys of the previous generation. The best combination of strength and corrosion resistance in these alloys was achieved by additional alloying using manganese, chromium, zirconium, titanium, cobalt, and nickel.

Alloying by transition metals has the most effective impact on hardening semi-finished products with minimum content or full absence of phase T. This leads to a slight fall in strength properties, but at the same time significantly increasing the characteristics of structural strength. Considering this phenomenon was developed alloy 01959. Considering this phenomenon was developed alloy 01959, semi-finished products made from this alloy are recommended for products with increased resource of critical applications, see Table 1.

As seen from the data presented in the table, the ratio of strength, fatigue and corrosion characteristics of extruded semi-finished products of alloy 01959 T2 significantly surpass all alloys produced by traditional methods of casting ingots and their deformation. Similarly describe large-sized sheets produced by rolling forged plates.

Extruded and rolled semi-finished products from alloy 01969 have almost the same strength characteristics as of alloy 01996, but it has a higher elongation and, most importantly, it has higher structural strength characteristics.

Level of strength properties of hardness and corrosion resistance of semi-finished products of alloy 01969 have an advantage compared with the analogous semi-finished products from ingots. During hot stamping of rods be absent softening alloy unlike rods of alloy В96ц1 that allows using this alloy to produce details, which during of operation take up critical static and dynamic force with a high level of operational reliability. Therefore, semi-finished products from this alloy are recommended for a number of aerospace products.

Concentration of the main alloying elements in the alloy 01979 was increased. This alloy is recommended for engineering and instrumentation products of general purpose, as well as for a single-purpose. For characteristics of the structural strength of this alloy are not applied such highest

Table 1. Averaged data of physical and mechanical properties of semi-finished products produced by extruding high rapidly solidified alloys

Properties of extruded semi-finished products	Alloy identifier, thermal treatment identifier			
	01959T2	01969T1	01979T1 Ø80mm	01979 T1 Ø30mm
Tensile strength, MPa	680	720	780	840
Yield strength, MPa	640	670	760	820
Elongation, δ_{10}, %	10	6	9,5	10
Impact strength, kJ/m^2	200	70		
Endurance strength based on 2x10^6 cycles, MPa - for smooth specimen - for notched specimen	 195 117			
Low-cyclefatiguebasedon2×10^6 cycles at K_t=2,6 σ_{max}=157 MPa	478600			
Depth of grain-boundary corrosion, mm	0,21			
Tendency to layer corrosion, score	3-4	4-6	4,5-5	

requirements, as for semi-finished products for critical application. In relation to the conservation in the alloy structure 01979, up to the latest technological operations, partially supersaturated solid solution of transition metals, semi-finished products have very high strength characteristics. In pilot production this alloy used in the production of bands with cross-section up to 20x300mm, rods with diameter of 10-80mm and profiles. All of these products can be used at defense industry, during of production elements for ring spinning machines and friction units, in electronic devices for various applications, for single-use products, etc.

Highly-modularized alloys with low density. In the 70-es of the last century by the initiative of Fridlyander I.N. aluminum alloys with lithium have been actively used in domestic technology, providing it with a competitive advantage in terms of weight and a number of other characteristics. Therefore 1420 alloy - one of the first domestic materials of this group, had a density of 2.47 g/cm3. The use of this alloy in a number of aircraft designs allowed reducing their weight by 12-15 %. In further research work of "VIAM" and "KraMZ" Basic Scientific Research Laboratory was found that rapidly solidified aluminum alloys containing lithium have the best combination of strength and stiffness than their analogues produced by traditional technological schemes. Used methods of rapid solidification alloys allowed entering more alloying elements than used conventional casting processes and as a result to obtain the proportional distribution of particulate phase components.

The first domestic rapidly solidified alloy with lithium obtained used protective alloying by beryllium is 01429 of Al-Mg-Li system. The fatigue strength and the fracture characteristics of the extruded semi-products from this alloy is for 10-15 % higher than from alloy 1420 which produced by traditional technology. The following modification of this alloy with cipher of 01429y has a higher concentration of anti-crystallizers elements and increased values of strength, hardness and wear resistance. This alloy has found application in domestic technology, at the production of strips, rods and forgings from them. Pilot production of products from this alloy was organized by "KraMZ" with the guaranteed level of tensile strength is more than 520 MPa, yield strength is more than 380

MPa, hardness is more than 140 HB with the elongation is more than 7 % and density is less than 2.47 g/cm^3.

Foreign companies such as “Alcan”, “Lockheed” and others have focused on the development and research of alloys containing lithium up to 4 %.The task of these companies was to increase strength, toughness, corrosion resistance and specific rigidity by 30 %.

Alloys with low linear expansion coefficient. The basis of aluminum alloys with low thermal expansion is the Al-Si system. At high cooling rates in this system alloys are solidified in accordance with the metastable phase diagram, even when content of silicon is up to 35 % it produces eutectic structure and good deformability of the material. Taking this factor, domestic specialists developed a large enough group of aluminum-silicon alloys with the following coefficient of linear expansion $\alpha_{0\text{-}100°C} \times 10^{-6}$ = 13,5-15,5 1/°C.

Under the guidance of Frindlyander I.N. (“VIAM”) were created several ternary alloys of type Sintered Aluminum Alloys (SAA), containing as an additional alloying elements Ni, Fe or Cr. Take into account the characteristics of these alloys it should be noted that the best alloy is SAA-1 having the lowest coefficient of linear expansion (close to steel), and higher ductility. This can be explained more preferred form of Ni-intermetallic in comparison with form of Fe- and Cr- intermetallic. However, elongation of alloys type SAA obtained by powder metallurgy methods, does not exceed 0.6-1.5 % that limit their use in all other areas except tool engineering.

Shmakov Y.V., Litvintsev A.I. and others (“VILS”) developed 01379 alloy containing 17-19 % of silicon, copper, magnesium, and transition metals. This alloy has average strength at room temperature and high strength, hardness and wear resistance, sufficiently low coefficient of linear expansion at temperatures up to 300 °C. The task of further reducing the coefficient of linear expansion was solved by entering in alloy 35-40 % of silicon, during solidary alloying by increased amount of transition elements. The specialists of Dnepropetrovsk Metallurgical Institute offered the most doped alloy with Al-35 % Si-2 % Fe for manufacturing of pistons engines internal combustion with maximum wear resistance and dimensional stability. The specialists of “VIAM” and “KraMZ” Basic Laboratory were developed production technology of rods from this alloy with diameter up to 120mm and forgings from rods for the following application in pistons engines internal combustion. This technology is characterized by high wearing resistance and functional reliability.

Research showed that the operational properties complex of rapidly solidified 01379 and Al-35 % Si-2 % Fe alloys surpass all known piston materials, including Al-12 % Si. Indicators of long-term strength, fatigue strength and wear resistance of alloys 01379 and Al-35 % Si-2 % Fe exceed the corresponding indicators of Al-12 % Si alloy, and also have low values of linear expansion coefficient, providing dimensional stability during operation.

Work on creation of rapidly crystallized alloys and products made therefrom are geared not only to manufacture mechanically assembled structures. Within the development of production technology brazed constructions also was developed method of producing an effective filler material made from hypereutectic silumin (Al - 18-35 % Si) using modifier Al – 1 % Sc or Al – 5 % Ti – 1 % B.

The material is melted and sprayed onto the baffling element in the form of a cylinder with a diameter of 150-160 mm. Then material is pressed at 450 °C into rod with diameter of 8.6 mm and drawn into wire with diameter of 1.2 mm for use as the filler material during laser welding; or roll into band with thickness of 1.2 mm. Such operations are possible with the use of high silicon material (usually fragile) due to the very fine-grained structure obtained during spraying. Compared with eutectic additional elements (Al – 12 % Si) the new filler materials much reduce weld cracking during laser welding of aluminum alloys, such as AA6082 alloy.

Conducting alloys with extra high temperature strength. In the works of specialists from "VILS" and "KraMZ" shown that the most promising alloys for creation of current electricity conductor for flying machine on-board systems are aluminum alloys of rare-earth metals. Dispersed additives of rare-earth metals practically insoluble in aluminum, also at a concentration of 2-3 % it provides a significant increase in strength and heat resistance of semi-finished products without significant influence on the electrical conductivity of materials.

Technological works have shown that the most functional alloy is the 01417 containing about 7 % of rare-earth metals. It has high electrical conductivity (ρ = 0,029-0,031 mc Om m) and can be used in products operating at temperature up to 250 °C. The alloy has high corrosion resistance, good welded and soldered. Alloy properties are almost not change after heat treatment within the temperature range from -60 °C to +250 °C for curing period up to 500 hours.

Specialists of "VIAM" and "KraMZ" Basic Laboratory were developed pilot production of wires from alloy01417 for use in on-board systems of supersonic aircraft. Such application allowed to provide a significant weight advantage as compared with the use of electric conductors based on copper. However, the drawing technology of small diameter wire, which is necessary for production cables, was not stable enough due to frequent breakages (due to the presence of internal defects) and due to not high enough yield ratio. In addition, there were problems with repair wiring from aluminum alloys during maintenance of products. Therefore, at this stage wire of 01417 alloy have not received wide application.

X-ray contrast materials. One of the methods of nondestructive testing of welded joints from aluminum alloys is X-raying cast zone. On the border of this zone is artificially created chemical heterogeneity by using foil material with high X-ray absorption coefficient between the welded parts

As a result of prospecting work performed by "VILS", Research and Manufacturing Association "Composit", "Siberian Federal University Institute of Nonferrous Metals and Material Science" and "KraMZ", as the foil material has been chosen alloy containing 01415 misch metal from aluminum and cerium.

Production of aluminum foil was realized by two- technological schemes. On the first stage (in Laboratory of "Siberian Federal University Institute of Nonferrous Metals and Material Science") was implemented scheme continuous rolling of heated granules from alloy 01415 into bands sized 2x120mm with followed by rolling it into foil. The next stage was development stage of industrial technology containing volume reduction of granules, extrusion of billets into bands sized 5×130mm and followed by cold rolling to final dimension. Using foil from alloy 01415 instead of band from aluminum alloy with silver during nondestructive inspection of flying machines welded joints provided to realization the clear radiopaque picture and excluded using of silver.

The review shows the uniqueness and variety of physical, mechanical and operational factors of alloys with highly reduced structure, as well as the prospects of applying the developments of topics under consideration of various fields of modern industry. However, the technology chosen for the research and development of alloys above groups, namely melt dispersion, thermal desorption, rapidly solidified granules, it volume reduction and followed by treatment into semi-finished products by methods of metal forming, characterized by a number of drawbacks, the main of which are:

– greater labour intensity of processing, low yield ratio of the product and as a result the high cost of produced semi-products.
– difficultly controlled thermal desorption of particle surface of rapidly solidified alloys in different areas of large-sized capsules and granulation surface oxides during volume reduction and deformation of alloys
– insufficiently stability of technology parameters of equipment used at the stage of research and development; and at the stage of experimental-industrial production engineering of semi-finished products.

The consequence of listed disadvantages is not always stable behavior of semi-finished products, as well as it high cost. Based on these reasons, can conclude that in recent years in Russia the activity of works on rapidly solidified alloys has decreased significantly. At the same time, as the search for compromise solutions to resolve some of the above problems have been proposed and explored other approaches.

Micro Alloying melt by transition metals with ultrasonically-actuated during solidification. Specialists of "VILS" under the guidance of Eskin G.I. and Pimenov Y.P. were proposed cost reduction of deformed semi-finished products from aluminum alloy by using as a basis of charging material with silicon the ligature Al-Si, obtained by ecologically clean methods. Scientists have proven that the use of this charge from cheap raw materials during preparation of aluminum alloys containing silicon up to 17-19 % can enhance the effect of the modification, due to the presence of microquantity of macroquantity of active metals in the ligature. The result of using charge with phosphorus-containing ligature and complex treatment with ultrasonic vibrations of melt on the way into casting mold allowed to obtain a homogeneous structure of ingot with primary crystals of silicon sized 20-30 micron. Alloys with such a structure, as well as rapidly solidified alloys are well deforms and provides high-quality of semi-finished products.

As a result of research conducted by the authors with colleagues were developed a series of aluminum-silicon alloys with the following ciphers 01390, 01391 and 01392, and were proposed the piped semi-finished products with diameter up to 200mm for use in oil and gas fields, as well as in other industries.

Continuous casting of billets small diameter in to electromagnetic casting mold and their after-treatment in the wire of different diameters. Author proposed the use of continuous casting billets with sections into electromagnetic mold to obtain aluminum alloys of systems Al-Si and rare-earth metals for semi-finished products with finely divided structure that would not contain deficiencies materials produced by powder diffraction and granular technologies. The proposal was implemented by a group of specialists under the guidance of Professor Timofeev V.N. and Docent Pervukhin M.V. used developed by them the pilot unit.

Effective cooling of the melt Al-12 % Si during crystallization provided production using of equipment for continuously casting of billets with diameter of 12-15 mm and unique combination of mechanical properties. Tensile strength of castings produced by methods of electromagnetic casting is 280-300 MPa and elongation is 18-20 %. For comparison it can be noted that the tensile strength of well modified castings from this alloy, obtained by low-pressure molding does not exceed 170-180 MPa and elongation is up to 10.7 %.

Author in collaboration with professor Sidelnikov S.B. and Kravtsov D.V. using methods of continuously casting billets has been developed an effective technology for producing wire with diameter of 1 ,2-2mm for solder, including extrolling by section mill and cold drawing to finished size. Tests of produced wire during production and maintenance of structural elements for spacecraft showed that technological characteristics and properties of welded joints exceeds domestic analogue, previously produced at "KraMZ", this wire is quite competitive with wire from alloy 4047 European production. Another example of implementation of the proposed process was to obtain by specialists of Metal Treatment under Pressure academic department of "Siberian Federal University Institute of Nonferrous Metals and Material Science" wire from alloy 01417M which free from defects granulated predecessor.

Therefore, extensive materials obtained during development and research of various groups of rapidly crystallized alloys show the production possibility of semi-finished products with a unique correlation of physical and mechanical characteristics. Semi-finished products of all groups of these alloys can and should find wide application in various industries. However, this requires the development of new, more fuel-efficient than the methods of powder and granular metallurgy. However, this requires the development of new, more fuel-efficient than the methods of powder and granular metallurgy, methods for producing compact billets from these alloys milled with disintegrated structure and conservation of congenital effect of structure during processing from incoming workpieces to semi-finished products.

Основные характеристики и перспективы развития сплавов алюминия с высокой дисперсностью фаз легирующих элементов

Ю.А. Горбунов
Инженерно-технологический центр «СИАЛ»
Россия, 660111, Красноярск, ул. Пограничников, 103

В статье представлено описание и даны основные характеристики алюминиевых сплавов с высокой дисперностью фаз легирующих элементов. Рассмотрены перспективы развития и области использования жаропрочных и высокопрочных алюминиевых сплавов, а также сплавов специального назначения.

Ключевые слова: алюминий, микролегирование, непрерывное литье, жаропрочность, механические свойства.