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ANALYSIS OF EQUIPMENT FOR OBTAINING A HIGH-STRENGTH HEAT-RESISTANT ALLOY WITH REDUCED DENSITY IN LABORATORY CONDITIONS

Abstract.*The work presents a systematic analysis of modern electrothermal equipment used to obtain high-strength heat-resistant nickel-based alloys with reduced density in research laboratory conditions. The relevance of the study is due to the needs of the aviation and energy industries for materials capable of operating at high temperatures, cyclic loads and in aggressive environments while simultaneously reducing the mass characteristics of parts. A comparative assessment of electric arc furnaces, vacuum arc and electroslag remelting installations, vacuum induction and electron beam systems has been carried out from the standpoint of metal purity, chemical composition stability, the possibility of precise alloying and suitability for use in laboratory conditions. It has been established that laboratory arc furnaces are appropriate for the initial development of alloy compositions, while electron beam installations are effective for obtaining ultrapure materials, but have significant economic limitations. It is shown that vacuum induction melting provides an optimal balance between the depth of refining, the accuracy of the introduction of alloying elements, the homogeneity of the structure and energy efficiency. Criteria for selecting laboratory equipment for the synthesis of new generation heat-resistant alloys are formulated, taking into account technological and infrastructural limitations. The results obtained can be used in the creation of mobile laboratory complexes for the research and development of new heat-resistant materials.*

Keywords: *heat-resistant alloys, nickel alloys, vacuum arc remelting, electron beam melting, vacuum induction melting*

Statement of the Problem

A key priority of modern aircraft engineering is to increase the service life of critical components while simultaneously reducing their inertial and mass characteristics. In this context, the specific gravity of a gas turbine engine serves as a

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fundamental parameter that links structural design with performance optimization. Further improvements require the development of advanced materials that can reliably operate under combined variable dynamic loads, high-frequency cyclic stresses, and significant thermal effects associated with extreme temperature conditions and the interaction of high-speed gas flows with the surface of the component [1].

A significant obstacle to the creation of new heat-resistant alloys is that due to the rapid development of technologies, the use of "classical" nickel-based alloys in today's realities is irrelevant. For example, in the aircraft industry, nickel-based heat-resistant alloys have reached their ceiling of capabilities, which is caused by working in conditions of achieving 85% of the temperature solidus [2, 3].

There are several ways to increase the heat resistance of parts. The main ones include optimizing the chemical composition of nickel alloys by predicting the specified characteristics using numerical methods [4-6] and using single-crystal structures in the manufacture of critical parts operating in extreme temperatures [7]. The first method involves alloying heat-resistant alloys with transition metals such as molybdenum, tungsten, and tantalum. In order to create heat-resistant alloys of the V generation, technological processes for additional economical alloying with elements such as rhenium and ruthenium are being developed [8, 9]. The exclusion of carbon from the alloy composition allows you to increase the solidus temperature to 1360 °C. This is an advantage of single-crystal blades of aircraft turbines, in which, due to the absence of high-angle grain boundaries, it is possible to exclude hafnium and carbon from the alloy. Also, minimization of carbon in the alloy composition is possible due to atmosphere-free melting.

In this regard, there is a need to conduct a comprehensive system analysis of existing technological solutions from the point of view of their functional capabilities for obtaining experimental heat-resistant nickel-based alloys of the V generation in a research laboratory. The organization of a research laboratory in conditions of military aggression imposes certain restrictions. Such restrictions include, first of all, the available area for placing equipment, as well as the permissible installed electrical connection capacity. Therefore, the scientific and practical task of the study is to substantiate the selection criteria and determine the most optimal type of technological equipment that will ensure the production of experimental alloys with a given set of physical, mechanical and operational characteristics in laboratory production.

Analysis of recent research and publications

The problem of obtaining high-strength heat-resistant alloys with reduced density requires the use of precision equipment capable of ensuring high purity of the metal and precise control of melting parameters. Modern foundry equipment for metallurgical research in the manufacture of precision alloys is represented by a wide range of nomenclature units - from classic arc furnaces to complex electron-beam installations. The main equipment for smelting heat-resistant alloys based on nickel is equipment that operates on the principle of converting electrical energy into thermal energy. The main equipment in this direction is electric arc furnaces, the basic principles of which were laid down at the beginning of the 20th century. Despite the more than 125-year history since the creation of the first electric arc furnace, their designs are constantly being improved. In the works [10], modern aspects of steelmaking in electric arc furnaces are considered in detail, while Maia T. A. C. and Onofri V. C. D focus on the analysis of electrical furnace-ladle systems [11]. The issue of designing and building arc furnaces specifically for metallurgical and semiconductor research is highlighted in [12], which is critically important for the creation of research laboratories.

To obtain alloys with special properties, in particular heat-resistant ones, the use of vacuum is key. The historical and technical basis of electric vacuum furnaces was laid in the early works of Arsem W. C., and the development of vacuum-arc remelting (VAR) methods with a consumable electrode is described in the studies of Gruber H. [13, 14]. Modern technologies for smelting zirconium alloy ingots by the VAR method confirm the possibility of using this approach to obtain high-purity materials [15].

Electroslag remelting furnaces are an important equipment in the smelting of precision alloys [16]. The features of melting heat-resistant alloys with reduced density in chamber electroslag furnaces are devoted to separate works [17, 18], in which a comparative physicochemical analysis of electroslag remelting with a consumable electrode and refining with liquid metal was carried out.

The most common equipment for creating experimental grades of heat-resistant steels in laboratory conditions is equipment that works due to induction methods of melting metals. The works of Saunders C. consider the use of vacuum induction electron-beam furnaces for engineering tasks of creating innovative alloys [19]. Particular attention is drawn to the possibility of purifying alloys with hydrogen in vacuum induction furnaces to achieve ultra-high purity [20]. Research into the issue of energy balance during metal melting in induction and arc furnaces [21] indicates the prospects of vacuum arc furnaces for creating a laboratory complex of equipment for studying the processes of creating the latest heat-resistant alloys. Separately, it is necessary to highlight the use of centrifugal induction furnaces for casting titanium alloys, which allows obtaining complex parts with high accuracy [22], which is an additional advantage when creating single-crystal compounds.

Separately, it is worth paying attention to the equipment, the principle of which is based on electron beam technologies (EB). For example, using the processing of zirconium alloys, a team of scientists in [23] considered electron beam remelting furnaces as an effective tool for processing refractory waste and microfabrication. Despite the high cost of the process, Matsui S. proves the possibility of using such equipment in the field of electron beam microprocessing [24]. Despite the wide coverage in open access sources of industrial installations and individual methods of remelting refractory alloys, there is still a need for a comprehensive analysis to develop the optimal configuration of highly mobile laboratory equipment for the creation and study of the properties of high-strength refractory alloys based on nickel.

Purpose of the Study

The purpose of the study is to conduct a comparative analysis of modern electrothermal equipment to select the optimal technological scheme for smelting high-strength heat-resistant alloys with reduced density in laboratory conditions, which will ensure high purity of the metal and stability of its physicochemical properties.

Statement of the main research material

Analysis of open sources of scientific and technical information allows us to identify the following equipment that can be used in the creation of innovative heat-resistant alloys:

- electric arc furnace (EAF);
- vacuum arc remelting furnace (VAR);

- electroslag remelting furnace (ESR);
- vacuum induction furnace (VIM), which also includes centrifugal casting induction furnaces;
- electron beam installation (EB).

Within the framework of the conducted study, the disadvantages and advantages of each of the groups of proposed equipment were highlighted, which are given in Table 1. According to the analysis of the ordered advantages and disadvantages, three groups of equipment can be distinguished as the most promising for obtaining heat-resistant alloys with reduced density in laboratory conditions:

- laboratory arc furnaces - for initial development of the recipe of small samples of refractory components;

– vacuum induction machines (VIM) – due to the possibility of precise control of chemical composition and deep refining, as well as the possibility of creating single-crystal systems;

– for the case of obtaining ultra-pure alloys or processing specific raw materials (scrap), electron beam systems are best suited.

Therefore, the main emphasis of further research was shifted to these three groups of equipment. The designs of electric arc furnaces (Fig.1) have been known since the beginning of the last century and are reliable and predictable in operation. The technological processes of smelting alloys in electric arc furnaces are quite simple and well-established in organizational terms. However, despite the high temperature of the arc, which allows working with refractory metals, this method has the following limitations for the development of new alloys with reduced density:

the electric arc creates a zone of extremely high temperatures at the point of contact, which leads to the evaporation of light alloying elements (Al, Mg, Li), which must be introduced into the melt when creating heat-resistant alloys with low density [10, 25];

difficulties with homogenization – in arc furnaces there is no intensive electrodynamic mixing, typical for induction systems, which often leads to chemical inhomogeneity of the ingot (liquefaction) in small volumes [21];

contamination with electrode material, which is critical in creating heat-resistant alloys of the V generation [14];

vacuum arc remelting (VAR) has special limitations in preparation for melting, as it requires the preliminary manufacture of a consumable electrode of a certain shape, which significantly complicates the process of creating new experimental alloys in laboratory conditions [14].

Table 1

Analysis of the advantages and disadvantages of electrothermal equipment for the production of heat-resistant alloys

Equipment type	Main purpose and features	Benefits for research	Limitation
Electric arc furnace (EAF)	Melting of the charge using an electric arc.	Ability to work with refractory metals, flexibility in system configuration.	Difficulty in controlling cleanliness without vacuum, high energy consumption.
Vacuum arc remelting (VAR)	Remelting of the consumable electrode in a vacuum.	High degree of purification from gases, obtaining dense ingots of zirconium and other alloys.	The need for a pre-fabricated electrode, the cyclical nature of the process.
Electroslag remelting (ESR)	Refining the metal through a layer of active slag.	Effective removal of non-metallic inclusions, possibility of melting titanium alloys.	High thermal inertia, complexity of implementation on a micro-scale.
Vacuum induction furnace (VIM)	Heating of metal by induction currents in a vacuum chamber.	Possibility of precise alloying, hydrogen refining, and obtaining ultra-high purity alloys.	Possibility of precise alloying, hydrogen refining, and obtaining ultra-high purity alloys.
Electron beam installation (EB)	Melting by a directed electron flow in a deep vacuum.	The highest level of vacuum, the possibility of scrap processing, precision micromachining.	High cost of equipment, complexity of operation.
Centrifugal induction furnace	Combining induction heating with centrifugal casting.	Obtaining high-precision shaped castings.	Limitations on the geometry and mass of castings.

Figure 1 – Model of an electric arc furnace with a rolling hearth in the laboratory of the Department of Metallurgical Equipment of Zaporizhzhia National University

Although electron beam (EB) technologies are considered as an effective tool for the processing of refractory waste [23, 24], there are a number of insurmountable obstacles that significantly limit their use within a small research laboratory with little funding, namely:

- deep vacuum in combination with high beam energy causes intensive evaporation of metals with high vapor pressure, such as chromium and aluminum [19]. This leads to an increase in the cost of manufacturing alloys with reduced density in such installations;
- creation of an electron beam installation requires complex beam focusing systems, high-voltage power supplies and continuous service, which is economically impractical in a small laboratory [19, 23, 24].
- due to selective evaporation of elements under the beam, the final chemical composition of the ingot may differ significantly from the calculated one, which requires several iterations of experiments and cost analyses [23].
- most laboratory EB systems are focused on microprocessing or scrap refining, rather than on the synthesis of multicomponent alloys with precise dosage of alloying elements [23].

The designs of vacuum induction furnaces (Fig.2) satisfy the basic requirements for minimizing the occupied area and relatively economical energy consumption. The advantages of vacuum induction furnaces include:

- high purity and refining of the metal - the melting process in a deep vacuum provides effective degassing of the melt (removal of nitrogen and oxygen), which is critical for heat-resistant alloys. As noted in studies [20], the use of hydrogen refining in induction furnaces allows for the production of ultra-high purity alloys, which directly affects the indicators of long-term strength and plasticity of the material.
- unlike arc furnaces, where uncontrolled burnout of alloying elements in the arc zone is possible, induction heating ensures composition stability. This allows the introduction of light alloying elements (for example, aluminum or lithium) to reduce the density of the alloy with high dosing accuracy [27-29].
- electrodynamic forces arising in the induction furnace ensure natural mixing of the liquid metal. This guarantees homogeneity (uniformity) of the chemical composition throughout the volume of the sample, which is especially important when developing new alloying systems on a laboratory scale;
- allow for precise control of the melt overheating temperature and holding time, which is necessary for complete dissolution of refractory components and formation of the optimal primary structure of the ingot.
- the design of modern laboratory induction furnaces often allows for the integration of centrifugal casting systems [22], which makes it possible not only to obtain an alloy, but also to manufacture prototypes of complex shape from it for further mechanical testing.

Figure 2 – Vacuum induction furnace of the company Zhuzhou Hanhe Industrial Equipment Co., Ltd. [26]

Thus, vacuum induction melting is the most rational method for laboratory research of high-strength heat-resistant alloys with reduced density, since it provides the best balance between material purity, alloying accuracy and the ability to control the structure of the future alloy. But it is worth noting that in the event of military aggression, there are somewhat limited opportunities for the delivery of foreign equipment. Therefore, an important technical issue arises of developing highly mobile laboratory complexes with the possibility of their reproduction with a minimum fleet of mechanical equipment and using the technological capabilities of domestic enterprises.

Conclusions. Thanks to the research, the criteria for selecting laboratory equipment for the synthesis of multicomponent systems based on nickel have been generalized, taking into account the specifics of introducing light alloying elements to reduce the specific gravity of the heat-resistant alloy. The relationship between the design features of vacuum-induction systems and the possibility of implementing hydrogen refining in micro-volumes of the melt to obtain heat-resistant structures has been established. The use of induction heating methods as the most effective way to minimize liquation heterogeneity when obtaining high-strength heat-resistant light alloys in laboratory conditions has been substantiated.

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АНАЛІЗ ОБЛАДНАННЯ ДЛЯ ОТРИМАННЯ В ЛАБОРАТОРНИХ УМОВАХ ВИСОКОМІЦНОГО ЖАРОСТІЙКОГО СПЛАВУ ЗІ ЗНИЖЕНОЮ ЩІЛЬНІСТЮ

Анотація. *Сучасний розвиток авіаційної та енергетичної техніки обумовлює зростання вимог до матеріалів, що працюють в умовах високих температур, складного напружено-деформованого стану та інтенсивних термоциклічних* *навантажень. Особливої актуальності набуває створення високоміцних жаростійких сплавів на основі нікелю зі зниженою щільністю, що дозволяє одночасно підвищувати ресурс відповідальних деталей та зменшувати масу конструкцій. Водночас традиційні нікелеві жаростійкі сплави наближаються до межі своїх експлуатаційних можливостей, що зумовлює необхідність розробки нових багатокомпонентних систем легування та вдосконалення технологій їх отримання.*

Метою роботи є проведення комплексного порівняльного аналізу сучасного електротермічного обладнання для вибору оптимальної технологічної схеми лабораторного отримання експериментальних жаростійких сплавів зі зниженою щільністю. У роботі розглянуто особливості застосування електродугових печей, установок вакуумно-дугового переплаву, електрошлакового переплаву, вакуумно-індукційних та електронно-променевих систем з урахуванням їх технологічних можливостей, енергетичних характеристик, рівня вакууму, стабільності хімічного складу та можливостей рафінування металу.

Показано, що електродугові печі доцільні для первинного відпрацювання рецептур сплавів та роботи з тугоплавкими компонентами, проте характеризуються обмеженими можливостями контролю чистоти металу. Установки вакуумно-дугового та електрошлакового переплаву забезпечують високий рівень очищення металу, однак мають технологічні обмеження для швидкого створення нових експериментальних композицій у лабораторних умовах. Електронно-променеві технології забезпечують надвисоку чистоту металу, але характеризуються високою вартістю та складністю експлуатації.

Встановлено, що найбільш раціональним рішенням для лабораторного синтезу багатокомпонентних жаростійких сплавів є вакуумно-індукційне плавлення, яке забезпечує ефективну дегазацію, високу точність легування, гомогенізацію розплаву та можливість отримання зливків із прогнозованою структурою. Сформульовано критерії вибору лабораторного обладнання з урахуванням обмежень виробничої площі, енергоспоживання та доступності технологічної інфраструктури. Отримані результати можуть бути використані при створенні мобільних лабораторних комплексів для дослідження та розробки нових жаростійких матеріалів.

Ключові слова: *жаростійкі сплави, нікелеві сплави, вакуумно-дуговий переплав, електронно-променеве плавлення, вакуумно-індукційне плавлення*

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