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A review of research on high-entropy alloys, its properties, methods of creation and application

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ABSTRACT

Introduction. The paper discusses the prospects for studying high-entropy alloys (*HEA*), metal materials with unique properties. The study of high-entropy alloys is an urgent area of research in connection with its properties, environmental sustainability, economic benefits and technological potential. *HEA* are of interest to researchers due to its stability, strength, corrosion resistance and other characteristics, which makes it promising for use in the aerospace industry, automotive, medicine and microelectronics. Thus, *HEA* research contributes to the development of new materials and technological progress, providing opportunities for creating innovative products and improving existing solutions. To effectively use the potential of high-entropy alloys, research is required in a number of areas. First, it is necessary to improve the production technology of such alloys and develop new methods for obtaining *HEA* with improved characteristics and reduced cost. Secondly, it is necessary to establish the basic principles of operation of high-entropy alloys and to study the mechanisms influencing its properties. It is also necessary to develop new alloys with specified properties and conduct experiments and computer simulations to optimize the characteristics of the alloys and determine the best compositions. **The purpose of the work** is to study developments in the field of high-entropy alloys and conduct a comparative analysis of published studies on improving the properties of high-entropy alloys. **The research method** is a review and analysis based on developments mainly for 2020-2024, which were carried out by domestic and foreign scientists. The paper discusses the prospects for the study of high-entropy alloys, materials with a wide range of applications in various industries. The paper presents the results of research, mainly for 2020-2024. The main properties of high-entropy alloys are described, such as high strength, corrosion resistance, fatigue properties, plasticity and deformability, thermal stability, electrical conductivity and magnetic properties, as well as the possibility of creating alloys with specified characteristics. The most common methods of changing the properties of alloys have been identified. The directions of further development of research in this area are considered. **Results and discussion:** a literature review shows that developments and research are carried out on all possible properties of *HEA*, but most of it is devoted to corrosion-resisting properties and thermal stability. Of the methods used in high-entropy alloys, the most common and universal can be considered the alloying of high-entropy alloys with other metals. Studies also confirm that alloying metals are selected depending on its characteristic properties. The number of scientific works also confirms the relevance of this topic and the need for its study. The authors noted that future studies on the fatigue properties of high-entropy alloys, as well as the properties of alloys under the influence of magnetic and electric fields are the most interesting.

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Introduction

The study of high-entropy alloys (*HEAs*) began relatively recently, in the early 21st century. Its investigation is driven by interest in creating new materials with unusual properties and potential for various applications.

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HEAs were proposed and studied in the early 2000s by a group of scientists led by Professor *J. W. Yeh* from the National Tsing Hua University in Taiwan. They published their research findings in journals in 2004 [1].

HEAs represent a class of materials where five or more distinct elements are mixed in equal or near-equal proportions [2]. This allows for the formation of new types of crystal structures and phases, including unconventional crystalline structures, amorphous regions, and other forms of atomic organization, which may exhibit unique properties. Modern research shows that high-entropy alloys can form structures and phases that have not previously been discovered or well-studied, expanding traditional ideas about the capabilities of this class of materials.

The first *HEAs* were created by melting and mixing elements in appropriate proportions, followed by cooling the resulting melt to obtain an alloy. This process distinguishes these materials from traditional alloys, where typically one or two primary elements dominate.

HEAs are characterized by high configurational entropy of atoms, resulting from the even distribution of five or more distinct elements in its structure. Although it was once thought that the formation of a single-phase structure and equal presence of elements are mandatory conditions, the modern concept of high-entropy alloys continues to evolve. The introduction of elements in equal proportions and the formation of a single-phase structure are no longer considered strict requirements, opening up new opportunities for further research in this field.

Alloys can exhibit remarkable mechanical properties, such as high strength, hardness, and wear resistance, making it useful for developing lightweight yet strong materials for aviation, automotive, and other industries. Some *HEAs* are resistant to aggressive environments, making it suitable for applications where materials need to retain its properties over extended periods. Due to its composite nature, *HEAs* can also be more accessible and cost-effective to produce compared to traditional alloys.

Over the past few decades, interest in alloys developed based on the entropy approach has grown significantly, driven by the potential of *HEAs*. Abroad, the idea of high-entropy alloys was proposed in the early 2000s. In Russia, research into high-entropy alloys began a little later. The first publications and studies by Russian scientists in this field appeared in the late 2000s and early 2010s. By 2010, Russian researchers were already actively engaged in studying *HEAs*, publishing papers, and participating in international conferences.

Researchers are particularly interested in the potential to discover properties in metals that are not typically found in conventional materials. This could include new forms of magnetic properties, electrical conductivity, superplasticity, unique stability at high temperatures, and other characteristics that not only overcome the limitations of traditional materials but also open doors to creating entirely new technologies and innovative applications. These discoveries may be the key to developing more efficient and advanced materials for use in a wide range of industries, from energy to medicine.

However, it is important to note that research on high-entropy alloys is still in its early stages, and further investigation and development are required to fully realize its potential and determine specific areas of application.

The purpose of this work is to review the latest advancements in *HEAs*, its properties, methods of fabrication, and applications, as well as to identify the most promising directions for further research.

Research objectives:

1) to review modern methods of obtaining *HEAs*;
2) to study the influence of alloying elements on the properties of *HEAs*;
3) to evaluate the properties of coatings based on *HEAs*;
4) to study the corrosion resistance of *HEAs*;
5) to study the heat resistance of *HEAs*;
6) to study the strength and plastic properties of *HEAs*;
7) to study the electrical conductivity and magnetic properties of *HEAs*;
8) to determine promising areas of application of *HEAs*.

Research Methods

This paper presents the results of a literature review of studies on *HEAs*. The research focuses on developments primarily from 2020 to 2024, conducted by both domestic and foreign scientists. Various methods of obtaining *HEAs* were studied to determine the most predominant. Given the high interest of researchers in both the corrosion-resisting properties of alloys in general and the properties of coatings in particular, the largest part of the review is devoted to this issue. The study also includes works on improving the heat resistance, strength, ductility, electrical conductivity, and magnetic properties of *HEAs*.

Based on an analysis of statistical data obtained from the interdisciplinary free scientific database *Scilit*, which indexes scientific materials, there has been a significant increase in publications and research on *HEAs* in recent years. This indicates growing interest in the topic and makes the current period particularly relevant for analysis in this field. The data analysis was conducted as of August 2024.

More detailed dynamics of the number of publications on the topic "*High-entropy alloys*" are illustrated using the bar graph in Fig. 1, which shows the number of publications by year of release.

The presented statistical data indicate that research in the field of *HEAs* has experienced significant growth in recent years. Since 2004, the number of publications on this topic has gradually increased, with the most noticeable surge occurring after 2015.

From 2015 to 2024, the number of publications increased more than tenfold, indicating growing interest in this field of research. This rapid growth may be due to both the expansion of knowledge in the field of *HEAs* and increased attention to the topic from the scientific community.

Currently, many research groups around the world, including in the USA, Japan, South Korea, China, and Europe, are actively studying *HEAs*. These groups not only conduct fundamental research but also develop new production methods, improve material properties, and expand its areas of application. Hundreds of scientists and engineers worldwide are deeply engaged in this area of materials science.

Today, around 100 countries actively participate in the development and study of *HEAs*, indicating that this field of science and technology attracts attention from researchers from all over the world, contributing to a deeper understanding and unlocking the potential of these materials. To visually demonstrate the geographic diversity of interest in *HEAs*, Fig. 2 presents a list of countries and the number of publications, which allows to assess each country's contribution to this research area.

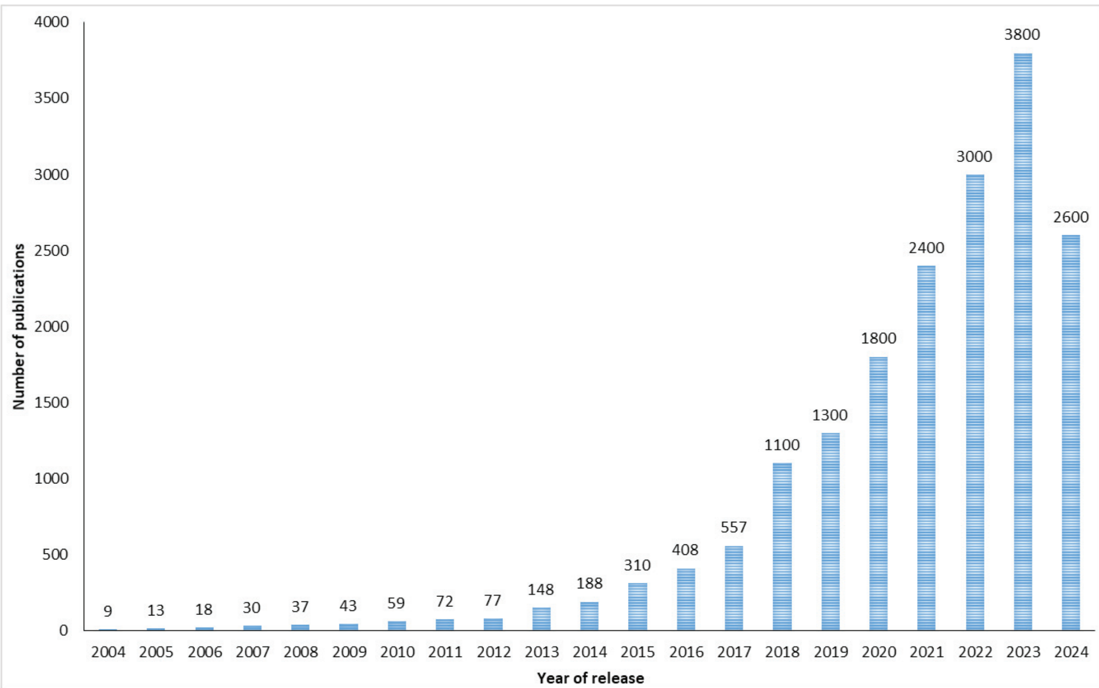

Fig. 1. The number of publications on the topic "*High-entropy alloys*" depending on the year of publication

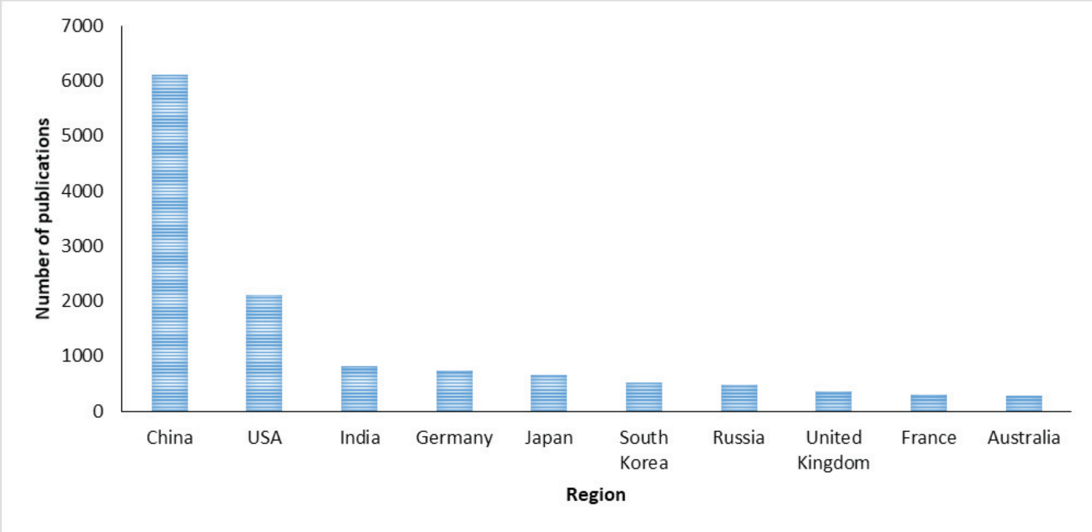

Fig. 2. The number of publications on the topic "*High-entropy alloys*" in different regions

China leads in the number of publications, significantly ahead of other countries. The USA ranks second, although its contribution is substantially smaller. India, Germany, and Japan follow, demonstrating moderate activity in this field. South Korea and Russia have comparable numbers of publications. The United Kingdom, France, and Australia round out the list. These data highlight the high relevance of the topic of high-entropy alloys in the global scientific community, with China being a notable leader.

This review includes publications from different regions, but most of the research was conducted at universities and research institutes in China. The choice to study the developments of foreign scientists, particularly in China, over the past four years is due to several factors: China is one of the leaders in *HEAs* research and development. The country actively conducts research in this field, creating new alloys and production technologies. Studying foreign developments allows assessing the level of science in other countries, as well as using their experience and achievements to improve our own research.

Results and Discussion

Methods of Obtaining High-Entropy Alloys

High-entropy alloys can be obtained using several approaches. Various technical solutions can be used, including melting processes, powder metallurgy (mechanical alloying of powders), welding, spinning, splat cooling, self-propagating high-temperature synthesis, magnetron sputtering of targets, and powder mixture surfacing on a metal base.

The first *HEAs* were produced by induction and arc melting followed by casting [1, 2]. This process involved melting various metallic components of the alloy using an induction or arc furnace, after which the molten material was poured into molds to create the desired shape and size. *A. S. Rogachev* in his study [3] notes that the most predominant methods of obtaining *HEAs* are:

melt crystallization;

mechanical alloying in planetary mills combined with spark plasma sintering;

spark plasma sintering;

combustion synthesis (*SHS*).

In addition to the methods listed, which can be called classical, other methods of obtaining *HEAs* have emerged in recent years. Scientists at the State Key Laboratory for Advanced Metals and Materials reviewed all alloy production methods for coatings and studied *HEAs* properties. They noted that the most promising method is laser additive manufacturing, which offers high technological precision [4].

The laser additive manufacturing method allows for the creation of complex three-dimensional structures of *HEAs* directly from powders or wire. Laser melting of the material with high precision and process parameter control enables the production of alloys with specific microstructures and properties. In [5], a review of various alloys produced using laser additive manufacturing was conducted. It was noted that these alloys are characterized by rapid design and manufacture, as well as good thermophysical and mechanical properties. In [6], a *CrMnFeCoNi HEA* with outstanding wear-resistant and corrosion-resistant properties was produced using laser additive manufacturing and subsequent laser shock treatment. After laser treatment, the results showed a significant improvement in performance. Specifically, the coefficient of friction and wear rate of the specimens were significantly reduced. For example, the scratch height on the untreated specimen surface varied from 0 to 4.5 µm below the surface and up to 4.2 µm above it, while on the specimen treated with a 2 J laser, the height ranged from 0 to 4.2 µm below and up to 5.6 µm above the surface. At laser energies of 4 and 6 J, significant ripple patterns and more pronounced microstructural changes were observed on the treated surfaces.

Corrosion tests showed that the laser-treated specimens had lower corrosion current densities and higher corrosion potentials compared to untreated specimens, indicating improved corrosion resistance. Specifically, the treated specimens exhibited a reduction in corrosion current to 0.1 µA/cm² and an increase in corrosion potential to −0.3 V, indicating the formation of denser passive films capable of protecting the material from aggressive ions.

The main conclusions of the work are that laser shock peening leads to the formation of a layer with increased microhardness and compressive residual stress, which in turn reduces wear and protects the material from corrosion. These improvements are due to grain refinement and the creation of compressive residual stresses, which contribute to the formation of more durable passive films. In a recent study conducted at the Siberian State Industrial University, an innovative arc surfacing method using flux-cored wire was discussed, offering a new approach to *HEAs* fabricating. The method involves the use of specially designed flux-cored wires and high-silicon manganese flux for surfacing, allowing for the avoidance of issues associated with traditional powder methods. The study showed that the resulting metal primarily consists of iron and alloying elements, but certain challenges were identified, such as the presence of non-metallic inclusions and relatively low hardness compared to equimolar *HEAs*. These results highlight both the potential and limitations of the new method, opening up prospects for further research and improvements in the field of *HEAs* and its applications [7].

Alloying of High-Entropy Alloys

One of the most promising methods for improving the properties of *HEAs* is alloying, a process of adding various elements to the base composition of the alloy. Alloying opens new possibilities for adapting *HEAs* to meet the specific requirements of different industrial sectors. The authors will consider various properties of *HEAs* modified by alloying.

Alloying can significantly influence the corrosion resistance of *HEAs*. Different alloying elements can interact with the environment in various ways, leading to different types of corrosion. In study [8], the effect of *Mo* on the microstructure, corrosion properties, and composition of the passive film of cast $AlCrFeNi_3Mox$ (x = 0; 0.1; 0.2; 0.3; 0.4) was investigated. The $Mo_{0.3}$ alloy has a corrosion rate of 0.0155 mm/year and exhibits superior corrosion resistance compared to the *Mo* alloy. The increased corrosion resistance is attributed to the superior protective properties of the passive film with higher Cr_2O_3 content and embedded *Mo* oxides. In study [9], it was found that adding the appropriate amount of *Co* to replace *Cr* in the $Fe_{35}Ni_{20}Cr_{20}$ alloy positively affects its corrosion resistance.

Wear resistance improvement is achieved through alloying with boron [10], niobium [11], and tungsten carbide [12]. Alloying with boron (0.3 atomic percent) modifies the microstructure and deformation mechanism of the alloy, leading to a 35-fold increase in wear resistance. The primary mechanism for this improvement is associated with the formation of nanostructured layers and changes in wear type under high loads. The study showed that adding niobium changes the alloy's microstructure, significantly increasing hardness and wear resistance but reducing corrosion resistance. Maximum wear resistance was observed at a niobium content of 1.5 mol. % while the wear coefficient decreased to 84 % at loads of 10 N and 20 N compared to the original alloy without niobium. Adding 5–20 % tungsten carbide (*WC*) to the *CrFeCoNi* high-entropy alloy significantly improves its mechanical properties. The alloy's hardness increases, and its corrosion resistance and wear resistance are enhanced. Particularly effective was the addition of 20 % *WC*, which resulted in a significant increase in overall corrosion resistance and a wear reduction of approximately 4.5 times.

For better comparison, the research results are presented in a Table 1. This table provides data on the wear rate of various *HEAs* before and after alloying. These data allow us to evaluate the effectiveness of alloying in improving the wear resistance of *HEAs*.

Table 1

Wear rate of high-entropy alloys before and after alloying

High entropy alloy	Metal for alloying	Characteristics before alloying		Characteristics after alloying	
		Load, N	Wear rate, $mm^3/(N·m)$	Load, N	Wear rate, $mm^3/(N·m)$
CoCrFeNi [10]	*B*	2	2.6×10^{-5}	2	8.3×10^{-6}
		5	2.9×10^{-5}	5	8.6×10^{-5}
		8	3.57×10^{-4}	8	8.9×10^{-5}
$AlCr_2FeCoNi$ [11]	*Nb*	5	18.7×10^{-6}	5	5.2×10^{-6}
		10	46.8×10^{-6}	10	6.5×10^{-6}
		20	40×10^{-6}	20	6.2×10^{-6}
CrFeCoNi [12]	*W*	5	1.7×10^{-4}	5	3.8×10^{-5}

From the data presented, it can be seen that alloying significantly improves the wear resistance of *HEAs*. For example, for *CoCrFeNi* alloy, alloying with boron (*B*) reduced the wear rate from 2.6×10^{-5} to 8.3×10^{-6} $mm^3/(N\ m)$ under 2 N load. Similarly, adding niobium (*Nb*) to the $AlCr_2FeCoNi$ alloy significantly reduced the wear rate from 18.7×10^{-6} to 5.2×10^{-6} $mm^3/(N·m)$ under 5 N load. Adding tungsten (*W*) to *CrFeCoNi* also showed a significant reduction in the wear rate from 1.7×10^{-4} to 3.8×10^{-5} $mm^3/(N\ m)$ under 5 N load. These results confirm that alloying is an effective method for enhancing the wear resistance of high-entropy alloys, making it more suitable for use under conditions of high loads and intense wear.

Alloying high-entropy alloys with elements such as *Nb* [13], *La* [14], *Y* [15] significantly improves its thermal stability by altering the microstructure and chemical composition. These elements promote the formation of thermodynamically stable phases and protective oxide films, which prevent grain growth, reduce atomic diffusivity, and protect the material from oxidation and corrosion. As a result, *HEAs* become more resistant to high temperatures and aggressive operating conditions, expanding its applications in various high-tech industries, such as aerospace, energy, and automotive industries.

A study on the temperature dependence of the mechanical properties of $Co_{20}Cr_{20}Fe_{20}Mn_{20}Ni_{20}$, $Co_{19}Cr_{20}Fe_{20}Mn_{20}Ni_{20}C_1$, and $Co_{17}Cr_{20}Fe_{20}Mn_{20}Ni_{20}C_3$ alloys in the range of 77 to 473 K, conducted by scientists from Tomsk [16], revealed that carbon alloying significantly affects its structural and mechanical characteristics. Alloying leads to an increase in the lattice parameter of the austenitic phase, an increase in the yield strength, and a strengthening of the temperature dependence of strength due to solid solution, grain boundary, and dispersion strengthening, especially in the heterophase alloy $Co_{17}Cr_{20}Fe_{20}Mn_{20}Ni_{20}C_3$. While single-phase alloys demonstrate improved mechanical properties and plasticity at low temperatures, the heterophase alloy becomes more brittle, despite an increase in strength.

Alloying *HEAs* with elements such as titanium (*Ti*) [17], aluminum (*Al*) [18], and neodymium (*Nd*) [19] plays a key role in improving its strength properties. Titanium contributes to increased hardness and deformation resistance, aluminum improves thermal stability and corrosion resistance, and adding neodymium enhances mechanical characteristics such as strength and ductility. These improvements make

HEAs more effective for use in high-load and critical areas such as aerospace, automotive, and energy industries.

The addition of *C* and *Mo* [20] to the alloy contributes to the improvement of its ductility. Carbon and molybdenum can be used for microalloying the alloy, which promotes the formation of fine carbide phases in the material structure. These carbides can act as barriers to dislocation movement, enhancing the alloy's ductility. Hydrogen can also be used to improve alloy ductility by reducing resistance to plastic deformation [21, 22]. Dissolved hydrogen can change the energy of defect formation in the material, which in turn can enhance its ability for plastic deformation.

Alloying with *Zn* [23] and *Cu* [24] plays a key role in modifying the electrical conductivity of high-entropy alloys. This opens the potential for developing energy-saving technologies, electrical conductors, sensors, and electronic components. The change in conductivity properties depends on the alloy composition, temperature, pressure, and the presence of impurities, highlighting the importance of alloying in the modification process of these materials.

The fatigue characteristics of high-entropy aluminum-based $Al_{0.5}CoCrFeNi$ alloy thin films with different aluminum additions were also investigated.

The results showed that addition of aluminum can effectively reduce the localization of cyclic deformations and improve fatigue resistance, which is associated with the reduction of cyclic slip irreversibility [25]. The study [26], also noted that with the addition of *Al* to the $FeCoNiTiAl_x$ coating, the hardness of the coating increased, and it demonstrated better wear resistance.

Alloying plays an important role in modifying various properties of *HEAs*. Various elements such as molybdenum, cobalt, boron, niobium, tungsten carbide, titanium, aluminum, neodymium, carbon, copper, and zinc are used to improve the corrosion resistance, wear resistance, thermal stability, strength, plasticity, and conductive properties of high-entropy alloys (fig. 3).

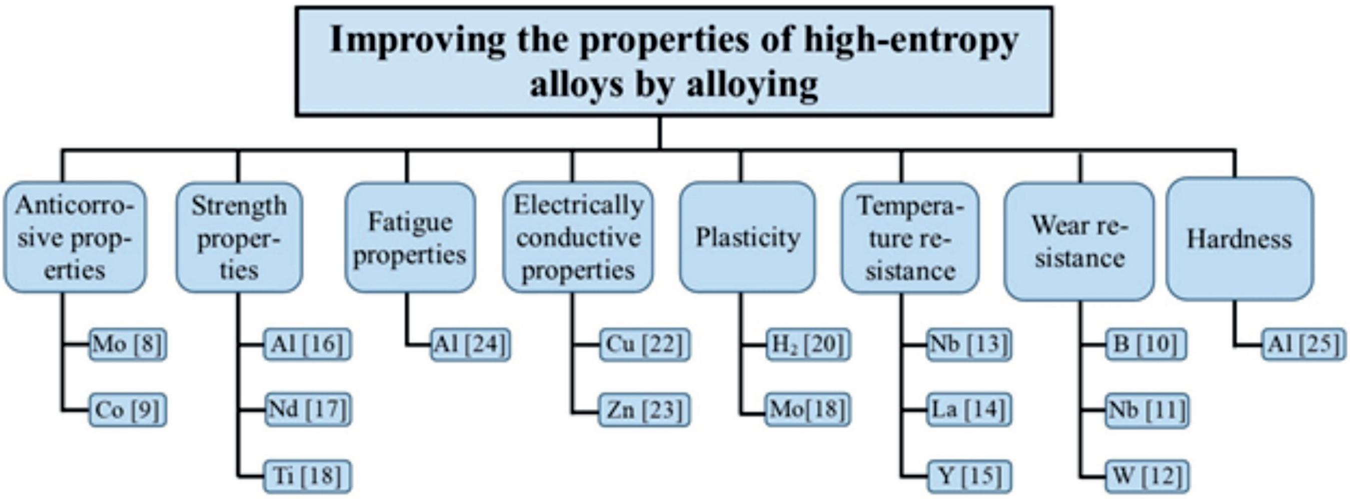

Fig. 3. Improving the properties of high-entropy alloys by alloying

Thus, alloying represents a powerful tool for modifying high-entropy alloys to achieve specific desired properties and expand its application areas.

Coatings and its Properties

Methods of Obtaining Coatings from *HEAs*

Studying the materials published in both Russian and foreign sources over the past few years, it becomes obvious that scientists are interested in obtaining thin films and coatings from *HEAs*. This conclusion is also confirmed by the study [27], which highlights a significant increase in the study of *HEAs* films and coatings and surface modification by various methods over the last five years.

HEA-based coatings are currently of great interest in materials science due to its compositional freedom and excellent properties, such as excellent hardness and impact toughness, high wear resistance, corrosion and oxidation resistance, and exceptional thermal stability [28].

The methods of applying *HEA* coatings play a key role in determining its final properties and areas of application. The choice of coating technology directly influences the microstructure, phase composition, adhesion to the substrate, as well as the mechanical and functional characteristics of the coating. In recent years, there has been significant interest in the development and improvement of various methods for applying *HEA* coatings, driven by its unique properties, such as high hardness, wear and corrosion resistance, thermal stability, and mechanical strength.

The main methods for applying *HEA* coatings include laser surfacing, magnetron sputtering, as well as nitriding and oxidation of substrates. Each of these methods has its own advantages and features that make it suitable for different applications and operating conditions.

Coatings of high-entropy *FeNiCoAlCu* alloy obtained by laser surfacing demonstrate high wear resistance. The results of the studies showed that such coatings have good thermal stability at temperatures below 780 °C. It is also noted that it demonstrates good wear characteristics at high temperatures, mainly due to the formation of oxide films on the surface of the coating. The wear mechanisms are predominantly abrasive and oxidative [29].

High-entropy ceramic films obtained by nitriding or oxidizing *HEAs* substrates exhibit good anti-wear, anti-radiation, anti-corrosion, and anti-oxidation properties. These properties make it attractive for use in extreme conditions, such as high temperature, high strength, and intense radiation [30].

Magnetron sputtering allows the production of *HEA* films with improved properties. For example, *FeCoNiCuAl* film obtained by magnetron sputtering exhibits enhanced corrosion and magnetic properties compared to the bulk alloy of similar composition. Studies show that such films have better corrosion resistance than its bulk counterparts [31].

Properties of *HEA* Coatings

The corrosion resistance, magnetic properties, and microstructure of the surfaced and annealed films were investigated. Results show that the surfaced *HEA* has better corrosion resistance than the bulk *HEA* of the same composition. The most relevant and notable developments in the field of anti-corrosion properties of coatings are reviewed by international experts in work [32].

In a study conducted by the authors [33], *HEA* coatings based on *FeCoCrNiMoTiW* composition, produced by mechanical alloying, were studied. The results showed that the hardness of these coatings exceeds the hardness of most stainless steels by 1.5–2 times, and the dry friction coefficients are in the range of 0.08–0.16. This significant difference in friction coefficients of *HEA* coatings is due to its nanostructural features and the manifestation of the size dependence of its properties. Thus, the study demonstrated the potential of these coatings in terms of mechanical properties.

In the study [34], a comparison was made between *HEA* coating and steel specimens. Researchers noted that the nanostructured *FeCrNiTiZrAl* coating has significantly greater hardness and wear resistance compared to stainless steels. Moreover, the friction coefficient of the *FeCrNiTiZrAl* coating is significantly lower than that of other materials, which contributes to an increased service life of products with such coatings.

Study [35] showed that the *HEA* $Al_{0.6}CoCrFeNiTi$ is a promising material for metal thermal insulation coatings due to its combination of low thermal conductivity and high thermal stability.

Overall, studies on the properties of *HEA* coatings have demonstrated its unique properties and potential applications. The results of the studies confirm the potential of *HEAs* in the field of mechanical properties, anti-corrosion properties and thermal insulation properties. Thus, *HEA* coatings may become promising materials for various industries, including aviation, automotive manufacturing, and biomedical industry.

Corrosion Resistance of High-Entropy Alloys

Corrosion is one of the main causes of material failure in various industries, such as energy, petrochemical, and marine engineering. Therefore, studying the corrosion resistance of *HEAs* is critical for its use in extreme operating conditions. This section is dedicated to analyzing the corrosion properties of *HEAs* and the mechanisms of its corrosion resistance.

The study [36] showed that the addition of aluminum to high-entropy *FeCoCrNiAlx* (x = 0.1; 0.3) alloy improves its mechanical properties and reduces weight. The effect of aluminum on the corrosion behavior and properties of alloy films in H_2SO_4 solutions was analyzed. Results showed that increasing aluminum content improves corrosion resistance in H_2SO_4 solution.

The study [37] evaluated the corrosion resistance of high-entropy *FeCoNiCr* alloy coatings obtained by electrochemical deposition. The coatings synthesized from *Fe*, *Co*, *Ni*, and *Cr* sulfate solutions formed a crack-free, granular surface with a grain size ranging from 500 nm to 5 µm. Electrochemical measurements demonstrated high corrosion resistance of the coatings in various environments, including *NaCl*, H_2SO_4, and *NaOH* solutions. The study highlights the potential of these coatings for engineering applications due to its excellent corrosion resistance.

The paper [38] examines the effect of ultrasonic shot peening on the corrosion resistance and antibacterial properties of the high-entropy $Al_{0.3}Cu_{0.5}CoCrFeNi$ alloy. The primary goal of the study was to eliminate the contradictions between the corrosion resistance and antibacterial properties of the alloy by using ultrasonic shot peening. The results of the study confirmed that ultrasonic shot peening improved the corrosion resistance and antibacterial properties of the high-entropy $Al_{0.3}Cu_{0.5}CoCrFeNi$ alloy. Electrochemical tests showed that ultrasonic shot peening contributed to the formation of a more protective passive film, reducing the corrosion current density.

Scientists have developed a new high-entropy $AlTiVCrCu_{0.4}$ alloy, which has low density and high hardness. The study showed that the dual-phase high-entropy $AlTiVCrCu_{0.4}$ alloy has unique mechanical and corrosion properties due to its complex structure consisting of *BCC* and *HCP* phases. The alloy exhibits outstanding corrosion resistance in aggressive environments, which is associated with the formation of a protective metal oxide film [39].

The study [40] examines the effect of cold rolling and annealing on the corrosion properties of $\mathrm{Al_2Cr_5Cu_5Fe_{53}Ni_{35}}$ alloy, focusing on grain size changes and its impact on corrosion behavior. The results show that reducing grain size improves the localized corrosion resistance of the material. The developed alloy demonstrates improved anti-corrosion properties, making it promising for marine applications. The best corrosion resistance was observed with 85 % thickness reduction and a 3-minute annealing period. The noble behavior of the material is maintained in solutions with varying seawater concentrations.

The effect of cold rolling and post-deformation annealing on the properties of the high-entropy *CrMnFeCoNi* alloy was studied [41]. The results showed that the grain size decreased from 207.5 µm to 4.6 µm. Microhardness, yield strength, and tensile strength increased by 28 %, 68 %, and 24 %, respectively, but the percentage elongation decreased from 59.3 % to 43.8 %. The strengthening mechanisms are associated with grain refinement and increased dislocation density. The corrosion resistance of the alloy also improved due to a decrease in grain size and residual compressive stress.

The paper [42] examines the effect of friction stir processing on the corrosion resistance of high-entropy *CoCrFeNiCu* alloy. Friction stir processing involves the use of a rotating tool that moves across the surface of the material, generating high temperatures and mechanical stresses. This results in plastic deformation and mixing of the metal, which reduces the grain size of the alloy, improving its strength and ductility. After processing, the alloy becomes more resistant to corrosion due to the formation of a more stable protective film on its surface.

The study [43] investigated the effect of thermal shocks on the microstructure, microhardness, and corrosion properties of $VCrFeTa_{0.2}W_{0.2}$ alloy with reduced activation. After thermal shocks, the content of different phases in the alloy changed, microhardness increased, and corrosion resistance improved. The alloy demonstrated excellent properties under harsh environmental conditions, making it a promising material for nuclear construction.

The studies conducted show that adding various elements, improving the methods of synthesis and processing of alloys, and optimizing the structure can improve the corrosion resistance of materials. Another important factor is the influence of various processing and annealing technologies on the microstructure and properties of alloys. Studies show that optimizing these parameters can significantly improve the corrosion resistance of materials.

Heat Resistance and Thermal Stability of High-Entropy Alloys

Heat resistance and thermal stability play a crucial role in the development of *HEAs*, which are a promising class of materials with unique properties. This section will explore the key aspects related to the resistance of these alloys to high temperatures and thermal cycling. It will analyze the influence of alloy composition, processing, and microstructure on its thermal properties, as well as discuss methods to improve the heat resistance and stability of *HEAs*.

In recent years, considerable attention of foreign researchers has been attracted by the development of refractory *HEAs*, which are considered as a promising class of materials for high-temperature applications. These alloys possess unique mechanical properties and have the potential to replace traditional nickel-based superalloys in the next generation of technologies [44].

Particular attention in the research is paid to the use of electrodeposited nanostructured alloys such as *NiFeCoW*, *NiFeCoMo* and *NiFeCoMoW*. These materials have high thermal and structural stability at elevated temperatures and show a significant increase in hardness after annealing. Electrodeposition is an effective and affordable method for synthesizing nanostructured alloys, providing high thermal stability [45].

Another important aspect is the use of methods aimed at improving thermal stability. Among these, long-term annealing and high-pressure torsion (*HPT*) are of particular importance. Long-term annealing promotes the recrystallization of the material, enhancing its properties [46]. *HPT* is an effective technological process for changing the shape and structure of materials by rotating under pressure, applied in various industries, including metallurgy, plastics, and composites [47].

The study [48] demonstrated that replacing molybdenum with vanadium in *HEAs* has a significant impact on its structural and thermal properties. This approach leads to the formation of crystalline complex nitride particles in a ribbon structure, which positively affects thermal stability and helps stabilize supercooled liquids in alloys with a fully amorphous structure.

Additionally, the study [49] confirms that the thermal stability of the high-entropy $Cr_{0.8}FeMn_{1.3}Ni_{1.3}$ alloy is significantly dependent on the aging temperature. When treated at 300 °C, the alloy microstructure remains stable with minimal changes in mechanical properties. However, at higher temperatures (500 and 700 °C), a complex phase decomposition is observed, which significantly affects its mechanical characteristics. These results highlight the need for strict control of heat treatment parameters to achieve optimal properties of *HEAs* for various engineering applications.

In conclusion, research in the field of *HEAs* continues to expand our understanding of its potential for high-temperature applications. Overall, studies in this field continue to open new horizons for creating materials with optimized properties for future technologies.

Strength and Plasticity Properties of HEAs

This section reviews the latest advances in developing and improving the strength and plasticity properties of *HEAs*, including methods of synthesis and processing, as well as the application of modern technological approaches and modeling.

Development of New Alloys with Embedded High-Strength Properties

The development of new alloys with embedded high-strength properties is actively underway. A lightweight, refractory alloy $AlNb_2TiV$ with a density of 6.19 g/cm³ and a specific yield strength of 167 MPa·cm³/g was proposed. The alloy demonstrates good deformability [50]. In another study, a matrix composite $Re0.5MoNbW(TaC)_{0.5}$ was successfully synthesized from a *HEA*. The composite microstructure remained stable after annealing at 1,300 °C for 168 hours. It showed remarkable high-temperature strength, with a yield strength of about 901 MPa and a true compressive strength of about 1,186 MPa at 1,200°C [51]. The composite creates an ideal balance between ultra-high strength and high plasticity at elevated temperatures. This discovery may be an important contribution to theoretical research and applications in high-temperature anti-softening. High yield strength and ultimate strength were noted in a study on *Mo*-based *HEAs*. The compressive yield strength of the *M20* alloy reaches up to 1,285 MPa, the ultimate strength is 2,447 MPa, and the elongation is 27 % [52].

Recent research conducted at Belgorod State University [53] resulted in the development of a new *HEA*, $Co_{40}Mo_{28}Nb_{25}Hf_7$, which demonstrated outstanding mechanical properties at high temperatures. This alloy, produced by vacuum arc remelting, includes *BCC* and *Laves C14* phases, as well as a small amount of hafnium oxides. Studies have shown that the alloy has a high yield strength at room temperature (1,775 MPa) and retains significant strength at 1,000 °C (600 MPa). In the temperature range of 22–1,000 °C, its specific strength surpasses many commercial superalloys and other *HEAs*, highlighting its potential for high-temperature applications.

Methods for Improving Strength Properties

Improving the strength properties of *HEAs* can be achieved by various methods, each of which is aimed at optimizing the microstructure and phase composition of the materials. One such method is the introduction of new gradient nanoscale structures of dislocation cells into a stable single-phase face-centered cubic (*FCC*) lattice. The face-centered cubic (*FCC*) lattice is a crystalline structure in which atoms are located at the corners and in the center of each face of the cube. This configuration provides the material with high plasticity and the ability to deform. Dislocation cells, being areas of local deformation in the crystal lattice, create additional resistance to dislocation movement, which increases the strength of the material without an obvious loss of plasticity [54].

The process of introducing such structures includes thermomechanical treatment, controlled cooling, or the use of nanoscale additives that promote the formation of dislocation cells with specific characteristics. As a result, *HEAs* with *FCC* lattices and gradient structures demonstrate improved performance, making them promising for use under high loads.

Another method is cold rolling followed by laser surface heat treatment. Cold rolling is a process of deforming a material at low temperatures, which strengthens the material due to the increase in the density of dislocations. Laser surface heat treatment involves the use of a laser for local heating and subsequent cooling of the material, which allows to modify its microstructure and improve mechanical properties [55].

Spinodal decomposition, which causes compositional heterogeneity in the structure, is the process of separating a solid solution into two phases with different chemical compositions. As a result of spinodal decomposition, nanometer-scale structures are formed that strengthen the material. This compositional heterogeneity significantly enhances the mechanical characteristics of *HEAs*, making it stronger and more reliable for use under high loads and temperatures [56].

The use of laser additive manufacturing for coherent strengthening of alloys is another effective method. Laser additive manufacturing is a technology where material is added layer by layer using a laser. This method allows precise control of the microstructure and phase composition of the material, leading to improved strength properties [57].

Thus, the implementation of these methods significantly improves the strength properties of *HEAs*, ensuring high strength and maintaining plasticity, making it promising for use in various high-load and high-temperature applications.

Property Prediction and Modeling

Research into increasing the strength of *HEAs* is of strategic importance for creating advanced materials that combine strength, low density, and resistance to various operational conditions. Research can be found on predicting the strength of *HEAs*, in particular based on *machine learning*.

Machine learning (*ML*) is a branch of artificial intelligence that trains computer systems to perform tasks without being explicitly programmed to do so. Instead of using explicit instructions, machines learn from data and algorithms, identifying patterns and making predictions or decisions.

In the field of materials science and nanotechnology, multiscale modeling has become an essential tool for understanding material properties across different levels – from atomic to macroscopic. The use of supercomputers and high-performance computing allows modeling of complex systems with millions of atoms and molecules.

One of the key methods in multiscale modeling is molecular dynamics, which allows simulating the dynamics of atoms and molecules at the microscopic level [58]. This method is used to study material properties such as strength, elasticity, thermal conductivity, and others.

Figure 4 shows how computer-assisted learning is applied in *HEAs* research.

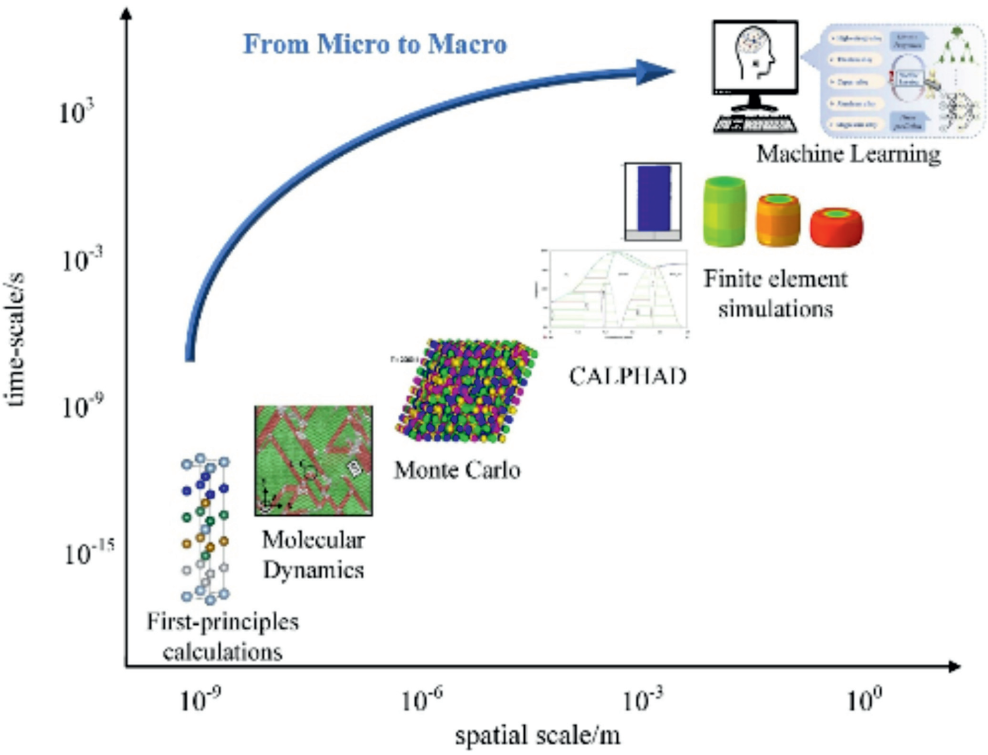

Fig. 4. Schematic diagram illustrating the application of multiscale modeling and machine learning in *HEA* research [58]

Moreover, machine learning methods also play a significant role in analyzing material data. It is used to classify materials, predict its properties, and optimize the production process. For example, machine learning algorithms can be used to determine the optimal material structure or predict its properties based on its composition and structure.

Thus, the combination of multiscale modeling and machine learning provides a deeper understanding of material properties and improves the design and production process.

By combining machine learning, phenomenological rules, and *CALPHAD* modeling, new promising compositions of refractory *HEAs* with specified phase compositions and mechanical properties (such as yield strength) were predicted. It is emphasized that the creation and modification of the properties of five-component *HEAs* can be achieved using *CALPHAD* software, designed to calculate phase diagrams. Studies conducted at the Siberian State Industrial University showed that *CALPHAD* phase diagram calculations are confirmed by experimental data, allowing the development of next-generation alloys with specified properties [59]. Below, in Table 2, a comparison of the predicted and experimental result of the yield strength for various alloys is presented.

It can be noted that the predicted yield strength values for the alloys generally show a good match with the experimental data, although there are cases where the errors in the estimates are significant. This may be due to various factors such as the complexity of the alloy structures, environmental effects, and others.

Regarding the prospects for using machine learning in this context, it can be highlighted that machine learning methods can be effectively applied to predict material properties based on its composition, structure,

Table 2

Comparison of predicted and experimental yield strengths of various alloys

High entropy alloy	Temperature, °C	Predicted yield strength, MPa	Experimental yield strength, MPa	Error (%)
MoNbTaTiW [60]	1,200	572	585	2.5
AlCrNbTiVZr [61]	600	1,409	1,093	13
AlCrNbTiVZr [62]	600	837	845	1

and operating conditions. This can help improve the accuracy of alloy property predictions and optimize the processes for developing new materials with specified characteristics.

Plasticity and Deformability Research

The study of the plasticity and deformability of *HEAs* is a significant field because these properties are essential for its application in various industries. This topic is covered by researchers from different perspectives: the plastic deformation of *HEAs* under mechanical processing is studied [63], as well as the simultaneous enhancement of the strength and plasticity of *HEAs* through purification mechanisms [64]. The effect of electron irradiation on the microstructure and plasticity after annealing at intermediate temperatures is also examined. The essence of irradiation-induced plasticity lies in the refinement and redistribution of nanoprecipitates. Optimization of the size and distribution improved the interaction between nanoprecipitates and dislocations, effectively preventing brittle fractures caused by stress concentration [65].

Increased thermal stability and plasticity of *HEAs* is achieved by introducing hard and brittle borides. Borides significantly increase the material plasticity without compromising its strength. In addition, a chemical order-disorder transition occurs near borides, which improves the mobility of dislocations and promotes plastic deformability of the material. The presence of stable borides also prevents grain growth in the material at high temperatures, as the borides pin the grains and stabilize its size [66].

Thus, this section emphasizes the importance of a comprehensive approach to developing and improving *HEAs*, including the synthesis of new alloys, refining processing methods, and using modern modeling and forecasting technologies. This contributes to the creation of materials with unique combinations of strength and plasticity properties, necessary for use in extreme operating conditions.

Electrical and Magnetic Properties

Research into *HEAs* in the fields of electrical and magnetic properties provides new opportunities for creating materials with unique electromagnetic characteristics, enabling the development of energy-efficient technologies, electrical conductors, sensors, or electronic components.

Changes in the electrical conductivity of *HEAs* depend on several factors, such as alloy composition, temperature, pressure, and impurities. Annealing is an important method for influencing the electrical conductivity properties of *HEAs*. Thermal treatment can lead to changes in the alloy's microstructure, including grain recrystallization, dislocation reduction, and phase composition alterations, affecting the material electrical conductivity. For example, annealing can help restore electrical conductivity after mechanical deformation or improve the structural uniformity of the alloy [67, 68].

Pressure can affect the change in electrical conductivity. In the normal state, the *TiZrHfNb* alloy demonstrates high electrical resistance, which is almost independent of temperature but significantly dependent on pressure; it decreases linearly by 12.5 % with an increase in pressure to 5.5 GP [69].

Regarding electrical conductivity, there is a study devoted to surface treatment using ultrasonic electropulse rolling [70]. The study used five elements: chromium (*Cr*), manganese (*Mn*), iron (*Fe*), cobalt (*Co*), and nickel (*Ni*), with a high purity level (99.9 %) and an equimolar ratio. These elements were melted in a vacuum melting furnace using electromagnetic induction, ensuring a high degree of alloy composition uniformity.

The main achievement of the study was a significant improvement in the alloy tensile strength at room temperature due to the application of the ultrasonic surface rolling method. This process was carried out on a self-assembled platform, allowing precise control of the processing parameters and ensuring high reproducibility of the results (fig. 5). Ultrasonic surface treatment improves the material mechanical properties by reducing microporosity and enhancing grain boundary adhesion, which is crucial for its electrical conductivity properties.

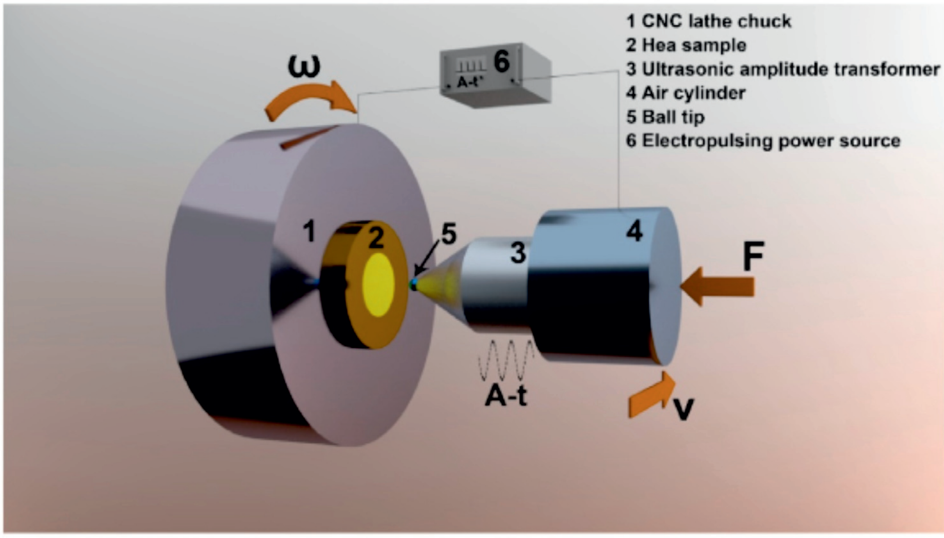

Fig. 5. Electropulse ultrasonic surface rolling process diagram [70]

Magnetic properties of HEAs are one of the most interesting and poorly studied areas in materials science. One factor influencing the magnetic properties of *HEAs* is its atomic structure.

The study showed that the *CoCuFeMnNi* alloy obtained using mechanical alloying and spark plasma sintering methods exhibits significant magnetic properties, including high saturation induction and low coercive force under given magnetic conditions. These characteristics make the *CoCuFeMnNi* alloy a promising material for application in the field of soft magnetic technology [71].

In another study [72], manganese was replaced by chromium in the high-entropy *FeCoNiAlMn* alloy, which significantly affected its magnetic properties. The best results are achieved at a certain concentration of chromium, at which a significant increase in saturation induction is observed. Specifically, the $FeCoNiAlMn_{0.4}Cr_{0.6}$ alloy demonstrates optimal magnetic characteristics, making it a promising candidate for soft magnetic technology. This effect is related to changes in microstructure and crystallite sizes depending on *Cr* content, which influences the alloy magnetic properties.

The study of the electrical and magnetic properties of *HEAs* highlights its potential for creating materials with unique characteristics for electrical and magnetic applications. The influence of alloy composition, thermal treatment, and pressure on electrical conductivity is actively researched, opening up ways to control its electrical conductivity.

In the field of magnetic properties, it has been revealed that the *CoCuFeMnNi* alloy exhibits high saturation magnetization and low coercive force, making it promising for soft magnetic technology. Optimization of the alloy microstructure and composition, including the replacement of manganese with chromium, also helps to improve its magnetic properties.

Prospects for the Application of High-Entropy Alloys

Despite a significant number of studies, *HEAs* remain a promising topic for research due to its unique properties, such as high strength, corrosion resistance, wear resistance, and others.

Moreover, these alloys have great potential for use in various industries. Chinese researchers see a great future for these alloys in the energy sector, particularly in the creation of supercapacitors, new electrode and dielectric materials, and the development of solid oxide fuel cells [73]. At the Siberian State Industrial University, researchers talk about the use of *HEAs* as coatings for ship parts, dissimilar welded joints, and nuclear reactor parts [74]. At South Ural State University, the study concluded that the strength and plasticity properties of the considered *HEAs* correspond to the best samples of high-alloy austenitic steels used in cryogenic technology [75]. At Voronezh State University of Forestry and Technologies, there is a mention of the potential for using *HEAs* to restore machine parts through atmospheric plasma spraying [76]. The University of Manchester notes that the extended compositional freedom offered by *HEAs* presents a unique opportunity for developing alloys for advanced nuclear applications, particularly in areas where existing engineering alloys fall short [77].

Discussion

The study of HEAs is a relevant and promising topic in modern materials science, covering a wide range of scientific and engineering research. The goal of this work was to highlight the latest achievements in this field, conduct a comparative analysis of published research, and identify the most promising directions for further investigation.

The section on *HEA* production methods reviews various technologies, including mechanical alloying, vacuum induction melting, and alloying element addition methods. These methods aim to achieve high homogeneity in alloy composition and microstructure, which is critically important for its mechanical and physical properties.

Alloying plays a key role in modifying the chemical composition of *HEAs* to optimize mechanical, thermal, and corrosion properties. *HEA*-based coatings represent a promising direction for protecting materials from corrosion and wear, which is particularly important in the aerospace and nuclear industries.

Special attention is given to research on the thermal resistance and thermal stability of *HEAs*, which is important for its application in extreme conditions, such as high temperatures and aggressive environments.

The strength and plastic properties of *HEAs* are at the forefront of research, as these materials often outperform traditional alloys in strength and resistance to deformation.

The most promising direction for future research is the study of the electrical conductivity and magnetic properties of *HEAs*. This field opens up significant opportunities for the development of new energy-saving technologies, high-performance sensors, and magnetic materials, which could lead to substantial innovations in areas such as electronics, energy, and information technology.

Conclusion

Based on the analysis, it can be concluded that *HEAs* represent a promising class of materials with great potential for innovation. Future research should focus on expanding the knowledge in the areas of *HEA* compositions, methods, and properties, as well as developing new materials with improved characteristics. This will open new horizons for technological advancements and improve the efficiency and reliability of materials used in various industrial sectors.

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Conflicts of Interest

The authors declare no conflict of interest.