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PRINCIPLES OF CREEP-RESISTANT ALUMINUM ALLOYS DEVELOPMENT

The work is devoted to monitoring and studying the principles of obtaining creep-resistant Al-based alloys. It is shown that aluminum alloys are constantly expanding their application fields. At the same time, the requirements for a number of aluminum alloys are also growing, which determines their wider use in extreme conditions and, in particular, at elevated temperatures. Examples of parts and details, made of such materials, are used in car engines and special equipment, turbine impellers, parts of heat exchangers and collectors, fittings, cladding elements, and casing parts for aviation and space purposes, etc. Development and production of new creep-resistant materials on the basis of aluminum with the increased level of operational characteristics demands detailed studying of mechanisms and ways maintenance of their optimum structural-phase conditions and finding of effective ways to produce them. The presented work considers the existing methods and principles of efficient creep-resistant aluminum alloys production, among which the greatest attention is paid to the principles of production of cast alloys, as the most profitable in terms of mass production and economic efficiency. It was shown that the main principles of achieving this goal include: the use of alloying elements (Cr, Mn, Fe, Co, Ni, Cu) and modifiers (Ti, Zr, Mo, Hf), which will promote the formation of stable insoluble phases with low diffusion activity and noticeable cubic or close to cubic morphology in a metal matrix of the alloy; Creation of eutectic alloys, including silicon-free compositions, which would consist a large proportion of high-temperature phases with favorable morphology; The temperature of the eutectic transformation should be as high as possible; Introduction of technological principles of melts casting and preparation, that are able to effectively grind the structure of the alloy and increase the solubility of insoluble components by creating specific thermodynamic conditions.

Keywords: aluminum alloys, heat-resistant aluminum alloys, principles of alloying, new cast materials, materials for work in extreme conditions.

Introduction

Aluminum and its alloys have a set of physical and mechanical properties, which determine the possibility of their widespread use in almost all industries - in aviation, engineering, shipbuilding and instrumentation, space, energy, and food industries, as well as in many households. In the EU, aluminum products are used in the transport industry (42%), in construction (23%), as packaging material (17%), in technological equipment and electrical engineering (12%), and in consumer durables (6%) [1, 2]. The simultaneous combination of low density, high specific strength, corrosion resistance,

manufacturability, and the possibility of aluminum and its alloys efficient recycling, makes these materials extremely economically and technologically attractive and promising. There are more than a hundred aluminum alloys in the world, but the growing needs and requirements of modern technology stimulate the constant development of new compositions with a high level of performance [3–5].

About 30% of all Al-based alloys belong to a class of casting alloys, which are sometimes alternatives to some iron-based and some titanium alloys in new techniques. Modern trends and problems of industry and materials science show that the most important tasks for the development of aluminum casting alloys are to increase their strength, ductility, wear resistance, and especially – the stability of mechanical properties at elevated temperatures and under extreme operating conditions. They find a wide application field in the production of pistons, cylinder heads, heat collectors and heat exchanger parts, aircrafts casing and covering, and turbine impellers, and many others. Such decisions are due to the desire to reduce the weight of equipment, its cost and reduce emissions [6–15].

The new requirements for car engine parts are based on the general principles of increasing working life, power, efficiency, and reducing harmful emissions into the atmosphere. Almost the most important task, in this case, is to increase the operating temperatures of the engine parts materials while maintaining the required high mechanical characteristics under both normal and operating conditions. Thus, the standard Al–Si–Cu, Al–Si–Cu–Mg, Al–Si–Cu–Mn, and Al–Cu–Mn alloys which are widely used worldwide for the production of internal combustion engine parts, lose relevance due to the loss of mechanical properties at operating temperatures above 250 °C [9–14]. Heat-resistant aluminum alloys in the aerospace industry are often represented by compositions with relatively high plasticity, but lower demands of working temperatures at a level of about 150 °C. Due to rising temperature demands, it is necessary to create alloys not only with moderate and high creep resistance but also with sufficient plasticity. Improving the performance of such parts requires the creation of new compositions of aluminum alloys with more suitable and improved structural and phase characteristics compared to already known alloys [16–18].

Some modern tendencies

The significant relevance of the development of heat-resistant aluminum alloys is all the more noticeable due to the efforts of well-known researchers who create aluminum alloys with nanostructured structure and complex chemical and phase composition [17]. For example, alloys with a high degree of amorphousness were obtained on the basis of the Al–Fe–Cr–Mo–Ti–Co system, which had a strength of 364 MPa and 520 MPa at 300 °C and 200 °C, respectively. It should be noted that the production of finished products from such alloys involves the use of powder metallurgy technologies and is quite expensive, but, according to the authors, remains fully justified.

Another trend in the development of heat-resistant aluminum alloys with a more classical approach is the creation of compositions based on eutectic systems with nickel and cerium. Such alloys have a significantly higher cost than classical Al–Si and Al–Si–Cu alloys due to the high content of cerium (about 10% wt.) and require technological solutions to obtain products that would provide nanostructured or amorphous metal structure to achieve the highest set of mechanical properties [18–20].

A new and so far little-studied method of obtaining heat-resistant aluminum alloys can be considered on the creation of aluminum matrix composites reinforced with refractory and insoluble particles. The processes of creating aluminum alloys reinforced with inclusions of B_4C , Si_3N_4 , BN, TiC, and AlB_2 in Al–Cu and Al–Si alloys are described in [21–23]. However, such products are also characterized by high cost, the complexity of production and they also have low recyclability, which significantly slows down their widespread introduction [23].

Another solution is based on the development of new complex-alloyed compositions of systems such as Al–Cu–Mn–Fe–Ni, Al–Ni–Mn–Fe–Zr, Al–Ni–Mn–Fe–Si–Zr, and some others [6, 7, 24, 25]. This type of alloy is characterized by a large number of stable primary phases with fine structure, which are able to provide a high level of mechanical properties

at room and elevated temperatures up to 250–350 °C. However, to achieve the optimal structural-phase composition, such alloys require specific methods of crystallization by spraying, semi-solid pressing, extrusion, and subsequent molding of finished products at later stages of production.

From the analysis of heat-resistant aluminum alloys, the current state of production existing problems follows the need to improve existing and develop new casting creep-resistant alloys that would have improved structural and phase characteristics and would be highly technological to obtain finished products from the shortest and most cost-effective technological cycle.

Principles and mechanisms of developing creep resistant cast aluminum alloys

Among the standard aluminum alloys, the systems that have the highest creep resistance are Al–Si–Ni, Al–Cu, Al–Cu–Mn, Al–Si, Al–Si–Cu, and several similar systems. Operating temperatures of these alloys are usually deposited in the range of 150–250 °C [11, 18] and they cannot be increased within the principles of classical doping of this type of composition. A fairly common solution to increase the heat resistance of aluminum alloys is the modification and microalloying of existing compositions with transition metals, among which the most commonly used are Ti, Zr, Cr, Fe, Ni, V, Co, and Ce [18–20, 24, 25].

In works [26, 27] it is shown, that the development of creep-resistant cast aluminum alloys is based mainly on the principles of alloying and consists of creating compositions that are able to simultaneously combine the next features:

1. Aluminum matrix alloyed with transition metals, which have a significant (more than 0,1 wt.%) solubility and are able to provide a sufficiently high strength of the alloy at room temperature due to the formation of fine stable intermetallic phases. Such elements include Zr, Mn, Cr, Ti, and Sc.

2. Eutectic phase, which has a certain content of Ni, Fe, Ce, or other low-soluble in aluminum transition metals, capable of forming dispersed intermetallics. In this case, the eutectic has to provide a high level of creep resistance and heat resistance and not have a significant negative impact on the mechanical properties of the alloy under normal conditions.

3. Minimizing a crystallization interval to ensure the maximum level of casting properties, reduce hot brittleness and achieve the dispersed structure of the phases of the eutectic component.

4. Maximizing solidus to obtain the high-temperature stability of the alloy and potentially to increase its creep resistance.

Additional criteria for increasing the creep resistance of aluminum alloys is alloying with elements that simultaneously strengthen the interatomic bonds and do not strongly distort the crystal lattice. Such elements include those that correspond to the dimensional principle of Dankov-Konabievsky, as well as those that form with aluminum coherently separated from its crystal lattice phase. Most of the elements, that are important for aluminum alloying (Cu, Li, Mg, Si, etc.) meet these conditions, but their strengthening role at elevated temperatures (> 170... 250 °C) is limited due to a marked increase in atoms diffusion mobility and alternating dissolution and separation from the aluminum matrix [16]. As a result, there is simultaneous coagulation of the reinforcing phases, increasing the mobility of dislocations, elevated ductility, and reducing the strength of the alloy [11, 18].

In [16], a number of mechanisms for increasing the creep resistance of alloys are presented and explained. Their essence is mainly aimed at the implementation of conditions for reducing the mobility of dislocations and inhibiting recrystallization at elevated temperatures. This approach is provided by the formation of stable insoluble intermetallic phases, which mostly have Al_3Me stoichiometry. It is also noted in the paper that along with the uniform distribution of dispersed intermetallics, their relatively large sizes also have a positive effect. Such parameters cause low diffusion activity with the simultaneous formation of noticeable and effective obstacles to the movement of dislocations under loads at elevated temperatures.

The most famous and perfect creep-resistant materials of nowadays, which can be

taken as an example, are nickel «superalloys», the high characteristics complex of which are determined by structural and phase features. The basis of the nickel-based superalloy is Ni_3Al intermetallic with an ordered L1_2 -type crystalline structure embedded in a face-centered cubic nickel lattice. This type of lattice is considered to be more heat-resistant due to the high packing density. By analogy with superalloys, aluminum also has an FCC lattice and is able to form Al_3Me type intermetallics with cubic or tetragonal crystal structures among a number of metals, that would correspond to the crystal structure of the base metal and perform the mechanisms to increase creep resistance. In this case, aluminum alloys require complex alloying, which will ensure the simultaneous formation of more different in size and function intermetallic phases and reduce the degree of tetragonality of some of them, which, in turn, may increase strength and plasticity [16, 28].

The theoretical maximum of aluminum alloys high-temperature strength is at the level of 425°C ($0.75 T_{\text{melting}}$). In attempts to approach these indicators, researchers pay special attention to the mechanisms of improving mechanical properties due to reinforcing emissions or inclusions and their stability under operating conditions. The implementation of such mechanisms is explained by the fact that some elements, having low diffusion activity in aluminum, form primary hardening phases and dispersed allocations of the Al_3Me type with a cubic lattice L1_2 , or tetragonal DO_{22} . When elements such as Cr, Mn, Fe, Co, Ni, Cu and Zn, are added to the alloys, it is possible to reduce the degree of tetragonality of some reinforcing phases, or even to transform them into cubic phases of L1_2 type of high symmetry [16, 29, 30].

An important feature in increasing both normal and high-temperature strength is the implementation of the Orowan mechanism, which consists of enveloping stable phases by dislocations and creating dislocation loops around them, in contrast to more common mechanisms of another phase particles cutting by dislocation or creating mobile atmospheric dislocations around impurities or diffusion-active strengthening phases. For the successful implementation of the Orowan mechanism, a necessary condition is not the too close location of inclusions, their temperature stability, as well as micron and submicron sizes [31–33].

At the structural level, an important aspect of increasing the creep resistance of aluminum alloys is also the heterogeneity of the structure and the presence of intermetallic compounds with transition metals: Al_6Mn , Al_7Cr , Al_9FeNi , $\text{Al}_{12}\text{Mn}_2\text{Cu}$, $\text{Al}_6\text{Cu}_3\text{Ni}$, and some others. These phases are stable at elevated temperatures, do not interact with solid solutions and, as a result, are not prone to coagulation. Accordingly, such intermetallics will not interfere with the movement of dislocations by the above-mentioned Orowan mechanism, provided that they are small in size and evenly distributed. It should also be noted that these intermetallics are mainly part of eutectics, so a positive effect from them is expected under the conditions of the fine-crystalline structure of alloys, sufficient doping of solid solution based on aluminum, uniform distribution of the eutectic, and minimum size of its components [18, 30].

If we talk about the creation of cast heat-resistant alloys based on aluminum, it is necessary to understand some features related to the provision of important technological features: the alloy must be based on a eutectic system, have a narrow crystallization interval, and low coefficient of thermal expansion. These conditions also depend on the chemical composition, so the components of the alloy should be selected so as to ensure the optimal combination of the above requirements and recommendations [34].

Conclusions

Considering the most effective approaches to solving the problem of increasing the creep resistance of aluminum alloys, we can identify the main ideas and directions of their implementation:

- The use of alloying elements (Cr, Mn, Fe, Co, Ni, Cu) and modifiers (Ti, Zr, Mo, Hf) that would promote the formation in the alloy matrix of stable insoluble hardening phases with low diffusion activity and appreciable cubic or close-to-cubic morphology
- Changing the composition of the eutectic so that it included a large proportion of

high-temperature phases of favorable morphology. The temperature of the eutectic transformation should be as high as possible.

– Creation of eutectic silicon-free alloys, the eutectic of which would include thermally stable and high-temperature, in relation to aluminum, phases of favorable morphology.

– Implementation of melt processing and application of casting technological principles, which are able to effectively grind the structure of the alloy and increase the solubility of insoluble hardener components by creating specific thermodynamic conditions.

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ПРИНЦИПИ ОДЕРЖАННЯ ЖАРОМІЦНИХ АЛЮМІНІЄВИХ СПЛАВІВ

Роботу присвячено моніторингу та вивченню принципів одержання жароміцних сплавів на основі алюмінію. Показано, що алюмінієві сплави постійно розширюють області свого застосування. Одночасно з цим, вимоги, які висуваються до ряду алюмінієвих сплавів також зростають та вимагають їх більш широкого використання в екстремальних умовах і, зокрема, при підвищених температурах. Прикладами деталей з такого роду матеріалів є деталі двигунів автомобілів та спеціальної техніки, імпелери турбін, деталі теплообмінників та колекторів, арматури, елементів обшивки та корпусних деталей авіаційного та космічного призначення, тощо. Розробка та виробництво нових жароміцних матеріалів на основі алюмінію з підвищеним рівнем експлуатаційних характеристик вимагає детального вивчення механізмів та способів забезпечення в них оптимального структурно-фазового складу та знаходження ефективних

Нові литі матеріали

способів виробництва. В роботі розглянуто існуючі методи та принципи ефективного одержання жароміцних алюмінієвих сплавів, серед яких найбільшу увагу приділено принципам одержання ливарних сплавів, як найбільш вигідних з точки зору масового виробництва та економічної ефективності. Показано, що до основних принципів досягнення вказаної мети можна віднести: використання легуючих елементів (Cr, Mn, Fe, Co, Ni, Cu) та модифікаторів (Ti, Zr, Mo, Hf), які сприятимуть утворенню в матриці сплаву стабільних нерозчинних фаз з низькою дифузійною активністю та помітною кубічною або близькою до кубічної морфологією; Створення евтектичних сплавів, в тому числі без кремнієвих, які б включала велику частку високотемпературних фаз сприятливої морфології; Температура евтектичного перетворення при цьому повинна бути якомога більшою; Впровадження технологічних принципів приготування розплавів та лиття, які здатні ефективно подрібнювати структуру сплаву та підвищувати розчинність нерозчинних компонентів шляхом створення специфічних термодинамічних умов.

Ключові слова: алюмінієві сплави, жароміцні алюмінієві сплави, принципи легування, нові литі матеріали, матеріали для роботи в екстремальних умовах.

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