ADVANCED HIGH ENTROPY MATERIALS

Abstracts of the V International Conference and School "Advanced High Entropy Materials"

Belgorod State National Research University
State Marine Technical University
Siberian State Industrial University, October 9-13, 2023

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A 20 **ADVANCED HIGH ENTROPY MATERIALS**: Abstracts of the Abstracts of the V International Conference and School "Advanced High Entropy Materials" Belgorod State National Research University, State Marine Technical University, Siberian State Industrial University (Saint Petersburg, Russia, October 9-13, 2023) / ed. G.A. Salishchev, M.S. Tikhonova, E.A. Povolyaeva. – Belgorod : LLC "Epicenter", 2023. – 173 p.
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The collection contains the abstracts of V International Conference and School "Advanced High Entropy Materials". It presents reports by leading scientists, young scientists, graduate students, students, industry representatives and highlights current trends in the development of high-entropy alloys and coatings, new materials, modern methods of their study and technologies for the manufacture of promising products. The international school will is supported under Russian Science Foundation grant No. 19-79-30066 "Advanced alloys and technologies for the aerospace industry". Additional support through "Priority 2030" program of Saint Petersburg State Marine Technical University (project: Industrial Digital Technologies) is gracefully acknowledged.

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ПЕРСПЕКТИВНЫЕ ВЫСОКОЭНТРОПИЙНЫЕ МАТЕРИАЛЫ

Тезисы V Международной школы-конференции
«Перспективные высокоэнтропийные материалы»

УДК 669
БДК 34.2
П 26

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П 26 **Перспективные высокоэнтропийные материалы :** Тезисы V Международнjq школs-конференциb «Перспективные высокоэнтропийные материалы» Белгородский государственный национальный исследовательский университет, Санкт-Петербургский государственный морской технический университет, Сибирский государственный индустриальный университет (г. Санкт-Петербург, Россия, 9-13 октября, 2023 г.) / под ред. Г.А. Салищева, М.С. Тихоновой, Е.А. Поволяевой. – Санкт-Петербург : «Заневская площадь», 2023. – 173 с.
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Сборник содержит тезисы международной школы-конференции «Перспективные высокоэнтропийные материалы». В нем представлены доклады ведущих ученых, молодых ученых, аспирантов, студентов, представителей промышленности и освещены актуальные направления в области разработки высокоэнтропийных сплавов и покрытий, новых материалов, современных методов их изучения и технологий изготовления перспективных изделий.

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TOPICS

Main directions of work:

- High-entropy metallic materials: structure, mechanical, and functional properties.
- Structure and properties of non-metallic high-entropy materials: ceramics, coatings, etc.
- Advanced metallic and non-metallic materials and their applications.
- Additive and laser technologies, and other methods for processing of advanced materials.
- Theoretical and computational prediction of the structure and properties of advanced materials.

The school will be supported under Russian Science Foundation grant No. 19-79-30066 "Advanced alloys and technologies for the aerospace industry". Additional support through "Priority 2030" program of Saint Petersburg State Marine Technical University (project: Industrial Digital Technologies) is gracefully acknowledged.

CONFERENCE ABSTRACTS

EFFECT OF PORE GEOMETRY ON THE MECHANICAL PROPERTIES OF POROUS SCAFFOLDS

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Metallic porous and lattice structures have interconnected porosity, which is very good for osseointegration and obtaining stiffness comparable to bone characteristics [1]. The complex structure of bone allows it to behave anisotropically, able to withstand compressive loads as well as a high strength cortex that resists torsional moments. Spongy bone is regularly subjected to tensile, compressive, shear, bending and torsional forces either singly or in combination in a multi-axial loading regime, which is necessary for bone formation and to maintain its mechanical function. None of the existing solid materials can replicate this level of properties. In this case, the solution may be the use of porous materials. Pore size, cell geometry and porosity percentage can be varied to obtain optimum mechanical properties. These advantages have led to the fact that porous metallic materials are now actively used in orthopaedics. In most cases, 3D printing is used to obtain such structures [2]. In this paper, firstly, the correspondence of the printed products with the model ones used for printing has been investigated. Secondly, the influence of pore geometry was investigated: two types of pores IWC and Diamond cells with the same wall thickness-to-cell volume ratio and approximately the same pore size, about 500 nm, were used. The mechanical behavior of the obtained structures was analyzed.

The research was supported by RSF (project No.№ 23-69-10003).

References:

1. Amer Nazir. A state-of-the-art review on types, design, optimization, and additive manufacturing of cellular structures [Текст] / Amer Nazir, K.M. Abate, A.Kumar, J-Y. Jeng // Int. J. Adv. Manuf. Technol.– 2019 – Vol. 104. – P. 3489–3510.

2. S.A.M. Tofail. Additive manufacturing : scientific and technological challenges, market uptake and opportunities [Текст] / S.A.M.Tofail,E.P.Koumoulos,A.Bandyopadhyay,S.Bose,L.O. Donoghue, C.Charitidis// Mater. Today. – 2018 – vol. 21. – P. 22-37.

INFLUENCE OF Mn AND Zr ADDITIONS ON STRENGTHENING AND STRUCTURE AT AGING OF Al-Cu-Sn ALLOYS

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Wrought alloys of the 2219 type (based on the Al-Cu-Mn system) are among the most durable and heat-resistant materials based on aluminum [1]. The high mechanical properties are due to the formation of strengthening nanosized precipitates during aging, which are primarily represented by the θ′(Al_2Cu) phase. To further improve the mechanical properties of these materials, for example, special addition of precious and transition metals (Ag [2], Zr, Sc) are used, which have a modifying effect on the precipitation structure. However, in our opinion, trace additions of low-melting elements (Sn [3], In, Cd) deserve special attention, which provide significant strengthening during aging due to a significant refinement of the precipitation structure.

The alloys based on Al-5Cu-Sn the system containing additions of transition metals Mn and Zr were chosen as the object of research. Previous works [4] demonstrated that wrought sheet semi-finished products obtained from an alloy based on Al-4Cu-Mn-Sn have a good combination of mechanical properties, characterized by high hardening (at the level of 2219 alloy) and elongation. Analysis of the fine structure, carried out using transmission electron microscopy, revealed that high hardening is due to the formation of fine precipitates with a high number density. However, grade 2219 type alloys also contain a Zr microadditive (and also Sc), which, as is known, makes it possible to increase the heat resistance of aluminum alloys. For a new group of wrought alloys based on Al-Cu-Mn-Zr(Sc)-Sn, influence of aging (in the temperature range 14-250 °C) on hardening and structure were studied.

The study was carried out with the financial support of the grant of the Russian Science Foundation (Project № 23-79-10147, https://rscf.ru/project/23-79-10147/).

References:

1. I.J. Polmear, Light Metals: From Traditional Alloys to Nanocrystals, 4th edition. (Oxford, Elsevier, 2006), p. 421.

2. Gazizov M, Kaibyshev R (2017) Precipitation structure and strengthening mechanisms in an Al-Cu-Mg-Ag alloy. Mater Sci Eng A 702:29–40. doi: 10.1016/j.msea.2017.06.110.

3. T.K. Akopyan, N.A. Belov, A.A. Lukyanchuk, N.V. Letyagin, F.O. Milovich, A.S. Fortuna, Characterization of structure and hardness at aging of the A319 type aluminum alloy with Sn trace addition. Journal of Alloys and Compounds 921 (2022) 166109.

4. Akopyan T.K., Letyagin N.V., Belov N.A. et al. The role of Sn trace addition in the precipitation behavior and strengthening of the wrought Al–Cu–Mn-based alloy. J Mater Sci 58, 8210–8229 (2023).

HYDROGEN-RELATED PHENOMENA IN HIGH-ENTROPY CANTOR ALLOY DOPED WITH NITROGEN

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Hydrogen-induced effects in multicomponent alloys CoCrFeMnNi (Cantor alloy), (CoCrFeMnNi)99.2N0.8 and (CoCrFeMnNi)98.6N1.4 were studied. The alloys were rolled and solution-treated to obtain a single-phase state, the resultant the grain size was ≈200 μm. The electrolytic hydrogen-charging of the samples was carried out at room temperature in a 3% NaCl aqueous solution with the addition of 3 g/L NH4SCN, the current density was 10 mA/cm2, the saturation time was 50 h. After hydrogen-charging, the samples were tensile tested at room and low temperatures, the strain rate was ~10–4 1/s and ~10–2 1/s.

Solid solution hardening with nitrogen does not affect the solubility of hydrogen in (CoCrFeMnNi)100-xNx alloys (120-130 ppm). According to spectrometry data, a thin (no more than 40 μm) surface layers of the 1mm-samples are saturated with hydrogen. The activation energies of hydrogen desorption are close for all alloys Ea = 17–19 kJ/mol, which are typical of the desorption from the crystal lattice and "weak" reversible traps, such as grain boundaries. Based on the analysis of the profiles of the distribution of hydrogen concentration over the samples' depth, the effective diffusion coefficient of hydrogen in the alloys under study was estimated to be 2.2·10-16 m2/s, 1.0·10-16 m2/s and 1,2·10-16 m2/s for CoCrFeMnNi, (CoCrFeMnNi)99.2N0.8 and (CoCrFeMnNi)98.6N1.4 alloys, respectively. The data above indicate an increase in hydrogen solubility in austenitic phase of the Cantor alloy due to alloying with nitrogen. Hydrogen-affected surface layers in the samples crack during tensile tests. In the CoCrFeMnNi alloy, cracking occurs predominantly along the grain boundaries, and for nitrogenous alloys, transcrystalline surface cracking is also characteristic.

Hydrogen-charging changes mechanical properties of the alloys: the yield strength increases, and the ductility of the samples decreases. The hydrogen embrittlement index kH, which indicates the relative change in sample elongation due to hydrogen-charging, decreases with nitrogen alloying (25%, 14% and 13% for CoCrFeMnNi, (CoCrFeMnNi)99.2N0.8 and (CoCrFeMnNi)98.6N1.4 alloys, respectively). That is, doping with nitrogen reduces the susceptibility of the Cantor alloy to hydrogen embrittlement. Hydrogen-charging decreases the stacking fault energy of all the alloys under study, which is promoting planar dislocation glide and splitting of dislocations upon straining. Despite this, the main mechanism of deformation of the alloys is dislocation slip, and the activity of mechanical twinning decreases both upon doping with nitrogen and upon hydrogen-charging.

The study was supported by the Russian Science Foundation, grant No. 20-19-00261, https://rscf.ru/project/20-19-00261/. The studies were carried out on the equipment of the "Nanotech" Center of the ISPMS SB RAS.

EFFECT OF THERMOMECHANICAL TREATMENT ON STRUCTURE AND MECHANICAL PROPERTIES OF MEDIUM ENTROPY ALLOYS DOPED WITH CARBON

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High-entropy and medium-entropy alloys (HEAs and MEAs) with TWIP/TRIP effects attract great interest due to a good balance of ultimate strength and ductility; in some cases, decreasing temperature to cryogenic conditions even improves their mechanical properties [1,2]. However, such alloys have rather low yield strength at room temperature, the increase of which can be achieved by alloying with interstitial elements, in particular carbon, as well as deformation and thermomechanical treatment.

Although the positive effect of carbon on the mechanical properties of the single face-centered cubic (fcc) phase HEAs is well known, its influence on the structure and properties of TRIP HEAs requires further study. In addition, many aspects of the effect of thermomechanical treatments on the structure and properties of such alloys remain unclear.

In this work, the effect of carbon addition on the structure and mechanical properties of a $Fe_{65}(CoNi)_{25}Cr_{9.5}C_{0.5}$ MEA was investigated. To study the effect of thermomechanical treatment, the alloy obtained by vacuum arc melting was additionally cold rolled to 80% and annealed at 700-900°C for 10 min followed by quenching in water.

Adding carbon enhanced the ductility of the alloy without a significant decrease in its strength. Furthermore, it caused a reduction in the amount of the bcc phase from 90% to 35%. Cold rolling increased the bcc phase fraction 40%. Subsequent annealing at 700-900°C for 10 minutes led to recrystallization of the microstructure, generating a higher volume fraction of the bcc phase and M23C6-type carbide formation.

Lowering the test temperature to cryogenic (-196°C) significantly increases the mechanical properties of the alloys in all states. The cold-rolled alloy has a high ultimate strength (2070MPa) and yield strength (1400MPa), together with ductility of 26%. The sharp increase in mechanical properties is due to the TRIP effect development. The relationship between the chemical composition, processing, structure, and mechanical properties of alloys are briefly discussed.

Financial support from the Russian Science Foundation (Grant No. 20-79-10093) is gratefully acknowledged. This work was carried out using equipment of the Joint Research Center of Belgorod State National Research University «Technology and Materials».

References:

[1] Li Z., Pradeep K.G., Deng Y., Raabe D., Tasan C.C. // Nature. 2016. V. 534. P. 227–230. doi:10.1038/nature17981.

[2] Li Z., Körmann F., Grabowski B., Neugebauer J., Raabe D. // Acta Mater. 2017. V. 136. P. 262–270. doi:10.1016/j.actamat.2017.07.023.

TEMPERATURE DEPENDENCE OF MECHANICAL PROPERTIES IN CARBON- AND NITROGEN-ALLOYED FeMnCrNiCo ALLOY

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The materials used in this study were $Fe_{20}Mn_{20}Cr_{20}Ni_{20}Co_{20}$ high-entropy Cantor alloy (HEA) and interstitial carbon- and nitrogen-alloyed $Fe_{19.9}Mn_{20}Cr_{20}Ni_{20}Co_{19}C_{1.1}$ (HEA-C) and $Fe_{19.7}Mn_{20}Cr_{20}Ni_{19.9}Co_{19}N_{1.4}$ (HEA-N) alloys. The cast HEA and HEA-N billets were subjected to a thermomechanical treatment (TMT): an annealing at a temperature of 1200 °C for 2 hours, cold rolling (80 % reduction) and final annealing at temperature of 1200 °C for 2 hours followed by water-quenching. The TMT for HEA-C alloy included annealing at a temperature of 1200 °C for 2 hours, hot forging at a temperature of 1230 °C, second annealing at a temperature of 1200 °C, cold rolling to obtain a thickness reduction to 80 % and final annealing at a temperature of 1200 °C for 1 hour following by water-quenching. All HEAs have been investigated using the X-ray diffraction analysis, transmission and scanning electron microscopy, tensile testing in temperature range from 77 to 473 K.

It has been shown that all alloys possess single-phase austenitic structure with FCC crystal lattice. Carbon and nitrogen alloying leads to increase of the lattice parameter of the investigated alloys (a_{HEA} = 3.598 Å, $a_{HEA\text{-}C}$ = 3.611 Å, $a_{HEA\text{-}N}$ = 3.607 Å). The analysis of the EBSD maps indicates that the average grain size of the HEA (d = 215±77 μm) is larger than those in carbon- and nitrogen-doped alloys (d = 128±59 μm for HEA-C, d = 186±70 μm for HEA-N).

The results of static tension demonstrate a strong temperature dependence of mechanical properties for all investigation alloys. With a decrease in temperature from 473 to 77 K, both the yield strength (YS) and the ultimate tensile strength (UTS) of all alloys increase. The maximum values of YS and UTS are observed at liquid nitrogen test temperature (77 K), and the highest values of YS and UTS correspond to the HEA-C (751±16 MPa and 1323±24 MPa). Temperature dependence of the elongation to failure (El) showed that all studied HEAs have a large plasticity. Solid-solution hardening of Cantor alloy with carbon leads to a slight decrease in plasticity over the entire temperature interval, but nitrogen-alloying promotes it at T > 250 K. A decrease in temperature is accompanied by an increase of El values for HEA and HEA-C, and a decrease for HEA-N specimens.

Dislocation slip is a dominating deformation mechanism of all alloys at 297 K. At liquid nitrogen temperature, dislocation slip remains a dominating deformation mechanism in HEA-C, but mechanical twinning is additionally activated in Cantor and nitrogen-containing alloys. HEA-N alloy shows lower activity of the mechanical twinning compared to the interstitial-free alloy.

The research was supported by the Russian Science Foundation (project No. 20-19-00261, https://rscf.ru/project/20-19-00261/).

QUALITY ASSURANCE IN LASER METAL DEPOSITION

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Spreading usage of additive manufacturing in high-end parts production requires continuous improvement of quality assurance. The article presents a review of systematic approach to quality control in laser metal deposition process. Four main aspects are discussed: material quality control and traceability, mechanical properties of deposited parts, heat treatment and geometrical accuracy. These aspects are interconnected and significantly affect each other, so complex approach is required. For example, heat treatment can influence both mechanical properties and geometrical accuracy, as high temperature heat treatment and high-speed cooling induce additional stresses and distortion in deposited part negating the increased mechanical properties. Proposed solution is based on cumulative review of all technological aspects of deposition process, heat treatment and postprocessing along to material quality control, mechanical testing and robust approach to distortion compensation.

THE MICROTRUCTURE HIGH-SPEED QUENCHED ALLOY OF SYSTEM AL-CU-FE

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Aluminum alloys remain one of the most demanded constructional materials in aviation and space technology, due to their low specific weight and high specific strength. In connection with the composite materials development for aviation technique, increased interest of quasi-crystalline Al-alloys as fillers that reinforce composite matrices of various types: polymer, metal, ceramic, etc. The main function of such a filler is to increase the strength characteristics and reduce the composite specific weigh as a whole.

Structural analysis methods (metallographic, X-ray diffraction, differential scanning microscopy) were used to complex research of the structure Al82Cu7Fe11 alloy obtained melt spinning method in the form of ribbons. Was shown that a multiphase amorphous-nanocrystalline structure of high dispersity, which includes an aluminum-based solid solution, intermetallic compounds Fe4Al13, CuAl2, and a small amount of a quasi-crystalline Al-Fe-Cu phase with a tenth-order symmetry axis (decagonal) is formed in the alloy. The crystallographic approximant of the latter is the primary Fe4Al13 intermetallic [1]. The main structural component alloy is iron aluminide, the which content varies from 68 to 61 wt.% over the ribbon cross section from the contact to the free surface. The temperatures of phase transformations in the alloy during heating were determined. A comparative analysis of the structure composition and morphology of the

phases formed in rapidly quenched ribbons and crystallized under equilibrium conditions same composition microingot was carried out. The difference in the alloys structure after various methods of crystallization was established. In microingot, unlike the ribbon, is missing decagonal phase. A dendritic structure with precipitates of large primary Fe4Al13 and CuAl2 intermetallic compounds is formed in it, the morphology of which adversely affects of the mechanical properties alloy as a whole. The microhardness of the ingot main structural components has been determined. Was shown that the high alloy hardness 615 HV after high-speed quenching is provided formed multiphase amorphous-nanocrystalline structure state.

The high hardness of the Al82Cu7Fe11 alloy with increased aluminum content makes it promising as a dispersion-strengthening filler in the production of high-strength composites with a lowered unit weight.

The work was carried out according to the state order № 075-01176-23-00

References:

1. Павлов И.С., Бахтеева Н.Д., Головин А.Л., Тодорова Е.В., Чуева Т.Р., Васильев А.Л. Особенности структуры быстро закаленного сплава системы Al–Cu–Fe с декагональными квазикристаллами. Кристаллография, 2023, 68(1),115–120.

METAL-POLYMER MATERIALS PRODUCED BY SOLID-PHASE METHOD OF MODIFICATION

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It is known that mechanical impact is a method of stimulating various physical and chemical processes. For these processes to occur between solids, it is necessary to activate their surface and make close contact. The solid-phase method of modification (SPMM) creates all the conditions for the processes mentioned above, in particular, for the production of metal-polymer materials. The study of the processes occurring during SPMM is aimed at further development of the technology of this modification method and its use to control the properties of metal-polymer materials and the characteristics of compositions based on them. This study presents some research results related to the investigation and explication of the mechanism of SPMM in the joint solid-phase mechanical processing of the surface of metals and polytetrafluoroethylene. The solid-phase method of modification was carried out in energy-intensive devices.

The main condition for the modification is the activation of the surface of the components under mechanical impact based on changes in the structure and defect of the surface, its size and chemical activity [1]. According to the results of the studies, it was postulated that the modification process consists of the following stages:

1. Mixing the components and transporting them to each other's surface.

2. An increase in the surface and defect structure of components under mechanical impact.

3. Creation of conditions for close contact of component surfaces.

4. The course of adsorption-chemisorption processes with the formation of intermediate surface compounds.

The high stability of the peroxyl macroradical of the fluoropolymer, confirmed by the results of EPR and IR spectroscopy, suggests that during the solid-phase mechanical processing of a mixture of metal and polytetrafluoroethylene in the presence of atmospheric oxygen, free macroradicals interact with the metal surface according to the following scheme [2]:

$$R - CF_2 - O - O - + Me \cdot\!\!\rightarrow R - CF_2 - O - O - Me \rightarrow R - CF_2 - O - Me + MeO.$$

That way, the combined mechanical processing of the components leads to the formation of a polymer coating on metal particles, accompanied by adsorption-chemisorption processes. interactions of macroradicals as products of mechanical degradation of the polymer with the metal surface.

References:

1. Gorohovsky G.A. Surface dispersion of dynamically contacting polymers and metals. – Kyiv: Naukova Dumka, 1972. – 151 p.

2. Investigation of the influence of mechanical impact on the EPR spectrums of polytetrafluoroethylene / E.G. Belov [and others.] // Bulletin of the Technological University. – 2013. – V. 16, №19. – P. 101-103.

STRUCTURE AND HARDENING OF THE Al–7.1Zn–2.8Mg–1.4Ni–1.1Fe (wt.%) ALLOY MANUFACTURED VIA ELECTROMAGNETIC CASTING

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A calculation technique (Thermo-Calc software) and experimental methods (scanning and transmission electron microscopy and microprobe chemical analysis) have been used to study the effect of thermo-deformation treatment on the structure and hardening of the Al–7.1% Zn–2.8% Mg–1.4% Ni–1.1% Fe alloy manufactured via casting in an electromagnetic crystallizer (EMC).

The experimental AZ6NF-2 alloy with contents of zinc and magnesium corresponding to those of the grade AZ6NF (GOST4784-2019) alloy and with two times higher contents of nickel and iron served as the object under study. The AZ6NF-2 alloy was produced using the EMC method on the operational facilities at the Magnetic Hydrodynamics Scientific and Production Center JSC. A 500-mm long rod was cut from a long-length billet 14 mm in diameter, which was the study object, both as-cast and after treatment using different thermo-deformation modes.

It has been shown that due to a high cooling rate (more than 10^3 K/s), the EMC method makes it possible to obtain the cast fine-grained structure, in which the size of a dendritic cell is ~5 μm and the entire content of iron is bound into eutectic submicron-sized inclusions of the Al_9FeNi phase. The heating mode at 450°C for 3 h +500°C for 3 h results in spheroidizing of Al_9FeNi particles and total dissolution of Zn and Mg in the

aluminum solid solution- (Al). This structure yields high ductility during hot and cold rolling, which makes it possible to obtain strips up to 0.5 mm in thickness. The structure typical of composites is formed during deformation: globular submicron-sized particles of the Al_9FeNi phase uniformly distributed over the aluminum matrix.

To estimate the hardening degree after thermal treatment, the dependences of the hardness of the initial rod and rolled strips on the aging temperature were plotted. The samples were preliminarily treated for a solid solution at 450°C and held for 1 hour with subsequent quenching in water. In the as-quenched state the hardness was less than 100 HV and after a week of storage at room temperature it was 140–150 HV, which indicates a considerable effect of natural aging. It has been shown that the maximum hardness (~190 HV) is reached in the rod at 125°C and in strips at 150°C due to the formation of secondary precipitates of about 50 nm in size, which contain Zn and Mg.

The study of decomposition products using the TEM method reveals particles smaller than 10 nm in size, whose content, according to calculation taking the experimental data on phase identification into account, is ~10 wt. It should be noted that nanoparticles are highly homogeneous. In particular, there are no grain boundary chains of secondary precipitates, which are typical for ternary alloys of the Al–Zn–Mg system with the same high content of zinc and magnesium. As was previously shown, globular particles of a eutectic origin contribute to an increase in the uniformity of the distribution of decomposition products (Al) during aging. According to the micro-diffraction data and the corresponding dark-field images, the precipitates at the aging peak correspond to the η′ ($MgZn_2$) phase, which is in good agreement with previous results obtained on AZ6NF alloys.

Summing up the results, the combination of high hardness and ductility may lead to high mechanical properties, which indicates that the EMC technology is promising for alloys of the AZ6NF type containing more than 1% Fe.

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VARIATION IN STRUCTURE, MARTENSITIC TRANSFORMATION AND MECHANICAL BEHAVIOR ON A RISE IN MIXING ENTROPY IN Ti-Hf-Zr-Ni-Cu-Co SHAPE MEMORY ALLOYS

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The aim of the study was an investigation of the variation in structure, martensitic transformation and mechanical behavior on a rise in the configuration entropy in the senary Ti-Hf-Zr-Ni-Cu-Co shape memory alloys. An increase in configuration (mixing) entropy was realized by an increase in the concentration of each Hf, Zr, Cu and Co atoms from 1 to 17 at. % in the senary alloy. It allowed to increase the configuration entropy from 0.89R to 1.79 R.

It was found that regardless of the mixing entropy, all alloys included the matrix and secondary phase. The matrix was in the B2 state, whereas, the structure of the secondary phases did not depend on the configuration entropy but it was determined by the concentration of Ti and Ni atoms as it was observed in binary NiTi alloy. An increase in concentration of doping atoms led to a dendrite liquation in main matrix that affected the chemical composition of the dendrite cell core and boundary.

On increase in the configuration entropy in the alloy, the temperatures of the martensitic transformation decreased. It was attributed to the Hf, Zr, Cu, Co increased the lattice distortion that increased the elastic energy. This energy changed the thermodynamic condition for the forward martensitic transformation and larger variation on Gibbs energy should be provided to overcome the dissipative and elastic energy to nuclear the martensite crystals. It was found that in the high-entropy Ti-Hf-Zr-Ni-Cu-Co shape memory alloys with a concentration of each doping elements of 10 or 17 at. %, the martensitic transformation was not observed on cooling to -180 ^{o}C. However, the martensite transformation could be initiated by stress that led to the observation of the superelasticity effect. It was found that in high-entropy alloys, the superelasticity is observed in a wide temperature range (more than 100 ^{o}C) that had never been found in the low and medium entropy shape memory alloys. It was shown that an increase in concentration of doping elements, the strain up to failure decreased and the strength of the alloys increased.

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INFLUENCE OF DEFORMATION TEMPERATURE ON MECHANICAL PROPERTIES OF THE HIGH-ENTROPY Ti30Hf10Zr10Ni30Cu10Co10 ALLOY

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The aim of the present work was to study the influence of deformation temperature on mechanical properties of the high-entropy $Ti_{30}Hf_{10}Zr_{10}Ni_{30}Cu_{10}Co_{10}$ shape memory alloy. The $Ti_{30}Hf_{10}Zr_{10}Ni_{30}Cu_{10}Co_{10}$ ingot was produced by electron arc melting with 5 remeltings to obtain the homogeneous structure. The cast alloy consisted of the main B2 phase and secondary Ti_2Ni-type phase. The main B2 phase did not undergo the martensitic transformations on cooling to -180°C. The ingot was cut into plates of 1 mm in thickness, which were used to cut the dog-bone specimens for tensile tests. The samples had a working length of 10 mm and a width of 0.8 mm. The samples were deformed to fracture with intermediate unloading. The deformation was carried out at temperatures of 100°C, 25°C, 0°C, -25°C, -50°C, -100°C at which all samples were in the austenite B2 phase.

It was found that at 100°C, the sample was elastically deformed with a small plastic strain before fracture. An ultimate strength was 1240 MPa and a strain up to failure was 2.8%. A decrease in deformation temperature to 0°C, suppressed the plastic strain and the

samples were deformed elastically with brittle fracture. The strength decreased from 1240 MPa to 700 MPa and the strain up to failure dropped to 0.9 %. Deformation at -25°C was accompanied by the martensite formation that increased the strain up to failure. The less the deformation temperature the larger the strain up to failure. As if the samples was deformed at -100°C, the strain up to failure increased by 11.4 %.

Using the stress vs strain curves, the transformation stress was determined and the dependence of this value on the deformation temperature was analysed. It was found that this dependence was linear, which corresponded to the Clausius-Clapeyron like relation. The dϭ/dT coefficient was equal to 2.3 MPa/°C that was 2.5 times less than in the binary NiTi alloys.

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HIGH-ENTROPY CANTOR ALLOYS CoCrFeNiMn AND CoCrFeNiAr: METHODS FOR IMPROVING PROPERTIES

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The highly entropic five-component alloys CoCrFeNiMn (Cantor alloy) and CoCrFeNiAl, created among the first and studied more than 20 years ago, continue to attract the attention of materials physicists because of their possible application in various industries due to successful combination of strength and plastic properties. To date, a lot of experimental data have been accumulated on ways to control the properties of these alloys.

In previous reviews [1,2], methods for improving the mechanical properties of high-entropy CoCrFeNiAl and CoCrFeNiMn alloys were analyzed from the point of view of their possible industrial use. The solution to this problem involved strengthening of grain-boundary hardening, solid-solution hardening, generation of a nanocrystalline state, hardening by precipitations, partial amorphization, use of hardening surface treatments, development of new methods for obtaining HEA, etc., ultrasonic exposure, formation of structure gradients, etc. Such approaches can stimulate a significant expansion of the application areas for these HEA.

In this paper, we review the publications of Russian and foreign authors in two directions of improving the properties of these alloys: alloying, isolation and heat treatment and the use of Calphad phase diagrams. Within the first direction, the role of alloying with B, Vi, Al, V, Si, Nb was analyzed; γ and γ′with nano precipitations, various modes of thermal and deformation treatment. It was concluded that it is necessary to conduct experiments on the HEA alloying with Zr and Nb, which have proven themselves well in the hardening of steels. Creation and modification of properties of five-component HEAs is possible using Calphad computer programs designed to calculate transformation diagrams. The analyzed results of publications on the thermodynamic description of five-component alloys are confirmed by comparing phase diagrams with available experimental data. In one of the analyzed works on the phase formation of five-component HEA consisting of Co, Cr, Fe, Ni, Al, Mn, Cu, 2436 compositions were

considered, which made it possible to determine 1761 variants of reliable prediction of the formation of BCC/B2 and FCC phases, bypassing amorphous phases and intermetallides, thereby constructing a certain level of mechanical properties. It is shown that the design of a new generation of HEA is possible on the basis of Calphad phase diagrams calculation.

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References:

1. Gromov V.E., Konovalov S.V, Ivanoy Yu.F., Osintsev K.A. Structure and properties of high-entropy alloys. Springer. Advanced structured materials; 2021: 110.

2. Gromov V.E., Ivanov Yu.F., Osintsev K.A., Shlyarova Yu.A., Panchenko I.A. Structure and properties of high-entropy alloys. Ru. Science Moscow; 2021: 203.

EFECT OF THERMAL TREATMENT ON PROPERTIESE OF THE COPPER ALLOY AFTER FRICTION STIR PROCESSING

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A Cu-0.3%Cr-0.5%Zr (wt. %) alloy was chosen as the starting material. The Cu-Cr-Zr ingot was forged at about 900 °C to a total strain of about 1. Then the alloy was subjected to solution treatment (ST) at 920 °C for 1 hour with subsequent water cooling. Part of the samples was aged at 450 °C for 1 hour (AT). The plates with a size of 3×70×95 mm were cut for friction stir processing (FSP). The tungsten carbide processing tool with shoulder diameters of 14.5 mm and 10.5 mm and pin diameters of 2.5 mm and 3 mm for solution treated and aged samples, respectively, was used for FSP. The tool rotation speed and tool travel speed are achieved at 400 rpm and 125 mm/min, respectively. The processing temperature was measured using K-type thermocouples placed into the plate in close proximity to the stir zone and reached 400 °C. The Vikers hardness was measured by the crossection of the friction stir zone by a load of 100 g during 10 sec using a Wolpert 420 MVD. Electrical conductivity was indicated using Constanta K-6 equipment by eddy current methods in the friction stir zone of samples.

Solution treatment provided microhardness and electrical conductivity of about 70 HV and 40% IACS, respectively. Aging leads to an increase in electrical conductivity to 50% IACS with a hardness of about 100 HV. Subsequent FSP is accompanied by significant strengthening of Cu-Cr-Zr alloys, regardless of previous thermal treatment. In solution-treated and aged samples, hardness achieved 170 HV and 130 HV, respectively. Electrical conductivity increases in the friction stir zone to 65% IACS in ST condition and 67% IACS in AT condition after FSP. The difference in hardness may be the result of microstructure evolution during FSP in the stir zone.

This work was carried out using equipment of the Joint Research Center of Belgorod State National Research University «Technology and Materials».

PRODUCTION OF PERMANENT MAGNETS BASED ON HARD MAGNETIC MATERIALS FE-CR-CO AND FE-SR-O BY PIM-TECHNOLOGY

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Nowadays additive manufacturing methods are being actively introduced into existing technological processes of enterprises. Their usage allows to manufacture products based on functional materials with a high configuration complexity and a high level of physical and mechanical properties in the short time. A potential method for the production of permanent magnets is the Powder Injection Molding (PIM) technology, which provides the ability of microstructure, composition and properties of products control at each technological stage.

«Green» articles based on Fe-Cr-Co and Fe-Sr-O alloys were obtained by compacting the granulate in an injection molding machine at the softening temperature of an organic binder. Then primary binder from this details was removed during the debinding stage to obtain «brown» articles.

Preforms of permanent magnets based on the Fe-Cr-Co alloy were subjected to thermomagnetic treatment (TMT) after sintering in a hydrogen atmosphere. TMT was utilized to create optimal microstructure, which provides the high magnetic properties. Sintering of strontium hexaferrite details was performed in the oxidizing atmosphere to form a single-phase samples.

The microstructure in the high-coercivity state, studied by transmission electron microscopy (TEM), confirmed that the spinodal decomposition of the α-solid solution into two phases occurred at the TMT stage. It allows to rich high magnetic properties: H_{CB} = 41.9 kA/m, B_r = 1.29 T, $(BH)_{max}$ = 39.3 kJ/m^3.

The properties of permanent magnets based on strontium hexaferrite (H_{CB} = 66.1 kA/m, B_r = 0.09 T) were lower in comparison with properties of magnets obtained by traditional ceramic technology because of the low density of the samples and the presence of defects in the form of cracks and pores.

As a result of the analysis of the structure, magnetic and mechanical characteristics of research samples, it was found that the using of PIM method allows production of high-quality permanent magnets based on alloys of the Fe-Cr-Co system. But the modes of obtaining products based on strontium hexaferrite require refinement in order to increase the density and the level of magnetic properties of permanent magnets.

PRODUCTION OF HIGH-EMISSION COATINGS BY DETONATION SPRAY COATING METHOD

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The depletion of traditional fossil energy sources leads to an intensification of the global energy crisis. It has been established that 30% of the energy consumed by industrial installations is lost in heating units and furnaces [1]. A promising way to increase the energy efficiency of such units is to form a coating with high heating emissivity on the inner surfaces. Such coatings significantly increase energy efficiency due to the high infrared radiation coefficient from the heated surface to the process gas.

The infrared emissivity of a material specifies how well an object emits radiation compared to a absolutely blackbody at the same temperature. The IR emissivity of a material depends on its composition and structure. Spinel materials Mg (Al, Ti, Mg)O_4 exhibit high infrared emissivity at high temperatures [2]. Literature data indicate that perovskites have a great potential for obtaining materials with high emissivity [3].

The possibility of using $MnAlO_4$, $FeAlO_4$ and $La_{0.9}Sr_{0.1}MnO_3$ coatings as high-emission energy-efficient coatings in the low-temperature region for baking ovens in the food industry was studied in this work.

Coatings were successfully obtained by detonation spraying coating method. Experimental samples of $MnAlO_4$, $FeAlO_4$, and $La_{0.9}Sr_{0.1}MnO_3$ coatings on structural steel St3 were successfully obtained by detonation spray coating (DSC) process. The microstructure, phase composition, and infrared emissivity of the resulting coatings were studied at a temperature of 500 °C in the wavelength range of 1–14 μm. Perovskite powder $La_{0.9}Sr_{0.1}MnO_3$ and powders of $MnAlO_4$ and $FeAlO_4$ spinels for detonation spraying were obtained by the solid-phase reaction method.

Based on the results of the study, it was found that the coatings obtained have a high emissivity in the wavelength range of 3-7 μm. Thus, the detonation spray coating process makes it possible to obtain high-quality high-emissivity ceramic coatings, which can be used as energy-efficient coatings for industrial bakery equipment.

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References:

[1] Švantner M., Vacíková P., Honner M. Non-contact charge temperature measurement on industrial continuous furnaces and steel charge emissivity analysis //Infrared physics & technology. – 2013. – T. 61. – C. 20-26.

[2] E.Y. Sako, H.D. Orsolini, M. Moreira, D. De Sousa Meneses, V.C. Pandolfelli, Emissivity of spinel and titanate structures aiming at the development of industrial high-temperature ceramic coatings, J. Eur. Ceram. Soc. 41 (2021) 2958–2967.

[3] Han R. et al. High infrared emissivity energy-saving coatings based on LaMnO3 perovskite ceramics //Ceramics International. – 2022. – T. 48. – №. 14. – C. 20110-20115.

INFLUENCE OF POWDER ON THE PROPERTIES OF MATERIALS OBTAINED BY LASER-DIRECT ENERGY DEPOSITION

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Laser-Direct Energy Deposition refers to additive processes in which energy and material are introduced simultaneously. The heat input in this case is by laser and the raw material is metal powder.

Powders for additive manufacturing are produced by a variety of atomisation methods including gas, water, plasma atomisation, plasma rotating electrode process (PREP). The characteristics of the powders depend on the fabrication method and the chosen production modes. Powder characteristics have a high influence on both the L-DED process and the properties of the resulting material.

Understanding the powder stream formation process is primary to L-DED technology as it determines the initial conditions for the formation of the melt pool. The powder flow parameter is used to characterise the powder stream. Depending on the resulting powder flow, the fraction of powder particles entering the melt bath can vary. Thus, the powder characteristics influence the capture efficiency.

The properties of the obtained material also depend on the characteristics of the powder material. The best quality material structure can be obtained from powders that fulfil the requirements in chemical composition and morphology. The chemical composition of the powder, the presence of metallic and non-metallic inclusions and the morphology of the particles have a major influence.

The powder chemical composition determines the structure and phase composition. Deviations from the content of alloying elements can lead both to changes in the required properties and to a decrease in processability for the L-DED process. Changes in the content of the main alloying elements and impurities can lead to the defect formation. Increase of iron content in nickel superalloy leads to the appearance of cracks due to the formation of TCP phases. Increase of carbon content in nickel superalloy powders leads to increase of cracking. Inclusions in powder particles are most often transferred into the material structure. Experimental results show that nitride and oxide inclusions in steels and nickel alloys can lead to cracks.The oxygen and hydrogen content and particle shape affect the appearance of porosity in the material.

1. M. Gushchina, O. Klimova-Korsmik, and G. Turichin, 'Features of the Powder Application in Direct Laser Deposition Technology', New Advances in Powder Technology [Working Title]. IntechOpen, Feb. 17, 2023. https://doi.org/10.5772/intechopen.108853.

2. Piscopo, G.; Atzeni, E.; Saboori, A.; Salmi, A. An Overview of the Process Mechanisms in the Laser Powder Directed Energy Deposition. Appl. Sci. 2023, 13, 117. https://doi.org/10.3390/ app13010117

STRUCTURE AND MECHANICAL PROPERTIES OF DEFORMABLE ALLOY SHEETS IN Al-Mg-Ca-Mn SYSTEM

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This work aims to show the principal possibility for obtaining sheets from calcium-doped alloy of type AA1530. Using the calculated data, phase composition was analysed and concentrations of alloying elements Al3Mg2Ca0.8Mn alloy were justified. Microstructure was analysed with SEM and TEM, phase composition data were confirmed by XRD analysis. Sheets 0.5 mm were produced from 10 mm thick flat ingots by hot and cold rolling (HR and CR respectively) under three paths. First path (R400): no pre-homogenisation HR at 400 ºC to 2 mm with annealing and CR; second path (R450): no pre-homogenisation HR at 450 ºC to 2 mm with annealing and CR; third path (R500): two-step homogenization (440 ºC at 6 h. and 550 ºC at 3 h.) HR at 500 ºC to 2 mm with annealing and CR. Strength was evaluated by measuring Vickers hardness and uniaxial tensile results at room temperature.

According to the calculated data, the cast microstructure should be represented by four phases: (Al), Al_6Mn, Al_4Ca, Al_3Mg_2. Mass fraction of phases is 22%, which decreases after solid solution treatment at 440 ºC to 12%. Based on SEM results, in the as-cast state, (Al) contains approximately 2% magnesium and an estimated concentration of manganese. As-cast microstructure consists of aluminium solid solution and micron-sized branched multiphase eutectic. Most aluminium dendritic cells are round or oval in shape. Subsequent homogenisation leads to fragmentation and spheroidisation of the eutectic phases.

As a result of rolling, a stringy elongated eutectic in the pulling direction can be observed. Moreover, eutectic crystals size did not change. At the same time, the microstructure after HR by paths R400 and R450 characterized by phase segregations in the middle of sheets. After R400 cold rolling, there is a delamination, indicating about low temperature of the pre-existing hot rolling. It does not occur in cold-rolled sheets under R450 and the elastic-tension state is maintained. This is expressed in mechanical properties, in particular the relative elongation is about zero. Annealing at [300 oC, 1 h.] of cold-rolled sheets under R450 leads to a decrease in UTS and an increase in plasticity (from 390 to 310 MPa and from 0.2 to 10%, respectively). The test results of sheets treated with R500 without subsequent annealing are similar to those of R450. However, in the annealed state after CR, the sheets have higher YS and relative elongation (183 MPa and 13 % vs. 171 MPa and 10 %). In both cases, the strength properties are significantly higher than those of 1530 and similar with the 1560 alloy. The study of thermal stability in the temperature range of 100-450 ºC showed that the alloy retains an unrecrystallised structure up to 300 ºC.

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VECTORIZATION OF HEA'S STRUCTURE AND COMPOSITION

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In the first stage of the development of a multiscale modeling system of HEA we consider the problem of transforming the data on the structure and composition of HEA into a format suitable for use as input data for machine learning systems and neural network prediction models.

We propose an alternative to quasi-random structure generation without computing the crystal cell of the alloy in order to preserve the randomized distribution of atoms at the positions given by the space symmetry group. For this purpose, a discrete-time Markov chain model (DTMC) [1] and a Delaunay triangulation algorithm for modeling and analyzing systems with random state changes and transition probabilities are constructed based on the quantitative alloy composition.

The transition matrix was calculated using the formula

$$T_{i,j} = \frac{N_{i,j}}{\sum_{k=1}^{n} N_{i,k}}$$

where $T_{i,j}$ is the transition probability from atom type i to atom type j, $N_{i,j}$ is the number of transitions from atom type i to atom type j, and n is the total number of atom types.

Based on the database [2] of equimolar HEA for stable and unstable compositions of four- and five-component alloys, the training of the neural network model for prediction of properties was carried out. The total database was 574952 compositions at 0.9 of melting temperature and 1350 K, of which stable: 24203. When trained on 4-component compositions and tested on 5-component compositions, the accuracy of alloy properties such as: melting temperature of the alloy, Young's modulus, stacking defect energy of the alloy, entropy of alloy mixing and others, was 94.4%. The difference between the training and validation error functions at 50 training epochs was 0.002.

References:

[1] A. A. Markov (1971). "Extension of the limit theorems of probability theory to a sum of variables connected in a chain". reprinted in Appendix B of: R. Howard. Dynamic Probabilistic Systems, Volume 1: Markov Chains. John Wiley and Sons.

[2] Chen, W., Hilhorst, A., Bokas, G. et al. A map of single-phase high-entropy alloys. Nat Commun 14, 2856 (2023). https://doi.org/10.1038/s41467-023-38423-7.

ENGINEERING BIOACTIVE POROUS TITANIUM SCAFFOLDS BY ADDITIVE MANUFACTURING: THE FUTURE OF BIOMIMETIC ORTHOPEDIC IMPLANTS

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One of the urgent tasks of modern materials science is the development of innovative metallic materials for biomedical applications. In particular, recently in the world literature much attention has been paid to the design of porous materials for the creation of implants used to replace diseased areas of bone tissue. The application of modern approaches, such as additive manufacturing, can significantly enhance the ability to develop regulated pore geometries and target material samples with controlled mechanical behavior and the ability to locally deliver antitumor drugs, which may lay the foundation for the development of bioactive scaffolds used in onco-orthopedics. We present methodological approaches to engineering innovative porous titanium scaffolds providing osteoconductivity and osteoinductivity, promising for use as platforms providing local drug delivery to the implantation area.

To develop models of porous titanium scaffolds with different configuration, shape, porosity, and pore geometry we used models based on triply periodic minimal surfaces. Calculation of strength and elastic properties of the developed materials with different pore parameters was carried out by finite element simulation. Porous materials were printed using selective laser melting with beam size up to 40 μm. Ti-6Al-4V titanium alloy traditionally used in medicine as the basis of orthopedic implants, was chosen as the printing material. Biocompatibility and biological activity of the developed materials were studied using various biological models, in vitro and in vivo.

It was previously shown that Ti-6Al-4V alloy is characterized by optimal biocompatibility, does not induce reliable hemolysis and cytotoxicity in vitro and systemic toxicity in vivo. To use this method of 3D modeling, the design of samples with penetrating pores of different geometry and configuration was carried out on the basis of analytical expressions and within the framework of computer-assisted design systems. Using finite element modeling, the influence of the elementary mesh design parameters of the specimens on their mechanical performance is evaluated. As a result of the study, three-dimensional models of porous material samples with different cell design and pore geometry are constructed and their influence on the mechanical characteristics of porous samples made of Ti-6Al-4V titanium alloy is numerically analyzed. The results obtained will be used to efficiently develop and analyze porous biomaterials for the fabrication of medical implants using 3D printing.

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DIRECT ENERGY DEPOSITION OF GRADIENT MAGNETIC MATERIALS

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Additive manufacturing is increasingly being integrated into everyday life and the mass production segment. The main advantage of additive technologies is the ability to manufacture complex geometries while maintaining mechanical characteristics comparable to materials obtained using classical production methods. In some cases, avoiding welded seams with intricate geometries allows for achieving higher mechanical performance in parts. A new advancement in the additive technology field is the printing of gradient materials with specified physical and chemical properties. However, printing with dissimilar materials is associated with challenges in connecting these distinct materials, as they might often be incompatible with each other. This necessitates the utilization of intermediate layers [1]. Furthermore, there are limitations inherent to 3D printers that prevent such printing endeavors.

Direct Energy Deposition is one of the technologies that enables the printing of gradient materials. Moreover, this technology provides *in-situ* mixing of materials [2]. In this study, the properties of gradient soft magnetic materials were investigated. The results demonstrated that *in-situ* alloying is preferable for obtaining magnetic materials with varying levels of saturation magnetization. The structural and magnetic characteristics of 316L-AlBronze, 316L-Al, and layered steels based on 316L, 410L, 431, and 09Cr16Ni4Nb were examined [3]. The outcomes of the conducted studies revealed saturation magnetization primarily ranging from 0 to 170 emu/g. Furthermore, the resulting materials exhibited commendable strength and durability.

References:

1. Mendagaliev R. V. et al. Direct energy deposition of Cu–Nb functionally graded layers for dissimilar joining titanium alloys and steels //Materials Letters. – 2022. – T. 324. – C. 132721.

2. Dubinin O. N. et al. Gradient soft magnetic materials produced by additive manufacturing from non-magnetic powders //Journal of Materials Processing Technology. – 2022. – T. 300. – C. 117393.

3. Mendagaliev R. V. et al. Direct Laser Deposition of Austenitic and Martensitic Steel Gradient Layers //Metals and Materials International. – 2023. – T. 29. – №. 5. – C. 1555-1562.

INVESTIGATION OF THE STRUCTURE AND THERMAL PROPERTIES OF 3D PRINTED COPPER ALLOY

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3D printing makes it possible to produce new and more effective designs, which is difficult or impossible to produce using traditional manufacturing [1]. Therefore, there are works where scientists are trying to come up with a new way to use materials in 3D printing more efficiently. One of such materials is Cu and its alloys [2]. The difficulty of printing with copper and copper alloys lies in the low absorption of laser radiation, which leads to an uneven melt bath [3] and damage to the printer [4]. But since copper alloys have outstanding thermal properties (TC = 400 W/mK), which makes it possible to manufacture elements such as radiators from them, then the use of 3D printing is a very attractive way of manufacturing. The heat sink's performance is determined by both the material properties and the shape of the part. Therefore, 3D printing can create thermal components with complex geometry that are hard to achieve with CNC machining. This work investigated the use of laser powder bed fusion (LPBF) for 3D printing with aluminum bronze. The appropriate process parameters for LPBF of aluminum bronze were selected. To do this, samples were printed using a standard matrix of parameters, such as laser power, scan speed, hatch spacing and layer thickness. Then the porosity of the samples was measured using two methods: optical microscopy and hydrostatic weighing. Based on the porosity measurements, five parameter sets that resulted in the lowest porosity were selected. The microstructure and thermal conductivity of the samples printed with these parameter sets were studied. Thixomet Pro software and ImageJ were used to analyze the optical images of the microstructure, and a thermal conductivity meter was used to measure the thermal properties. The results were compared with those of conventional aluminum bronze materials and the effects of LPBF on the properties of aluminum bronze were discussed.

References:

1. Wong K V and Hernandez A 2012 A Review of Additive Manufacturing ISRN Mech. Eng. 2012 1–10.

2. De Terris T, Baffie T and Ribière C 2023 Additive manufacturing of pure copper: a review and comparison of physical, microstructural, and mechanical properties of samples manufactured with Laser-Powder Bed Fusion (L-PBF), Electron Beam Melting (EBM) and Metal Fused Deposition Modelling (MFDM) technologies Int. J. Mater. Form. 16 32.

3. Colopi M, Demir A G, Caprio L and Previtali B 2019 Limits and solutions in processing pure Cu via selective laser melting using a high-power single-mode fiber laser Int. J. Adv. Manuf. Technol. 104 2473–86.

4. Jadhav S D, Dadbakhsh S, Goossens L, Kruth J-P, Van Humbeeck J and Vanmeensel K 2019 Influence of selective laser melting process parameters on texture evolution in pure copper J. Mater. Process. Technol. 270 47–58.

CORROSION-RESISTANT CHROMIUM-BASED COATINGS OBTAINED BY VACUUM-ARC METHOD

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Chromium-based coatings are widely used in metalworking due to their good mechanical and tribological properties, as well as corrosion and temperature resistance [1,2]. Coatings based on chromium nitride and chromium oxides on substrates of 40X steel with a thickness of about 1 μm were obtained by vacuum-arc method using a stationary arc source. Accelerated corrosion tests were carried out by chemical and electrochemical methods in 3% and 0,9% aqueous NaCl solution at room temperature, respectively [3]. It was found that the chromium oxide coating performs better in an aggressively corrosive environment than the CrN coating. The results of chemical studies show that the highest corrosion rate is observed for a sample of uncoated steel and is about 0.141 g/(m^2·h). Coating reduces the corrosion rate of steel by more than two times, performing a protective function. The obtained anode polarization curves also confirm that the chromium oxides coating has the best corrosion resistance. Visual analysis of coated steel samples after electrochemical tests and the results of profilometric measurements indicate the pitting nature of corrosion. Corrosion spreads locally, this is due to defects in the coatings formed during its deposition. Pores in the obtained coatings were detected by scanning electron microscopy. Interestingly, the microdroplets formed during the deposition of the coating and the pores have a similar shape and size, which suggests that the pore is formed at the site of the removed microdroplet. Image analysis showed that chromium microdroplets and pores have a diameter of 0.5 – 4 microns and occupy a total of approximately 1 – 1.4% of the coating area. It is assumed that the first microdroplets, trapped and deposited on the surface of the substrate at the initial moment of its purification by metal ions, are dangerous. In this case, the surface of the steel substrate is still cold and has a natural oxide layer and other contaminants, which leads to poor adhesion of the settled microdroplet. Further, this microdroplet shields the plasma flow in the technological processes of cleaning and coating, and falling off, creates a pore. Steel has the most negative value of the corrosion potential, which means that all chromium-based coatings under study are cathodic in relation to it, protecting it from electrochemical corrosion.

References:

1. Conde A., Nanas C., Cristobal A.B., Housden J., Damborenea J. Surface and Coatings Technology, 201, 2690 (2006).

2. Mutyala K.C., Ghanbari E., Doll G.L. Thin Solid Films, 636, 232 (2017).

3. GOST 9.912-89 Methods of accelerated tests for resistance to pitting corrosion.

THE INFLUENCE OF THE TEMPERATURE OF HIGH PRESSURE TORSION ON THE STRUCTURE AND MECHANICAL PROPERTIES OF A HIGH-ENTROPY ALLOY FeMnCrNiCo ALLOYED WITH CARBON

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One of the promising alloys in the last decade is Kantor's high-entropy alloy (HEA) (FeMnCrNiCo). Its practical application is constrained due to its low strength at moderate and elevated temperatures. The strength of the Kantor alloy can be significantly increased by alloying with additional elements [1] or by changing the structure of the material [2]. Carbon (C), as an interstitial alloying element in the Kantor alloy, plays an important role in the refinement of its microstructure and contributes to an increase in the dislocation density during severe plastic deformation by torsion [3]. The formation of a nanosized structure leads to the achievement of extraordinary strength and simultaneous brittleness of the alloy [2, 3]. Therefore, the search for a balance between the strength and ductility of this alloy remains relevant. In this study, the influence of the microstructure and phase composition on the microhardness of the Kantor alloy alloyed with carbon atoms after high pressure torsion (HPT) at room temperature and T = 300°C was analyzed. In deformed alloys $(FeMnCrNiCo)_{99}C_1$ and $(FeMnCrNiCo)_{97}C_3$, the microstructure and phase composition were analyzed by X-ray diffraction analysis and electron microscopy. It has been experimentally shown that an increase in the carbon concentration in the Kantor alloy from 1 to 3 at. % significantly affects the increase in microhardness during HPT performed at T = 20°C: from 550 HV to 650 HV. This is caused not only by differences in the nanosized microstructure being formed, but also by different solid solution hardening of the alloys: after HPT, the crystal lattice parameter of the alloy with 1 at.% C (a=0.3613nm) is higher than that of the alloy with 3 at.% C (a= 0.3615 nm). In this case, after HPT at a temperature of 300°C, the values of hardness (600 HV) and lattice parameter (a=0.3613 nm) do not depend on the concentration of interstitial atoms in the Kantor alloy. The paper discusses the mechanisms of influence of the structure formed during HPT at different temperatures on the strength and plasticity of Kantor's carbon alloys.

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References:

1. Zhihua Zeng, at al.Mechanical properties of Cantor alloys driven by additional elements: a review, Journal of Materials Research and Technology, Vol. 15 (2021) Pp 1920-1934.

2. A. Kilmametov, at al. High-pressure torsion driven mechanical alloying of CoCrFeMnNi high entropy alloy, Scripta Materialia,Vol 158 (2019),Pp 29-33.
3. Yemao Lu at al. Influence of carbon on the mechanical behavior and microstructure evolution of CoCrFeMnNi processed by high pressure torsion, Materialia, Vol. 16 (2021)101059.

CYCLIC REDOX MICRO- AND NANOMODIFICATION OF SINTERED BIPOROUS NICKEL

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In catalysis, membrane, sensor, and energy-saving technologies, sintered porous permeable materials based on nickel Ni, nickel oxide NiO, and Ni–NiO bulk compositions are widely used. In these technologies, it is efficient to use permeable materials that have a developed surface and combine pores of micron and nanometer sizes.

The aim of the present work was to create permeable materials with a developed surface and multilevel porosity by cyclic oxidation-reduction (redox) post-treatment of biporous nickel obtained by powder metallurgy using commercial Ni micropowder and NaCl salt as a space holder.

Cyclic redox treatment (1, 5 and 10 cycles) of sintered samples of porous nickel was carried out alternately in atmospheric air and in hydrogen at an overpressure of 0.06 MPa at a constant temperature of 750° C. The duration of the oxidation and reduction stages (half cycles) was 1 h.

The study of structure and phase composition of sintered samples before and after redox treatment was carried out by means of scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and X-ray diffraction analysis (XRD). The porosity of the samples was measured by hydrostatic weighing. The pore size distribution was analyzed by mercury intrusion porosimetry (MIP). The hydraulic permeability of porous nickel samples was determined using the Darcy–Forchheimer equation.

It was established that after the stage of annealing in air, a porous material with the Ni–NiO core–shell structure was obtained. A three-dimensional nickel framework provided such a material mechanical stability and thermal and electrical conductivity, while a nanostructured oxide shell ensured catalytic activity. Subsequent thermochemical treatment in a hydrogen environment led to the reduction of the material to metallic nickel and the formation of a highly developed surface. The surface of the sintered particles consisted of rounded bumps and was characterized by a raspberry morphology. Beneath the thin nanoporous surface layer, there was a layer of Kirkendall pores with a cellular structure.

The obtained metallic nickel and ceramic nickel oxide materials contain a hierarchical system of pores of different origin of four types: (a) macropores formed after the removal of the space holder; (b) interparticle micropores remaining owing to incomplete sintering of the nickel powder; (c) intraparticle Kirkendall pores created at the oxidation stage; and (d) nanopores formed during reduction.

The resulting hierarchically porous metallic Ni and ceramic Ni-NiO materials have the potential to be used as electrodes in catalysis and energy-saving technologies.

THE EFFECT OF Cr2N PRECIPITATES ON HYDROGEN EMBRITTLEMENT IN CoCrFeMnNi(N) ALLOY

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The effect of precipitate hardening on the features of hydrogen embrittlement of a nitrogen-alloyed high-entropy FCC alloy was studied. High-entropy alloy of the following chemical composition was chosen as a material for the study: 20.0Fe-20.0Cr-20.0Mn-20.0Ni-19.2Co-0.8N (HEA) (at. %). The thermomechanical treatment (TMT) of a cast alloy involved hot forging at 1230°C and annealing at 1200°C for 2 hours (HEA-1). After TMT, part of the specimens was subjected to age-hardening at 900ºC for 1 hour (HEA-2). Some of cast bars were subjected to annealing at 1200°C for 2 hours, cold rolling (80 % reduction) and age-hardening at 900°C for 1 hour (HEA-3). Electrochemical hydrogen-charging was carried out in the 3 % NaCl water-solution containing 3 g l^{-1} of NH_4SCN as a recombination poison at the current density of 10 mA cm^{-2} for 50 h.

Using electron microscopy, it was found that HEA-1 specimens have a single-phase coarse-grained (d = 221±97 μm) austenitic structure after TMT, while HEA-2 and HEA-3 specimens possess heterophase structure. Age-hardening leads to the formation of the Cr_2N nitrides with a plate-*like* morphology along grain boundaries in HEA-2 specimens (d = 177±39 μm). HEA-3 specimens are characterized by fine-grained structure (d = 6±4 μm) and homogeneously distributed spherical Cr_2N particles (d_p = 132±32 nm). The mechanical properties of HEA-1 and HEA-2 specimens are close ($\sigma_{0,2}^{HEA-1}$ = 254±5 MPa, $\sigma_{0,2}^{HEA-2}$ = 261±5 MPa, δ^{HEA-1} = 66±2 %, δ^{HEA-2} = 63±2 %), while an increase in yield strength (YS) caused by precipitation hardening and grain boundary strengthening is observed in HEA-3 specimens ($\sigma_{0,2}^{HEA-3}$ = 395±5 MPa). Hydrogen-charging does not significantly affect the YS ($\Delta\sigma_{0,2}^{HEA-1}$ = 7 MPa, $\Delta\sigma_{0,2}^{HEA-2}$ = 11 MPa, $\Delta\sigma_{0,2}^{HEA-3}$ = 4 MPa), but leads to decrease of ultimate tensile strength (UTS) and elongation to failure. The index of hydrogen embrittlement I_H, which describes the hydrogen-induced loss of plasticity, equals to 14 % in HEA-1 specimens and reduces to 2 % and 11 % in HEA-2 and HEA-3 specimens, respectively.

A brittle hydrogen-induced surface layers appear after hydrogen-charging in all specimens. The thickness of the brittle layer in HEA-1 specimens is W_H^{HEA-1} = 38±12 μm and it decreases in age-hardened specimens (W_H^{HEA-2} = 28±9 μm, W_H^{HEA-3} = 29±5 μm). Fracture mode of the hydrogen-induced layer in all specimens is mainly intergranular, but transgranular facets are observed as well.

Therefore, precipitation of Cr_2N particles due to age-hardening leads to a decrease in the thickness of the brittle hydrogen-induced surface layer and to an increase in the hydrogen embrittlement resistance of nitrogen-doped specimens of high-entropy alloy.

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ELECTROCHEMICAL PROPERTIES OF THE MULTILAYER COMPOSITE Ti-6Al-4 V/Cp-Ti ALLOY PRODUCED BY LASER DIRECT ENERGY DEPOSITION

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One of the promising areas for the development of additive manufacturing is the development of materials with local dependence properties in space, that will improve the mechanical and operational characteristics of the deposited product. The most interesting is development of materials with different properties that is achieve by the alternations of materials. Titanium alloys have high strength combined with low specific gravity. Commercially pure titanium has good ductility but relatively low strength; the two-phase titanium alloy Grade 5 has high strength but low ductility, which makes these two materials good candidates for combination in product with local dependence properties.

In this work, we carried out electrochemical studies of multilayer composite materials with alternating Grade 5/Cp-Ti layers produced by laser Direct Energy Deposition (DED), as well as similar Grade 5, Cp-Ti samples. A 15% solution of NaCl, prepared in distilled water, with a natural pH of 6.2 was used as a working electrolyte. All tests were carried out at a given constant temperature of 35 ± 1 °C. Five types of samples were tested: DED Cp-Ti, DED Grade 5, multilayer Cp-Ti/ Grade 5 as-deposited and heat treated and rolled Grade 5. Pitting-resistance basis for each investigated materials is 7,842, 4,149, 6,351, 7,814 and 5,583 V respectively.

Based on the analysis of polarization curves and values of pitting potentials and pitting resistance bases was shown that:

- The highest corrosion properties have samples of DED Cp-Ti и DED Cp-Ti/Grade 5 with heat treatment. Combination of Grade 5 and Cp-Ti lead to increasing of corrosion resistance with comparing to similar Grade 5 alloys. Particularly with comparing with rolled grade 5 alloy;
- Heat treatment of multilayer materials is increasing corrosion resistance that is associated with an structure change in Grade 5 layers.

The work was supported by «Priority 2030» program of the St. Petersburg State Marine Technical University, project: Digital Industrial Technologies.

EFFECT OF HAFNIUM ALLOYING ON THE STABILITY TO DEFORMATION-INDUCED PHASE TRANSFORMATIONS AND THE FORMATION OF PROPERTIES IN A BI-COMPATIBLE ALLOY OF THE ZR-TI-NB SYSTEM SUBJECTED TO QUENCHING AND COLD DEFORMATION

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The medium entropy alloy Zr51Ti31Nb18 (IMP BAZALM) is a promising biocompatible material in which it is possible to obtain relatively low values of the elastic modulus (up to 55 GPa) by quenching and cold deformation [1]. An additional alloying with biologically inert hafnium, which has the highest atomic weight in the alloy, can be used to increase the contrast of the alloy during fluoroscopy and MRT. However, the behavior of the Zr51Ti31Nb18 alloy with hafnium during quenching from the β- region and subsequent cold deformation is not completely clear. In this regard, the effect of alloying with hafnium (up to 10 at%) on the stability of the β-phase to deformation-induced phase transformations (DIPT) during cold deformation of hardened alloys Zr51-xTi31Nb18Hfx (where x=0...10 at.%) was studied.

It is shown that an increase in the hafnium content in the alloy leads to a decrease in the stability of the quenched β-solid solution, the occurrence of DIPT during cold deformation with a degree of 96% and thus contributes to the implementation of a number of transformations β–ω, β–α", β–α'. The change in the lattice parameters of phases formed during cold deformation is considered in the context of the elastic stresses arising during deformation and DIPT. The substantiation of the destabilizing effect of hafnium on the β-solid solution matrix is given based on its effect on phase equilibria in binary systems with Zr, Ti, Nb, as well as on the parameters of Bo, Md in the studied alloys of the Zr-Ti-Nb-Hf system. The relationship between the phase transformations realized during rolling and the characteristics of the formed texture with the level of physical and mechanical properties in alloys Zr51-xTi31Nb18Hfx (where x=0...10 at.%) is discussed.

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POSSIBILITY OF USING Al2O3 AND Al-Zn AS CORROSION PROTECTIVE COATINGS IN THE SALT MIST CHAMBER FOR HIGH-ENTROPY ALLOYS GdTbDyHoSc AND GdTbDyHoY

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High-entropy alloys (HEAs) with a hexagonal close packed (HCP) structure consisting of rare earth elements (REMs) are of particular interest at present. This is due

to the fact that REMs have close atomic sizes and crystal structure and can form homogeneous solid solutions. These alloys are highly chemically active and require either a special working environment or additional surface protection against chemical and in special cases electrochemical corrosion.

In the present work, the possibility of using Al_2O_3 and Al:Zn (1:1) as protective coatings for REM GdTbDyHoSc and GdTbDyHoY HEA have been investigated. The samples were synthesized from metals of purity ≥ 99.9% by melting in a Centorr Vacuum and Industries 5SA arc furnace under Ar (99.99) atmosphere [1]. The coatings were applied to the samples by supersonic plasma spraying [2]. Corrosion resistance tests were carried out in a Q-FOG, SSP60 salt mist chamber for 48 hours.

It was found that for all the studied samples corrosive effect in salt mist conditions leads to degradation of the base material, i.e., the HEA. Samples with Al_2O_3 coating under salt mist conditions are destroyed by the mechanism of local activation of the surface, pitting corrosion appears and at the same time a significant proportion of the coating on the base material is preserved. This is due to the interaction of Al_2O_3 with NaCl solution, which allows the use of this coating for the protection of REM alloy in salt mist conditions for a short time. Samples with Al-Zn coating with the ratio of metals (1:1) in salt mist conditions show less resistance than samples with Al2O3 coating due to the chemical interaction between aluminum and sodium chloride solution and to a large difference in the standard electrode potentials of the system components. The corrosion process proceeds very quickly and a layer of insoluble oxides $RO_{1.5}$ is formed on the REM surface under the coating layer.

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References:

1. Uporov S.A., Estemirova S.Kh., Sterkhov E.V. et al. Melts. 2022. No. 5. pp. 443-453. DOI: 10.31857/S0235010622050097

2. Ilyinykh S.A., Sarsadskikh K.I., Chusov S.A. at al. Journal of Physics: Conference Series. 2019. P. 012027. DOI: 10.1088/1742-6596/1281/1/012027

CORROSION RESISTANCE OF HIGH-ENTROPY 30Fe-30Cr-20Ni-10Mo-10W ALLOY

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Mo and W are used to increase the high-temperature strength of high-entropy alloys based on the Fe-Cr-Ni system. These refractory elements provide solid-phase hardening and contribute to improving of the corrosion resistance of alloys.

The purpose of this work is to evaluate the effect of heat treatment on the corrosion resistance of the HEA 30Fe-30Cr-20Ni-10Mo-10W, obtained by vacuum sintering of

mechanically alloyed powders, and to compare the resulting corrosion resistance with that of the austenitic corrosion-resistant steel 316L.

The Retsch PM-400 planetary mill with 500 ml steel cups and a 1:5 ratio of powder weight to grinding balls with a diameter of 5.5 mm made of bearing steel was used for mechanical alloying to obtain mixture of powders. The grinding time was 10 hours. The prepared powder mixture was pressed at room temperature on a hydraulic press. Greenbody was vacuum sintered with a temperature of 1350 °C for 180 minutes. Specimens for heat treatment were cut from the sintered sample.

Potentiometry and potentiodynamic methods were used to study the effect of heat treatment on the corrosion resistance of HEA in 0.03% aqueous NaCl solution. This solution was used to simulate the operation of heat treatment alloys in conditions of moderate technical impact. The anode and cathode polarization curves were determined on an IPC Pro MF potentiostat in an electrochemical cell with a silver-chloride reference electrode and a platinum auxiliary electrode. ASTM G 102-89 "Calculation of the corrosion rate and related parameters based on the results of electrochemical measurements" was used to calculate the depth and mass corrosion index. GOST 9.912-89 "United system of corrosion and ageing protection. Corrosion resistant steels and alloys. Methods of accelerated tests for resistance to pitting corrosion" was used to determinate the resistance to pitting corrosion.

Analysis of the effect of heat treatment on the phases content showed that the fragile sigma phase remains in all samples, but after quenching from 1100 °C its content is minimal.

The kinetics of the potential change in the solution indicates that with increasing time the potential of the HEA increases, which indicates its ability to repassivate. Austenitic corrosion-resistant steel has corrosion potential higher than the HEA potentials, which is associated with a single-phase structure.

It was revealed that the HEAs have increased resistance to pitting in any condition compared to 316L steel, which is due to the high content of chromium, molybdenum, tungsten in the alloy. Particularly high indicators against pitting corrosion were found after quenching from 1100 ° C, as well as during diffusion annealing, quenching and subsequent tempering of 200 °C.

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FORMATION OF AN INTERMETALLIC LAYER DURING DISSIMILAR FRICTION STIR WELDING OF ALUMINUM AND TITANIUM

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In this work, the formation of an intermetallic layer at the Al/Ti interface during dissimilar friction stir welding was studied. Friction stir lap welding was used for this

purpose. This welding method was carried out by plunging the welding tool exclusively in the aluminum part and the welding at a relatively high-heat input condition.

The intermetallic layer was found to be as narrow as ≈0.1 μm, thus giving rise to excellent bond strength between aluminum and titanium. Energy dispersive spectrometry (EDS) method showed that Intermetallic layer has composite structure: TiAl3 + TiAl and enriched by Si and Mn. Moreover, there is no principal influence of welding speed or chemical composition of Al alloy on thickness or chemical composition of intermetallic layer. Tensile tests showed that the failure usually occurred in the heat-affected zone of the aluminum part. This is in contrast to the typical deformation performance of dissimilar aluminum-titanium FSW joints, which frequently fail due to intermetallic compound cracking [1-3].

On the other hand, several important shortcomings were also revealed. First of all, the high-heat input condition provided significant microstructural changes in the aluminum part, thereby resulting in essential material softening. Furthermore, the new approach was not feasible in the case of highly alloyed aluminum alloys due to the relatively low rate of self-diffusion in these materials. An essential issue was also a comparatively narrow processing window.

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References:

1. J.-W. Choi, H. Liu, H. Fujii, Dissimilar friction stir welding of pure Ti and pure Al, Mater. Sci. Eng. A 730 (2018) 168-176; https://doi.org/10.1016/j.msea.2018.05.117.

2. Y. Huang, Z. Lv, L. Wan, J. Shen, J.F. dos Santos, A new method of hybrid friction stir welding assisted by friction surfacing for joining dissimilar Ti/Al alloy, Mater. Lett. 207 (2017) 172–175; https://doi.org/10.1016/j.matlet.2017.07.081.

3. M. Aonuma, K. Nakata, Dissimilar metal joining of 2024 and 7075 aluminum alloys to titanium alloys by friction stir welding, Mater. Trans. 52 (2011) 948-952; https://doi.org/10.2320/matertrans.L-MZ201102.

HEAT STRENGHT OF HIGH-ENTROPY 30Fe-30Cr-20Ni-10Mo-10W ALLOY

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The Cantor alloy has high ductility and strength at room and cryogenic temperature, but at high temperatures the strength of this alloy is low. One of the ways to increase the high-temperature strength of the Cantor alloy is to replace manganese with refractory elements. The introduction of refractory components into the Fe-Cr-Ni-Co matrix is complicated due to the difference in the melting temperature of the ligature and refractory elements, for example, tungsten, niobium, etc. Therefore, a rational way to introduce refractory elements into the composition of a high-entropy alloy is to use powder metallurgy methods. One of the trends in the field of high-entropy alloys is also the

replacement of cobalt due to its high cost. Therefore, a new group of high-entropy cobalt-free alloys has been created.

The purpose of this work is to evaluate the mechanism of deformation and the dependence of strength on temperature of high-entropy alloy of the composition 30Fe-30Cr-20Ni-10Mo-10W, that was obtained by mechanical alloying from elemental powders and subsequent vacuum sintering.

XRD analysis of the phase composition of the powder mixture revealed BCC, FCC phases, α-Mo, α-W, as well as Ni3Fe intermetallic. Analysis of the phase composition of the sample after vacuum sintering revealed BCC, FCC and sigma-phases, as well as the formation of chromium oxide.

Strength analysis at room and elevated temperatures of 773, 1123, and 1273 K was performed during compression testing on the Instron 3382 installation. 3 samples (diameter of 4 mm and height of 12 mm) were used for each test temperature.

The compressive strength of vacuum sintered high-entropy samples at room temperature is 1815 ± 10 MPa. The type of the deformation is brittle. Compressive strength with an increase of temperature to 773, 1123 K, respectively, decreases from 1618 ± 22 to 1554 ± 27 MPa. The type of the deformation is brittle, too. As the temperature increases, the stiffness of the samples decreases, and, consequently, the modulus of elasticity decreases. An increase of the test temperature to 1273 K leads to change in the deformation mechanism from brittle to plastic, and the ultimate strength is reduced to 265 ± 4 MPa. Such a change in the mechanism of deformation and ultimate strength is associated with the dissolution of the high-strength and brittle sigma phase.

The high-entropy 30Fe-30Cr-20Ni-10Mo-10W alloy obtained by vacuum sintering from mechanically alloyed powder is multiphase. The mechanism of compression deformation is brittle in the range up to 1173 K. The dissolution of the sigma phase at a temperature of 1273 K changes the deformation mechanism from brittle to plastic. The ultimate strength of the high-entropy 30Fe-30Cr-20Ni-10Mo-10W alloy at the 1273 K is 265 ± 4 MPa.

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DEFORMATION OF MULTI-COMPONENT Ti40Hf5Zr5Ni40Co5Cu5 ALLOY AT DIFFERENT TEMPERATURES

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The aim of the work is to explore the influence of deformation temperature on mechanical properties of multi-component $Ti_{40}Hf_5Zr_5Ni_{40}Co_5Cu_5$ shape memory alloy. The alloy was manufactured by electric arc melting with some remeltings to obtain the homogeneous structure. The cast alloy consisted of the main B2 phase and the secondary Ti_2Ni-type phase. On cooling and heating the main phase underwent the B2 ↔B19' martensitic transformation at temperatures of M_s = -40°C, M_f = -103°C A_s = -51°C, A_f =

35°C. It is well known that the deformation of the shape memory effect occurred by different mechanisms depending on the position of the deformation temperatures compared to the temperatures of the martensitic transformation. That was why the mechanical properties were studied at different temperatures at which the main phase was in various structural states: The alloy was in the austenite state at 100°C, 23°C, 0°C and -25°C. The sample was in the B2+B19' state at -50°C and it was in the martensite B19' phase at -100°C. At all deformation temperatures, the samples were subjected to tension up to failure with intermediate unloading. The $\sigma_{0.2}$, strength and strain up to failure were measured using the stress vs strain curves and their dependences on the deformation temperature was analysed.

At a temperature of 100°C, the sample was in the austenite phase far from the temperatures of the martensitic transformation. In this case, the sample was first deformed elastically and the plastic deformation by dislocation movement occurred since 650 MPa. The sample failure was of 2.7%. A decrease in the deformation temperature to room temperature led to the decrease of yield limit to 500 MPa, while the stain up to failure increased by 7.3%. It is known that a decrease in deformation temperature increases the yield limit. At the same time, the obtained results showed that the yield limit decreased. Thus, one may conclude that an inelastic strain found during deformation at room temperature was not caused by plastic deformation. It was induced by the B2 $\rightarrow$ B19' transformation. Therefore, the stress-induced martensite appeared in the $Ti_{40}Hf_5Zr_5Ni_{40}Co_5Cu_5$ alloy. The martensite was partially stable and remained in the sample after unloading because the deformation temperature was less than the A_f temperature. A further decrease of the deformation temperature up to -50 led to a decrease in $\sigma_{0.2}$ value because the close the deformation temperature to the M_s temperature, the less stress could induced the martensitic transformation under a stress. As a result, the strain up to failure increases with a decrease in deformation temperature.

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THE EFFECT OF THE HIGHENERGY DEFORMATION TREATMENT ON THE COLD SPARAYED Ni COATING

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Cold gas dynamic spraying of low pressure is one of the most common methods of coating formation. According to the classification of additive manufacturing, this spraying method refers to the methods of directed energy deposition (DED). One of the main advantages of the cold gas-dynamic spraying method is the formation of coating at low temperatures, which prevents oxidation of the sprayed material. In addition, cold gas-dynamic spraying makes it possible to apply coatings to products with special heat treatment, which is difficult with other methods of directed energy exposure. For example, after surfacing on products with special heat treatment, additional heat treatment is required. But the coatings formed by cold gas dynamic spraying of low pressure have

low cohesive strength and high roughness. Therefore, such coatings require additional post-processing for using in tribological applications.

The purpose of this work is to evaluate the effect of high-energy deformation effects on the structure and microhardness of nickel coating obtained by cold low-pressure gas dynamic spraying.

Cylindrical samples from low-carbon steel with diameter of 32 mm were used for spraying. Nickel powder spraying was performed on the Dimet-421 installation. Nickel powder of the N3-00-02 brand, which is a mechanical mixture of metallic nickel and electrocorundum powder, was used for spraying. 0.3 mm thick coating was formed. The high-energy deformation effect on the powder coating was performed by the method of hot surface plastic deformation with simultaneous resistive heating of the deformation focus. For experiments, resistive heating modes with linear energy of 76, 142, 212 J/m were selected. The rate of resistive heating of the deformation focus was ~10^4 K/s. The load on the working tool (WC-6Co hard alloy roller) with a contact track width of 1 mm varied from 100 to 300 kgf in increments of 100.

The use of a new post-treatment method helps to reduce the surface roughness from 30 ± 5 to 3 ± 1 microns, and the residual porosity is less than 0.5%.

As a result of compaction of the coating and the implementation of solid-phase welding processes along the boundaries of the sprayed particles, the microhardness and elastic modulus of the powder coatings increased by 1.3-1.5 times to 244 ± 12HV.

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MECHANICAL AND FUNCTIONAL PROPERTIES OF THE MULTICOMPONENT Ti49 - 2xHfxZrxNi51-2xCuxCox ALLOYS

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It is well known, that the high-entropy alloys demonstrate high strength and high yield limit due to a partial suppression of the dislocation movement in the alloys with complex composition. It was assumed that a decrease in the dislocation movement in the high-entropy shape memory alloys could improve their functional behaviour. Therefore, the aim of this work was to study the mechanical and functional properties of multicomponent $Ti_{49-2x}Hf_xZr_xNi_{51-2x}Cu_xCo_x$ alloys, where the x value increased from 1 to 17 at. % that allowed to change the entropy from low value (at X = 1 at. %) to high value (at X = 10 or 17 at. %).

The $Ti_{49-2x}Hf_xZr_xNi_{51-2x}Cu_xCo_x$ alloy ingots (X = 1, 5, 10, 17) were produced in a vacuum arc furnace under an argon atmosphere, with at least 5 remeltings to obtain a homogeneous structure. The ingots were cut into plates with a thickness of 0.8 mm. The dog-bone shaped specimens with 1 mm in width and 7 mm in length were cut from the plates using the electro-discharge machine. The specimens were isothermally deformed

to fracture with intermediate unloadings. Deformation temperature was varied from 100 ºC to -150 ºC.

Mechanical and functional properties of shape memory alloys depended on phase state. On the other hand, a phase state depended on deformation temperature. It was found, that alloy with X = 1 at. % underwent B2 – B19' martensitic transformation at temperatures M_s = -1 ºC, M_f = -50 ºC, A_s = -24 ºC, A_f = 29 ºC. In the alloy with X = 5 at. %, the forward transformation started on cooling at -100 ºC. The alloys with X = 10 or 17 at. %, martensitic transformation was not observed on cooling down to -180 ºC.

It was found, that alloy with X = 1 % plastically deformed at 100 ºC. The maximum strain and stress were 16 % and 500 MPa. If deformation took place at temperatures 25 and 50 ºC the martensite was induced by stress and microplastic deformation occurred. Deformation at -100 ºC (which less than M_f) was accompanied by the martensite reorientation that started at 150 MPa and give 8 %of unelastic strain? Then the sample is plastically deformed by 75 % and failure.

The alloys with X = 5 and 10 % were brittle regardless of deformation temperature. The alloy with X = 17 % elastically deformed at temperatures of 100 and 25 ºC. If deformation temperature was 0 ºC or less, the martensite was induced by stress and superelasticity was found in a wide temperature range (from 0 ºC to -100 ºC). The martensite critical stress linearly depended on temperature with a linear coefficient of 2,7 MPa/ºC

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FEATURES IN LOW-TEMPERATURE ELECTRICAL PROPERTIES OF THE HIGH-ENTROPY $(Bi_{2/3}Sb_{1/3})_2(Te_{2/5}Se_{2/5}S_{1/5})_3$ ALLOY

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Currently, topological insulators are considered as ones of most attractive and promising solids in which a specific quantum state with uncial properties can be formed. Key features in the properties of topological insulators are originated from combination and interaction of bulk insulating band gap states and surface conducting gapless states with a linear Dirac dispersion.

The aim of this work is to find features in the electrical resistivity of high-entropy single-crystalline $(Bi_{2/3}Sb_{1/3})_2(Te_{2/5}Se_{2/5}S_{1/5})_3$ alloy, prepared as a thick film, which can be attributed to specific properties of topological insulators. Developing high-entropy and medium-entropy alloys is known to be effective approach in modern materials science, allowing improving the properties of structural and functional materials in desired manner.

High-entropy $(Bi_{2/3}Sb_{1/3})_2(Te_{2/5}Se_{2/5}S_{1/5})_3$ alloy has been for the first time prepared by the self-propagating high-temperature synthesis, spark plasma sintering and melting

methods. Single-crystalline and single-phased film of the alloy with thickness of ~0.11 mm was applied to find and analyze features in its electrical resistivity, which are characteristic of topological insulators. A crossover from high-temperature metal to low-temperature insulating behavior was observed in temperature dependence of the resistivity at $T_C \approx 32$ K. The insulating behavior can be due to electron-electron interaction between the 2D-electrons, existing in the surface conducting gapless states of topological insulators. Transverse magnetic field dependences of the resistivity are remarkably non-symmetric within temperature 3.5÷80 K range. The non-symmetric behavior of the magnetoresistivity is resulted from combination of antisymmetric linear and symmetric quadratic contributions. Around zero magnetic field, sharp cusps were observed within narrow magnetic field range. With increasing temperature, the cusps are gradually weaken and totally vanishing above T_C. These cusps are characteristic of weak antilocalization that is one of key features of topological insulators. Analyzing the cusps by using the Hikami-Larkin-Nagaoka expression allowed extracting temperature dependence of the effective dephasing length, which was steady growing from ~120 nm at 25 K to ~220 nm at 3.5 K.

DESIGN OF POROUS TITANIUM MATERIALS AND NUMERICAL ANALYSIS OF THEIR MECHANICAL CHARACTERISTICS

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Currently, the development of porous metallic materials for use in biomedicine, including onco-orthopedics to create bioactive scaffolds, is an urgent task. The development of new approaches and methods of treatment has led to the need to create bone porous implants capable not only of replacing affected areas of bone tissue, but also of locally delivering drugs. This paper presents the results of designing samples with penetrating pore meshes of different geometry and configuration on the basis of analytical expressions and within the framework of automatic design systems. In addition, using finite element modeling, the influence of the design parameters of elementary cells of the samples on their mechanical characteristics has been evaluated.

As a result of the study, three-dimensional models of porous material samples with different unit cell design and pore geometry were constructed and their influence on the mechanical characteristics of porous samples made of titanium alloy type BT6 was numerically analyzed. The obtained results will be used for effective development and analysis of porous biomaterials for manufacturing of medical implants by additive printing.

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OXIDATION BEHAVIOUR OF A DUCTILE REFRACTORY $Al_{7.5}(NbTiZr)_{92.5}$ MEDIUM-ENTROPY ALLOY

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Refractory high/medium entropy alloys have shown a great promise as potential substitutes for current heat-resistant materials. However, their application is greatly hindered by the presence of intermetallic compounds, among which the B2 phase is the most frequent one. For the Al-Nb-Ti-Zr system, it has been demonstrated that limited alloying with Al improved both the strength and ductility of the alloys via controlled B2 ordering. Nonetheless, high-temperature applications require an acceptable oxidation resistance, which has not been extensively explored for refractory high/medium entropy alloys with tensile ductility.

This study focuses on investigating the oxidation resistance of the previously introduced refractory $Al_{7.5}(NbTiZr)_{92.5}$ (at. %) medium-entropy alloy, which has a structure consisting of a bcc matrix and evenly dispersed B2 nanodomains. Additionally, the mechanical properties of the alloy after the oxidation resistance tests were analyzed. The effect of temperature and duration of oxidation on the kinetics of this process and the mechanical properties of the alloy are extensively discussed.

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THERMOMECHANICAL TREATMENT OF TINIHF ALLOY WITH HIGH-TEMPERATURE SHAPE MEMORY EFFECT

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Among the high temperature shape memory alloys (SMA) TiNiHf seems to be more attractive for wide practical application because of required mechanical and functional properties in combination with relatively low cost as compared to alloys with precocious metals (Pd or Pt) and greater stability of the operational characteristics as compared to TiNiZr. It was established that TiNiHf alloys with low Ni content (less than 49.5 at. %) have insufficient technological plasticity due to the precipitation of $(Ti, Hf)_2Ni$ type phase, while an increase in the Ni content leads to a decrease in the characteristic temperatures of martensitic transformations. Therefore, in order to obtain a high-temperature state in the alloy, the content of Hf also should be increased. That makes alloy more expensive and make it difficult to obtained temperature range of shape

recovery between 100 and 200 °C. For example, the most commonly applied $Ti_{29.7}Ni_{50.3}Hf_{20}$ alloy has the finishing temperature of shape recovery A_s about 300 °C or higher, in dependence with the applied melting and deformation modes. Based on the foregoing, the aim of the present work consists in the production of high-quality long-length rods from TiNiHf alloy with a reduced content of nickel and hafnium, providing high mechanical and functional properties in combination with the finishing temperature of reverse martensitic transformation of about 120-160 °C. Another approach for the melting procedure was also used: finished Ti-Ni billets instead of raw Ti and Ni and high-purity hafnium wire were applied for the melting process. Initial ingots with 1.5, 3.0 and 5.0 at.% Hf were obtained by electron beam melting in a copper water-cooled stream-type mold. The obtained ingots were rotary forged at the temperature of 950 °C, with the relative strain from 5 to 10% per one pass. The obtained results revealed that the ingots with 3.0 and 5.0 at.% Hf demonstrated insufficient technological plasticity, presumably because of the excess precipitation of $(Ti,Hf)_2Ni$-type particles. The premature destruction of ingots during the deformation process does not allow obtaining high-quality long-length rods. A long-length rod with a diameter of 3.5 mm and a length of 870 mm was produced by rotary forging from the ingot with 1.5 at.% Hf. The obtained TiNiHf rod had relatively high values of mechanical properties (a dislocation yield stress σ_y of 800 MPa, ultimate tensile strength σ_B of 1000 MPa, and elongation to fracture of 24%), functional properties (a completely recoverable strain of 5%), and a required finishing temperature of shape recovery of 125 °C in the as-forged state and of 155 °C after post-deformation annealing at 550 °C for 2 h.

The study was carried out within the framework of the state task of IMET RAS No. 075-01176-23-00

DEVELOPMENT OF AN ANTI-DIFFUSION COATING FOR THE PRODUCTION OF HOLLOW STRUCTURES BY THE DB/SPF METHOD

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The manufacture of hollow blades made of titanium alloy VT6 for aircraft engines is realized by combining two methods – diffusion bonding (DB) followed by superplastic molding (SPF). To obtain a cavity when using this method, an anti-diffusion coating is necessary that prevents welding of workpieces in places where the pattern is applied, for the possibility of obtaining stiffeners. Most of these technologies, including Russian ones, use coatings based on yttrium oxide (Y_2O_3), usually produced by Western firms. In order to ensure technological sovereignty in the manufacture of hollow blades made of titanium alloy VT6, it became necessary to develop a new domestic coating.

Thus, the development of an anti-diffusion coating and research aimed at determining its technological parameters and determining the effect on the material of the workpiece are relevant for the modern domestic aviation engine industry.

Based on the analysis of patents on available coatings, the composition of a domestic anti-diffusion coating based on yttrium oxide was developed. Studies aimed at establishing the effect of the coating on blanks made of titanium alloy VT6 have shown that areas with a clear change in structure, having an insular character, are observed on the surface. At the same time, on a sample with a domestic coating, this effect is manifested to a lesser extent than when using an imported analog. It was also found out that when using a domestic anti-diffusion coating, the formation of an alphated layer on the surface of a titanium alloy does not occur during diffusion welding. The main technological parameters of imported and new coatings have been determined, which indicate that the adhesion of the new coating was higher than the imported one, as a result of which the risk of coating shedding when assembling the package for diffusion welding is reduced, the viscosity of the developed coating is significantly higher than the imported analog, but this does not affect when coating the workpieces through a stencil.

References:

1. ANALYSIS OF ALTERNATIVES FOR DEHP USE NONCONFIDENTIAL REPORT // ECHA URL: https://echa.europa.eu/documents/10162/2030b1f3-5a47-4880-aeaf-fea8aad7c3f6 (31.05.2023).

2. *Patent № 1466692 EP B23K 20/18. Method of manufacturing a hollow workpiece by diffusion welding and superplastic forming : № 04290853.3 : 01.04.2004 : publ. 13.10.2004 / Jean-Michel Franchet, Gilles Klein, Patrick Gesmier – 14 p.*

MACHINE LEARNING-BASED PREDICTION OF THE PLASTICITY OF HIGH-ENTROPY ALLOYS

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The compositional space of high-entropy alloys is incomparably larger than that of conventional alloys. Therefore, developing the methods for forecasting of a structure, mechanical, and functional properties of the new high-entropy alloys is a challenge of a modern material science.

In the present work, machine-learning algorithms were used for the classification of alloys on plastic and non-plastic alloys with a threshold value of fracture elongation e = 10%. The elastic net algorithm was used for the selection of features for the training model. The ADASYN (Adaptive Synthetic) algorithm was used for training dataset rebalancing. As a result, the surrogate model based on the AdaBoost classifier showed an accuracy of more than 90% for both classes (plastic and non-plastic) on the validation set.

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PECULIARITIES OF FUNCTIONALLY-GRADED MATERIALS PRODUCTION USING DIRECT LASER DEPOSITION TECHNOLOGY

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Functionally Graded Materials (FGMs) are composite materials with varying properties across their volume, achieved through Direct Laser Deposition. This technology allows for the seamless transition of one material into another within a single component, offering unique mechanical and thermal properties. For instance, FGMs can be designed to withstand high temperatures on one end while maintaining toughness on the other. The aerospace and automotive industries are particularly interested in FGMs for their potential to reduce weight while improving performance. The medical industry is also exploring the use of FGMs for implants that can mimic the varying properties of biological tissues. Direct Laser Deposition of FGMs is a complex process that requires precise control over the laser parameters and material feed rates, but the potential benefits in terms of material performance and functionality are immense.

The paper presents the results of obtaining functionally graded materials using direct laser deposition technology. Experimental FGM samples from steels and titanium alloys were obtained. The grade2/grade5 titanium-based gradient material showed average values for tensile strength, yield strength and relative elongation between the two alloys and increased values for impact toughness. A similar layered material can be used to limit crack growth under impact loading in a more ductile alloy.

FGM materials produced of different types of austenitic steels showed increasing of tensile characteristics. The combination of layers of 321/316l steels allowed to increase the strength at low temperatures while maintaining high ductility. Combination of austenitic 321 steel and low-alloyed bainite steel 15Cr2MoV showed the applicability of direct laser deposition technology for the production of bimetallic products. Also, ferromagnetic and paramagnetic steel combination can be applicable to the manufacture of synchronous motor elements using DLD technology.

The most challenging task was to obtain FGM from materials with metallurgical conflict. In this work, dissimilar gradient transitions between titanium alloys and steels were obtained using intermediate layers of bronze, niobium, vanadium and molybdenum. The research results on the structure and mechanical characteristics of the gradient transition showed the possibility to use DLD technology to obtain products of dissimilar metals and for the fabrication of FGMs.

THE EFFECT OF HEAT TREATMENT ON THE STRUCTURE AND PROPERTIES OF AUSTENITIC STEELS AND ALLOYS MANUFACTURED BY ADDITIVE METHODS

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Currently, additive manufacturing technologies for parts and products are extremely relevant for many industries, since their use significantly increases the speed of manufacture and reduces the cost of machining and welding, which in the future can increase the economic efficiency of any production. The technologies of direct laser deposition (DLD) and laser powder bed fusion (LPBF) are most often used for metal products. For this purpose, metal powder compositions (MPC) are used mainly of stainless steels and alloys. This is due to the fact that steels type 321 have low thermal conductivity and are little susceptible to oxidation, which makes it possible to effectively melt metal with laser radiation, forming a dense structure after cooling.

Stainless steels are effective in a corrosive environment, therefore they are used in shipbuilding, reactor engineering, medicine and other fields. Precision alloys of the 80Ni3CrSi type, which also have an austenitic structure, are used for the manufacture of small-sized transformers, chokes, relays, magnetic field sensors, elements of various devices and electrical devices, as well as magnetic screens. Combining the advantages of these materials with additive methods, it is possible to increase the level of mechanical properties and the economic efficiency of the production of parts and products having a complex geometric shape.

In this paper, the results of studies of the effect of heat treatment (annealing) on the formation of the structure and properties of steel 321 and precision alloy 80Ni3CrSi, made on 3D printers by DLD and LPBF methods, respectively, are carried out. Studies have shown that heat treatment can significantly change the structure and properties of additive materials. It has been established that recrystallization and twinning of the studied materials occur at higher processing temperatures compared to traditional technologies, which is probably due to the formation of dispersed refractory non-metallic particles during laser consolidation of the MPC. By changing the annealing modes, it is possible to form a given level of strength properties and impact strength in the material.

AB INITIO STUDY OF ELASTIC PROPERTIES OF CoCrFe(40-x)MnxNi (x = 5, 10, 15, 20) HIGH-ENTROPY ALLOYS

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One of the most promising fields of alloy design is the high-entropy alloys, which are multicomponent (5 and more elements) systems with each component varying from 5 to 35 at. %. The properties of these alloys depend on how much of each element is present and how they interact with each other. The Co-Cr-Fe-Mn-Ni system is a common high-entropy alloy, and the role of each element on his properties has been established.

However, the influence of altering the Fe and Mn contents concurrently on the mechanical properties of this system is still unknown. In this work, we present the results of ab initio calculations of the bulk modulus of CoCrFe(40-x)MnxNi (x = 5, 10, 15, 20) high-entropy alloys, which is relevant for their mechanical behavior.

The bulk modulus reflects how resistant a material is to compression. To calculate the bulk modulus of CoCrFe(40-x)MnxNi (x = 5, 10, 15, 20) HEAs, we used the Burch-Murnaghan equation of state, which is a polynomial fit to the energy-volume curves obtained from density-functional theory (DFT) calculations. The disordered crystal structures consisted of 32 atoms of CoCrFe(40-x)MnxNi (x = 5, 10, 15, 20) HEAs were generated by means of the Special Quasi-random Structures (SQS) method using ATAT tool. The optimized calculations of SQS supercells are performed through the Quantum Espresso package. The cutoff energy of plane wave basis was set as 60 Ry. Each atom in the supercell was fully relaxed by the Davidson diagonalization method to obtain the optimal structure, and the corresponding convergence atomic force and convergence energy were set to 0.001 Ry/atom and 10^{-4} Ry/atom, respectively.

The results show that all the considered structures are stable since the total mixing energy, which is the difference between the energy of the crystal and the energy of its constituent atoms in their isolated state is negative. The most stable structure which has the largest negative value of -603.06 eV is the CoCrFeMnNi alloy. With the increasing of Fe and simultaneous decreasing of Mn the total mixing energy is steadily increasing: CoCrFe25Mn15Ni (-595.33 eV), CoCrFe30Mn10Ni (-587.5 eV), CoCrFe35Mn5Ni (-583.82 eV). However, the changes of the bulk modulus are not linear. CoCrFe25Mn15Ni, has the highest bulk modulus of 237.9 GPa, indicating a stronger resistance to compression than other alloys. CoCrFeMnNi has the static bulk modulus of 234.6 GPa. The HEAs with the high Fe and low Mn contents have the least bulk modulus of 229.1 GPa. This can be explained by considering the atomic size and electronegativity differences among the alloying elements. Mn has a larger atomic size (135 pm) than Fe (124 pm) and a less electronegativity. When the content of Mn is low the lattice distortion is lower than in equiatomic alloy which leads to the weaker interatomic bonds. However, the same reasoning cannot be used to explain the increase of the bulk modulus in CoCrFe25Mn15Ni alloy. Therefore, further studies should be conducted.

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ADDITIVE TECHNOLOGIES BASED ON DIRECT ENERGY DEPOSITION FOR MAINTENANCE, REPAIR AND OVERHAUL

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Nowadays additive technologies (AT) have become an integral part of many metalworking industries, such as shipbuilding, power engineering, aviation, automobile industry, etc. One of the main prospects for the use of AT in metalworking is the possibility of creating more precise and structurally complex products with increased

values of physical, mechanical and operational properties. The world experience of AT application has shown the possibility of their use not only for rapid prototyping, but also of high-precision blanks for finishing treatment of products. The use of AT allows significantly reducing time and costs of production, as well as to improve the quality of products.

Of all the variety of additive technologies, only two methods are used to work with metal materials: selective laser fusion and direct energy deposition (DED). The second one, has a number of advantages, such as high productivity, unlimited size (as larger the manipulator, as larger the product), the possibility of creating hybrid structures combining a cast or stamped part with a deposited one.

Despite the widespread popularity of AT in R&D departments, until recently many industrial enterprises doubted their effectiveness and justification for use in production. However, with advances in technology, equipment and improvements in filler material quality, AT is becoming increasingly popular and in demand. As already mentioned, AT allow creating not only parts with higher accuracy and fewer tolerances, but also parts and assembly units combined with workpieces obtained by conventional technologies. This makes it possible to use AT in repair production to quickly and accurately restore damaged parts. In addition, parts made by AT can be strengthened and more durable than traditional metal parts.

Two DED technologies, laser cladding and wire-arc additive manufacturing, which differ in both their technical, technological and economic characteristics, are considered in this study.

Like all additive technologies based on material melting, and DED technologies in particular, they can be seen as an evolution of cladding technology. In turn, surfacing is the process of applying a layer of metal to a part to restore its geometry or improve its surface properties. Laser beam, as a heating source, has a high concentration of energy and localization of the treatment zone. This allows precision machining of metallic materials that are considered difficult to weld or even non-weldable by traditional industrial arc welding and cladding methods. Laser cladding allows not only avoiding the formation of cracks in the clad metal, but also increasing the strength, hardness and wear resistance in the treated area. A typical example of laser cladding application is geometry restoration of gas turbine engine components made of heat-resistant alloys based on iron, nickel or cobalt.

Wire-arc additive manufacturing has several advantages over other AT methods. Firstly, WAAM has high productivity, which makes it effective for the production of large parts. Secondly, the used electric welding equipment and welding wires used as filler material make it several times more economical when working with cheap structural materials compared to laser growing using powder compositions. WAAM allows cladding to be carried out both in the bottom position, traditional for additive technologies, especially those using powder as filler material, and in vertical and ceiling positions. This characteristic is particularly relevant if there is no possibility of upturning the part. A typical example of WAAM is the reproduction of parts for heavy machinery equipment made of structural steels and aircraft bodies made of aluminum alloys.

SYNTHESIS, STRUCTURE, AND THERMAL STABILITY OF ALLOYS OF THE TiZrHfNbTa SYSTEM

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Expanding the capabilities of tensometric systems, increasing their sensitivity and durability, stimulates the search for new materials with desired properties. Among the wide variety of transducer types, only metal sensors demonstrate high accuracy and linearity, which allows them to be used in precision measuring technology.

The promise of high-entropy alloys (HEAs) for tensometric applications is due to a variety of favorable factors. Many HEAs form single-phase and thermally stable solid solutions. Depending on the elemental composition, it is possible to obtain both superplastic and exceptionally hard alloys with different coefficients of thermal expansion, and the inclusion of 4-6 subgroups in the composition of elements ensures high corrosion resistance. The presence of elements of different radii and valence leads to a distorted crystal structure with a very high defect density, providing low and practically temperature-independent electrical conductivity.

The alloy for investigations was prepared of pure elemental metals (>99.97) by conventional arc-melting process under a flowing argon atmosphere. To ensure chemical and structural homogeneity, the alloy ingot was inverted and remelted at least twelve times. The mass loss after melting was less than 0.25. Isothermal annealing of the samples was performed in previously degassed and sealed silica ampules at the temperatures of 523, 673 K for 1 - 500 h. X-ray diffraction analysis (XRD) was performed at room temperature.

Metallographic analysis of the samples was performed using an OLYMPUS GX-57 optical inverted microscope (magnifications from 50 to 1500) and Carl Zeiss EVO 40 scanning electron microscopes. To determine the chemical composition of the matrix the energy dispersive X-ray microanalysis (EDX) was carried out using an Oxford Instruments INCA X-Act system.

This work was supported by Russian Science Foundation (grant 23-13-00162). Experiments were performed using scientific instruments included in the Collective Equipment Center" Ural-M".

EVOLUTION OF THE PHASE COMPOSITION OF THE CANTOR CoCrFeNiMn ALLOY DURING PROLONGED ANNEALING

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The stability of high entropy alloys was discussed soon after the discovery of HEAs [1]. Many works considered the basic four component alloy as thermally stable [2, 3]. The introduction of the fifth element, Mn, into the basic CoCrFeNi alloy should increase the stability of HEAs due to an increase in its entropy factor. However, an increase in the lattice distortion due to the larger Mn atomic radius compared to other elements can lead to the opposite tendency, a decrease in the stability of the CoCrFeNiMn alloy. This work aimed to study the phase composition of the high entropy CoCrFeNiMn alloy fabricated by high energy mechanical treatment after prolonged isothermal annealing.

The thermal stability of the Cantor CoCrFeNiMn alloy fabricated by mechanical alloying of metal powders in a planetary mill has been studied after a 30 day annealing in the 873–1273 K temperature range. X-ray diffraction and microstructural analysis have shown that the phase composition of the alloy changes during isothermal annealing. The general laws typical of all annealing temperatures are as follows:

- the phase composition changes in the first day of annealing and further isothermal annealing does not change the phase composition;
- the main phase of the HEA, the FCC solid solution, is retained for 30 day annealing;
- the unit cell parameter of the FCC solid solution decreases with increasing annealing time. Isothermal annealing at 1273 K results in a minimum unit cell parameter for the alloy, which is caused by a decrease in the Mn content in the HEA due to its partial evaporation.

Annealing at 873 and 1073 K resulted in the precipitation of an intermetallic chromium-rich σ-phase from the FCC solid solution. Annealing at 1073 and 1273 K resulted in the decomposition of the homogeneous FCC solid solution and the formation of solid solutions that retain their initial FCC structure but differ in their elemental compositions. Consequently, the alloy fabricated by the HEMT technique at these temperatures is in a thermodynamically unstable state

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References:

1. B. Cantor Stable and metastable multicomponent alloys. Ann. Chim. Sci. Mater. 32 (3). 245–256 (2007).

2. M. S. Lucas, et all. Absence of long-range chemical ordering in equimolar FeCoCrNi. Appl. Phys. Lett. 100, 257907 (2012).

3. S. Guo, et all. Phase stability in high entropy alloys: Formation of solid solution phase or amorphous phase. Prog. Nat. Sci. 21, 433–446 (2011).

DIRECT ENERGY DEPOSITION OF FeCoNiCrAl HIGH-ENTROPY ALLOY FROM PURE POWDERS

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High-entropy alloys (HEA) are a type of alloy composed of several major elements with the same or close atomic ratio, where the atomic concentration of each element is approximately 5% to 35%. The term "high-entropy" indicates the high configurational entropy in the alloy, which is created by the random colonization of lattice sites by several species at significant concentrations on a single solid solution lattice.

Several conventional methods, including melting and sintering, have previously been used to produce HEAs. However, fabrication of homogeneous bulk HEAs by arc melting is challenging because several subsequent treatments (e.g., remelting) are required. As an advanced alternative method to overcome the limitations of traditional processing methods, three-dimensional (3D) printing or additive manufacturing (AM) is considered as a promising technology for manufacturing HEAs with fewer defects.

Among all AM techniques for HEAs fabrication, Direct Energy Deposition (DED) deserves special attention. DED is an advanced additive manufacturing technique that enables the creation of complex three-dimensional metal structures by stepwise melting and depositing metal powder with a laser. This process allows precise control of temperature gradients and cooling rates, which affects the formation of the microstructure and material properties.

In this paper we focus on the study of Direct Energy Deposition of high-entropy alloys of the FeCoNiCrAl system. We will consider the influence of key parameters of the DED process on the structure and properties of the obtained alloys, and analyze their microstructure and phase composition. We will also focus on the mechanical properties of HEAs obtained via DED and discuss their potential applications in various branches of engineering.

The research has yielded data that can contribute to the further development of high-entropy alloys and additive manufacturing technologies, opening new horizons for the creation of innovative materials with improved characteristics.

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DEVELOPMENT OF TECHNOLOGIES FOR MANUFACTURING PARTS OF A HOLLOW STRUCTURE FROM V95PCH ALUMINUM ALLOY

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The widespread use of aluminum alloys of the Al-Zn-Mg-Cu alloying system in the aircraft industry requires the creation of technologies for manufacturing parts of hollow structures. In the manufacture of parts of a hollow structure from V95pch alloy, it is required to perform a welding operation followed by a set of heat treatments in order to ensure high strength characteristics of the product. Due to the peculiarity of welding aluminum alloys containing a particularly strong Al_2O_3 oxide film on the surfaces to be welded, electron beam and diffusion welding were chosen for study.

It was determined that the use of diffusion welding made it possible to form a welded joint with the following mechanical properties: σ_v = 256 MPa, $\sigma_{0,2}$ = 128 MPa, δ = 4.8%. These properties were obtained on a sample welded according to the following conditions: T=550 °C, Pressure 12 bar, Vacuum 4·10-2 Pa, draft 2 mm. At the same time, the subsequent complex heat treatment, consisting of hardening followed by artificial aging, made it possible to increase the ultimate strength of the welded joint to 480 MPa, while the plastic properties decreased to 0%.

An experiment on obtaining a welded joint using electron beam welding made it possible to form a welded joint with the following mechanical characteristics: σ_v = 163 MPa, $\sigma_{0,2}$ = 161 MPa, δ = 1.2%. It has been established that the best properties, providing high strength properties, are achieved after EBW and complete heat treatment, consisting of annealing (T=510°C, holding time 20 hours), hardening (T=475°C, holding time 2 hours) and aging (T= 125°C, exposure time 20 hours), the level of mechanical characteristics is σ_v = 463 MPa, $\sigma_{0,2}$ = 374 MPa, δ = 10.6%.

References:

1. S. Venugopal, G. Mahendran, Effect of the Microstructure on Diffusion Bonded AA5083, AA6082 and AA7075 Aluminum Alloys. – The Institution of Engineers (India) 2018.

2. Shchavlev V.E. Thesis for the degree of candidate of technical sciences "Automation of focus control in electron beam welding based on secondary electron current in plasma." - Perm. - 2015. - S. 121.

INFLUENCE OF CELL GEOMETRY ON THE MECHANICAL BEHAVIOR OF POROUS SCAFFOLDS

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Metal porous structures are actively studied and implemented in medicine [1]. In addition, the technological capabilities of 3D printing have greatly facilitated the fabrication of complex porous structures [2]. Most often, titanium or titanium alloys are used for orthopedic use. On the one hand, titanium has exceptional properties in terms of biocompatibility, corrosion resistance, specific strength, and modulus of elasticity; on the other hand, the mechanical properties of titanium differ too much from those of bone [3-6]. To solve this problem, cellular lattice structures can be used in the design of orthopedic implants. On the one hand, this will bring the mechanical characteristics of the implant closer to real bone, on the other hand, it opens up opportunities to imitate the unique properties of the bone material, and these pores can be filled with locally acting bioactive components, as well as cells for accelerated post-operative tissue regeneration.

At the same time, to obtain optimal mechanical characteristics, it is possible to vary the pore size, the percentage of porosity. In this work, the influence of the ratio "wall thickness - cell volume" for a certain pore geometry (IWP) with the same number of cells on different pore sizes of 686 and 374 μm was studied. A comparison of model structures with structures obtained in the course of 3D printing was carried out, and a study of the mechanical behavior of the resulting structures was also carried out.

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References:

3. AmerNazir. A state-of-the-art review on types, design, optimization, and additive manufacturing of cellular structures [Текст] / AmerNazir, K.M. Abate, A.Kumar, J-Y. Jeng // Int. J. Adv. Manuf. Technol.– 2019 – Vol. 104. – P. 3489–3510.

4. S.A.M. Tofail. Additive manufacturing : scientific and technological challenges, market uptake and opportunities [Текст] / S.A.M.Tofail,E.P.Koumoulos,A.Bandyopadhyay,S.Bose,L.O. Donoghue, C.Charitidis// Mater. Today. – 2018 – vol. 21. – P. 22-37.

5. M. Jäger. Antimicrobial and Osseointegration Properties of Nanostructured Titanium Orthopaedic Implants [Текст]/ M. Jäger, H. Jennissen, F. Dittrich, A. Fischer, H. Köhling // Materials (Basel). – 2017– Vol.10 (11) – P. 1302

6. Z. Wang. Analysis of factors influencing bone ingrowth into three-dimensional printed porous metal scaffolds: A review [Текст] / Z. Wang, C. Wang, C. Li, Y. Qin, L. Zhong, B. Chen, Z. Li, H.e. Liu, F. Chang, J. Wang // J. Alloys Compd. – 2017 – vol 717 – pp. 271-285

7. A. Ataee. Ultrahigh-strength titanium gyroid scaffolds manufactured by selective laser melting (SLM) for bone implant applications [Текст] / A. Ataee, Y. Li, M. Brandt, C. Wen // Acta Mater. – 2018 – vol 158 – pp. 354-368

8. M. Kaur, K. Singh Review on titanium and titanium based alloys as biomaterials for orthopaedic applications [Текст]/ M. Kaur, K. Singh //Mater. Sci. Eng. C. – 2019 – vol 102 – pp. 844-862

INFLUENCE OF SILICON DOPING ON THE PROPERTIES OF TI-AL-TA-N COATINGS

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Ti-Al-N coatings are increasingly used to improve wear resistance and corrosion protection of parts and mechanisms in various industries due to their high hardness and wear resistance, as well as thermal stability and oxidation resistance [1]. At the same time, Ti-Al-N coatings are characterized by low fracture toughness and a decrease in protective properties at temperatures above 800-850 °C. One of the most promising ways to improve these characteristics is alloying Ti-Al-N coatings with additional chemical elements. In particular, the addition of Ta to Ti-Al-N-based coatings significantly increases their fracture toughness and ensures that their high hardness is maintained at elevated temperatures. At the same time, large columnar grains with straight even boundaries are formed in Ti-Al-Ta-N coatings, which contribute to the rapid propagation of cracks and diffusion of oxygen through the entire thickness of the coatings. The solution to this problem can be the formation of a nanocrystalline structure in coatings based on Ti-Al-Ta-N, for example, by alloying with Si. Thus, the simultaneous introduction of Ta and Si into coatings based on the Ti-Al-N system will provide a combination of improved properties characteristic of Ti-Al-Ta-N and Ti-Al-Si-N compositions. The purpose of this work was to study the structure and mechanical properties of coatings of the Ti-Al-Ta-Si-N with various Si content.

$Ti_{1-x-y-z}Al_xTa_ySi_zN$ coatings were deposited by reactive magnetron sputtering with Si content in the range from $z = 0$ to $z = 0.35$. It is shown that coatings with $z < 0.10$ are a Ti-Al-Ta-Si-N solid solution with a columnar grain structure. At a silicon content in the range $0.10 < z < 0.15$, a composite amorphous-nanocrystalline structure is formed in the $Ti_{1-x-y-z}Al_xTa_ySi_zN$ coatings. A further increase in the Si content in the coatings leads to an increase in the volume fraction of the Si_xN_y phase, which causes the amorphous structure of $Ti_{1-x-y-z}Al_xTa_ySi_zN$ coatings at $z \geq 0.20$. It is shown that the formation of an amorphous nanocrystalline structure at $z = 0.10$ determines the maximum values of hardness H and reduced Young's modulus E^*, as well as the ratios H/E^* and H^3/E^{*2}, which indicates its increased crack resistance. Thus, the studies performed have shown that varying the silicon content in $Ti_{1-x-y-z}Al_xTa_ySi_zN$ coatings makes it possible to control their microstructure, providing a significant improvement in mechanical characteristics.

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References:

1 PalDey S., Deevi S.C. Single layer and multilayer wear resistant coatings of (Ti,Al)N: a review // Mater. Sci. Eng. A. 2003. Vol. 342, P. 58-79.

SIMULATION OF MULTICOMPONENT AND HIGH-ENTROPY CARBIDES WITH SUBSEQUENT SYNTHESIS

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Carbides of transition metals usually considered as industrially important materials as they display ultrahigh melting temperatures, high hardness and wear resistance. Moreover they are considered as refractory materials important for many industrial applications. Over the past few years, both theoretical and experimental development of refractory high-entropy materials has been actively pursued, including high-entropy carbides (HEC)[1,2].

Here we perform an evolutionary search for stable crystal structures in the ternary Hf–Ta–C system[3] with subsequent selective large-scale experimental synthesis of coatings using a unique plasma dynamic experimental setup. Next, we have expanded our methods towards the simulations and controllable synthesis of HEC $TiZrNbHfTaC_5$ [4] based on theoretical and experimental techniques.

Optimization of the experimental process allowed us to perform selective synthesis of coatings made of ternary compounds with predefined stoichiometry, crystal structure, and properties. Along with more than 70 compounds, the Hf–Ta–C system belongs to ternary and quaternary carbides of group 4 and 5 transition metals, and this study opens the door to synthesis of a large number of functional coatings composed of other carbides including high-entropy carbides.

References:

1. Oses C., Toher C., Curtarolo S. High-entropy ceramics // Nat Rev Mater. 2020. Vol. 5, № 4. P. 295–309.

2. Hossain M.D. et al. Entropy Landscaping of High-Entropy Carbides // Advanced Materials. 2021. Vol. 33, № 42. P. 2102904.

3. Kvashnin A.G. et al. Large-Scale Synthesis and Applications of Hafnium–Tantalum Carbides // Advanced Functional Materials. 2022. Vol. 32, № 38. P. 2206289.

4. Pak A.Y. et al. Machine learning-driven synthesis of $TiZrNbHfTaC_5$ high-entropy carbide: 1 // npj Comput Mater., 2023. Vol. 9, № 1. P. 1–11.

SIMULATIONS OF PROPERTIES OF COMPOSITE MATERIALS BASED ON LIGHT METALS AND LOW-DIMENSIONAL NANOMATERIALS

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Obtaining of lightweight but mechanically strong materials is critical to the development of the automation and space industries. This development is associated with increased payloads, improved fuel efficiency, reduced environmental pollution, and an overall reduction in the cost of operations. Most aluminum-based materials (especially aluminum-based alloys) currently in use demonstrate a trade-off between price and strength. Important that decrease in strength properties of aluminum-based alloys with increasing temperature is an important challenge to their application in extreme environmental conditions. In the Inorganic Nanomaterials Research Laboratory, it was obtained that room temperature hardened aluminum, which has a partially amorphized structure, shows better thermal stability of mechanical properties than used aluminum alloys. The mechanical performance of aluminum can potentially be improved by reinforcing the aluminum matrix with stronger materials such as carbon [1] or nitride-boron nanostructures [3], which have high mechanical properties, excellent flexibility and low equilibrium defect concentration due to their high formation energy [3].

This chapter describes the results of the study of the improvement of mechanical properties of promising composite and nanomaterials. The first part of the chapter is devoted to the study of adhesion properties of composite materials based on aluminum, magnesium and two-dimensional nanostructures such as graphene and boron nitride, as well as their derivatives. The role of defects in improving the mechanical properties of composite materials was determined. Using modern computer modeling methods, the physical and chemical properties of the predicted structures were described.

References:

1. Carbon Nanotubes: Advanced Topics in the Synthesis, Structure, Properties and Applications / ed. Jorio A., Dresselhaus G., Dresselhaus M.S. Berlin Heidelberg: Springer-Verlag, 2008.

2. Golberg D. et al. Boron Nitride Nanotubes and Nanosheets // ACS Nano. 2010. Vol. 4, № 6. P. 2979–2993.

3. Banhart F., Kotakoski J., Krasheninnikov A.V. Structural Defects in Graphene // ACS Nano. 2011. Vol. 5, № 1. P. 26–41.

HIGH-TEMPERATURE DEFORMATION OF PURE TUNGSTEN CARBIDE CERAMICS WITH DIFFERENT GRAIN SIZES

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Products made of tungsten carbide are operated at elevated temperatures, so the problem of studying the high-temperature deformation of tungsten carbide is topical. Currently, there are many studies devoted to the problem of high-temperature deformation of hard alloys based on tungsten carbide, and the available data on pure tungsten carbide are rare and difficult to explain in terms of traditional models of high-temperature deformation.

The aim of this work is to study the high-temperature deformation behavior of sintered tungsten carbide ceramics with different grain sizes.

The objects of study were powders of tungsten monocarbide α-WC with different initial particle sizes: nanopowder No. 1 with an initial particle size of ~95 nm, as well as powders No. 2 and No. 3 industrially produced by the Kirovograd Hard Alloy Plant with an initial Fischer particle size of 0.8 μm and 3 μm, respectively. Nanopowder No. 1 was obtained by plasma-chemical synthesis followed by reduction annealing in hydrogen at a temperature of 1050°C (3 hours).

The compaction of samples with a diameter of 12 mm and a height of h = 12 mm was carried out by the method of electric pulse plasma sintering (EPS) using the Dr. Sinter model SPS-625 (Japan). Sintering of nanopowders was carried out in vacuum (2-5 Pa), in the mode of continuous heating up to the maximum sintering temperature. Sintering was carried out under conditions of uniaxial pressure of 70 MPa. The temperature was determined with a CHINO IR-AH optical pyrometer focused on the surface of a graphite mold.

High-temperature deformation of sintered samples was carried out using the Dr. Sinter model SPS-625. For creep tests, the samples were placed in a graphite mold with an inner diameter of 20 mm, which was larger than the diameter of the sintered ceramic samples. The study of creep mechanisms of samples of pure tungsten carbide was carried out in the temperature range of 1300-1375 °C and at stresses of 50-90 MPa.

During the experiments, the dependence of shrinkage/deformation (L) and shrinkage/deformation rate (S) of powders/samples on the heating temperature and isothermal holding time was controlled.

It is shown that the creep activation energy decreases from 31 kTm (790 kJ/mol) to 15-22 kTm (380-560 kJ/mol) with an increase in the average grain size and a decrease in the content of the W_2C phase in sintered samples. The power-law creep coefficient n lies in the range from 2.4 to 3-3.7. The results obtained indicate that the process of low-temperature creep under these conditions is controlled by the process of sliding of lattice dislocations in the field of uniformly distributed obstacles.

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THE REINFORCED WITH CERAMIC PARTICLES HIGH-ENTROPY ALLOYS COATINGS SYNTHESIS BY LASER CLADDING

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The purpose of the work carried out was to develop methods for obtaining composite coatings based on high-entropy alloys by laser cladding from mixtures of low-entropy powders, as well as the subsequent study of the composition, structure and properties of the coatings.

To obtain coatings, powders of pure copper, titanium carbide, aluminum oxide, as well as commercial powders of low- and medium-entropy alloys were used for the implementation of laser additive technologies. The powder particle size ranged from 40 to 150 μm. The particle morphology is spherical. The powders were mixed in a rotary mixer for 2 h and then loaded into a direct laser deposition setup. Coatings were obtained using an FL-Klad-R-4 ytterbium fiber-optic laser with a power of 4 kW on a steel substrate. The surface of the substrate was sandblasted for better adhesion to the coating.

The study of the phase structure of the obtained samples was carried out by XRD analysis using a Rigaku Ultima IV powder diffractometer using Cu-Kα radiation. The structure of the experimental samples was studied on a scanning (scanning) electron microscope Jeol JSM7001F. In order to confirm the composition of the zones found in the studied samples (for chemical and structural analysis of phases in the studied samples), X-ray spectral microanalysis was performed using an Oxford INCA X-max 80 energy-dispersive X-ray spectrometer.

The technique used made it possible to obtain composite coatings with inclusions of Al_2O_3, WC and TiC.

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THE EFFECT OF A THERMAL-MECHANICAL TREATMENT ON PHASE COMPOSITION AND GRAIN STRUCTURE OF A Fe40Mn40Co10Cr10 MEDIUM-ENTROPY ALLOY

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At this study, the research of microstructure, phase composition and microhardness of cast, rolled and homogenized $Fe_{40}Mn_{40}Co_{10}Cr_{10}$ samples was carried out. The ingots of the $Fe_{40}Mn_{40}Co_{10}Cr_{10}$ alloy were produced by vacuum induction melting and casting in a pure Ar atmosphere. The homogenization was performed by cold rolling to 65% thickness reduction, followed by annealing at four different modes, where temperature (T) and time (t) of the annealing were varied: mode I (T = 1200 °C, t = 2 h), mode II (T = 1200 °C, t = 1 h), mode III (T = 1100 °C, t = 2 h), mode IV (T = 1100 °C, t = 1 h). The samples were annealed in Ar atmosphere and quenched in water.

The cast alloy had dendritic microstructure presented by two austenite phases, which possess similar microstructure and lattice parameters but one of them (dendritic) is depleted by Mn. This contributes to the shift of the martensitic transformation temperature to room temperatures for dendritic regions and formation of the epsilon phase in them. The volume fraction of the ε-martensite is not high, but it is revealed by X-ray diffraction method. The intensities of the lines for the ε-phase are low but visible.

A sharp increase in the volume fraction of the epsilon phase was observed in the rolled sample. Apparently, plastic deformation contributes to an increase in the volume fraction of the ε-phase, and the martensitic transformation intensity is high. TEM (transmission electron microscopy) study of a rolled sample reveals the formation of a structure with a high density of dislocations, twins and epsilon martensite plates. Microhardness increases significantly from 1.4 GPa to 3.4 GPa for cast and rolled samples, respectively.

The epsilon phase was completely absent in the homogenized samples (after a solid-solution treatment). According to XRD (X-ray diffraction) and EBSD (electron back-scattered diffraction) analyses, the phase composition was only presented by austenite phase. This suggests that the resulting grain structure has a more uniform distribution of chemical elements compared with the cast sample. The average grain sizes equaled 146 μm, 88 μm, 41 μm, 32 μm were obtained for modes I, II, III, IV, respectively.

Thus, the use of thermal-mechanical processing makes it possible to form a single-phase structure with a wide range of grain sizes in the $Fe_{40}Mn_{40}Co_{10}Cr_{10}$ medium-entropy alloy.

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CORROSION RESISTANCE OF PEDICLE SCREW DEVICE COMPONENTS IN BIOLOGICAL ENVIRONMENT

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The susceptibility to pitting, crevice, and fretting corrosion of titanium nickelide (NiTi) based alloy rods has been studied as a function of the volume fraction and size (d_{max}) of inclusions of $Ti_4Ni_2O_x$ particles upon *in vitro* testing of implanted elements of pedicle screw device in 0.9% NaCl solution.

The starting ingots were fabricated using two metallurgical processing routes:

(*i*) vacuum induction melting (VIM) – ingot No. 1 (Ti-55.8Ni-0.013O-0.012C-0.006N, wt.%) and ingot No. 2 (Ti-55.7Ni-0.02O-0.013C-0.006N, wt.%);

(*ii*) combined skull melting followed by vacuum-arc remelting (SM + VAR) – ingot No. 3 (Ti-55.7Ni-0.17O-0.015C-0.009N, wt.%).

The NiTi rods with a diam. of 5.5 mm were hot worked, center-less ground to final dimensions and subjected to barrel grinding and electro-polishing to surface roughness of Ra 0.04±0.01 μm. All rods were heat treated and phase composition was represented by the austenite B2 phase and Ti-rich $Ti_4Ni_2O_x$ inclusions.

The resistance to pitting corrosion was investigated by performing potentiodynamic polarization up to +1000 mV versus SCE with rate of polarization of 0.167 mV/s and the breakdown potential (E_b) was recorded. Fretting corrosion tests were carried out using 3-point bending in 10% solution of calf serum in 0.9% NaCl at 37°C. The rods locked (torque at fixation of 12 Nm) in pedicle screws made of Ti6Al4V were subjected to a sinusoidal cyclic load between 100…650 N at 1 Hz using a hydraulic loading machine (RDP Howden Ltd.), and potentiostatic measurements of the fretting current was carried out using Metrohm Autolab PGSTAT 101 multi-channel modular potentiostat/galvanostat. Investigation of crevice corrosion were performed by long-term immersion of the rods locked in pedicle screws. The contents of Ni, Ti, Al, and V ions in the testing medium were measured and the corroded area on the rods was evaluated after both tests.

It has been established that a decrease in the fraction of $Ti_4Ni_2O_x$ particles from 5.1±1.2 vol.% (d_{max}=10 μm) to 3.5±0.7 vol.% (d_{max}=7 μm) makes it possible to increase the pitting potential from 552±70 to 854±123 mV and reduce the fretting corrosion current from 11±2.7 to 6.7±2.8 μA. Also, the content of Ni ions in the test corrosion medium decreases from 84±6 to 64±5 wt.ppb after crevice corrosion testing, and from 74±6 to 57±4 wt.ppb after fretting corrosion testing, while the area of corrosion damage reduces 1.3- and 1.8-fold, respectively.

It may be concluded that the VIM method is preferable for improving corrosion resistance of implant components from NiTi based alloys in biological environment since it provides higher purity of the produced material, in particular, in terms of oxygen content resulting in the reduction of $Ti_4Ni_2O_x$ particles volume fraction and size.

The research was carried out within the framework of the basic part of the state assignment to universities No. FSFF-2023-0004.

PREDICTION AND VALIDATION OF PHYSICAL AND MECHANICAL PROPERTIES OF A PARTICLE-REINFORCED COMPOSITE MATERIALS OBTAINED BY LASER DIRECT ENERGY DEPOSITION FOR SPACECRAFT ENGINEERING

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The key aspects of predicting physical and mechanical properties of a particle-reinforced composite materials based on the Ti-4.25Al-2V titanium alloy and SiC particles with a relative content of 1% are discussed. This is achieved by applying numerical modeling for a representative volume of the matrix and cermet particles, as well as finite element modeling of samples produced by laser direct energy deposition. These methods are used by the MSC.Digimat and Ansys software complexes. The scope of application of the particle-reinforced composite materials in rocket and space technology are also considered.

As a result of the study, it was found that the MSC.Digimat software package with the method of finite element modeling of a representative volume of material at the micro level in the Digimat-FE module provides sufficiently accurate predictions of the mechanical properties of the particle-reinforced composite materials. This method allows to determine not only the basic mechanical characteristics, such as the Young's modulus and density, but also establishes the relationship between the yield and tensile strength, of the composite material and its deformation.

It is also noted that the software modeling of tensile tests of digital doubles of samples of DCM using the Ansys software package and the Explicit Dynamics plug-in module provides fairly accurate predictions and allows ~~you~~ to build diagrams of the stress-strain state of the material, as well as to identify areas of possible destruction of the material.

In the course of the work, tensile tests were carried out on samples of the particle-reinforced composite materials based on Ti-4.25 Al-2V titanium alloy at various temperatures (20 ºC, 250 ºC, 350 ºC and 450 ºC), and the results of numerical modeling were compared with the results of a full-scale experiment, with an error of 5-8%.

In conclusion, the study showed that the prediction of physical and mechanical properties of the particle-reinforced composite materials based on Ti-4.25Al-2V titanium alloy with the SiC reinforcing ceramic particles, using the method of numerical modeling of a representative volume in the MSC.Digimat software package and analysis of the

finite element model of samples in the Ansys software package has sufficient accuracy to determine the necessary characteristics of the material. Such an approach to the design of structures can significantly accelerate the development of design documentation, minimizing the number of experimental studies of the material.

FEATURES OF COATINGS FORMATION USING NANOSCALE POWDER OF HIGH-ENTROPY Ni29Fe29Mo20Cu13Co9 ALLOY BY PULSE LASER CLADDING WITH MICRO- AND NANOSECOND PULSES

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The increased characteristics of strength, heat resistance, wear and corrosion resistance of high-entropy alloys (HEAs) make them promising for use as multifunctional materials for protecting machine parts and components from wear, corrosion, and exposure to high thermal and mechanical loads. The saving of expensive alloys is achieved due to the formation of a relatively thin protective layer of HEAs on the surface of the parts. One of the most promising methods for applying coatings is laser cladding. The advantages of laser cladding compared to other methods, such as thermal spraying, lie in the possibility of obtaining a dense and uniform coating with good adhesion by creating a "coating-substrate" transition zone. The use of low-power pulsed high-frequency lasers, as well as the need to obtain thin coatings, determines the use of dispersed powders. The possibility of wide adjustment of the dispersed and elemental composition of powder particles is provided by the method of synthesizing multicomponent alloys by joint electrical explosion of wires (EEW) of various metals/alloys. In this work, nanoscale Ni29Fe29Mo20Cu13Co9 powder obtained by the EEW method was used to form protective coatings. Two laser systems operating in a repetitively pulsed mode were used to deposit coatings on a AISI 5140 steel substrate. (1) Using the «LaserScan F2» system, the pre-applied powder was melted at pulse duration and frequency τ=120 ns and υ=100 kHz, respectively. The coating formed from 3 sequentially deposited layers had a thickness of 15–20 μm and a low microhardness (280 HV0.025). This indicates the suppression of the precipitation of hardening phases from the HEA solid solution due to ultrahigh rates of crystallization and cooling during nanopulse laser cladding. (2) On the "LRS AU" system by laser microsecond pulses with τ=3.5 ms and υ=20 Hz, a coating with a thickness of 100-110 μm was obtained, which has an increased microhardness (800-850 HV0.025). For the first time, hardened regions 60–90 μm thick with a microhardness of 750–800 HV0.025 were found under the applied

coatings in the steel substrate. The structure, phase and microchemical analysis of the coatings and the hardened substrate were studied by SEM, TEM, and XRD.

The research was carried out within the state assignment of Ministry of Science and Higher Education of the Russian Federation (theme "Structure" No. 122021000033-2).

INVESTIGATION OF THE STRUCTURE AND PROPERTIES OF THE CERMETS BASED ON INCONEL 625 WITH Co[Al2O4] OBTAINED BY DIRECT LASER DEPOSITION

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Modern requirements for engineering structures under extreme conditions, such as high temperatures, corrosion environment and mechanical loads, present challenges for materials science and industrial technology. Cermets, combining the advantages of metals and ceramics, are a promising direction for creating new high-strength and corrosion-resistant materials. The method of direct laser deposition (DLD) is becoming more popular in the creation of complex metal components. Investigation of new sintered materials using DLD can improve the properties and performance of the materials.

The objective of this study is to analyze the composition and characteristics of a cermet produced through DLD, utilizing an Inconel 625 base with the addition of Co[Al2O4].

The optimal parameters of the DLD for the synthesis of Inconel 625 + Co[Al2O4] have been established. An increase in the mechanical properties of the synthesized cermet materials compared to pure Inconel 625 is shown.

The DLD makes it possible to create cermets with improved properties. The addition of Co[Al2O4] improves the mechanical properties of Inconel 625 based materials. It is expected that the results of this study will help to understand the effect of Co[Al2O4] on microstructure and mechanical properties. The data obtained will be important for the development of new components operating under conditions of elevated temperatures and mechanical loads, such as turbine blades, engine parts, components for the spacecraft engineering, as well as other areas where high strength and corrosion resistant materials are required.

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Ni-Al-BASED CATALYSTS PREPARED BY SOLUTION COMBUSTION SYNTHESIS FOR DRY REFORMING OF METHANE

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Solution combustion synthesis (SCS) is a technique for quickly preparing compounds. It can be used to synthesize catalysts, which are suitable for methane partial oxidation and dry reforming of methane (DRM). Ni catalysts are typically used in DRM, due to its availability and cost-effectiveness. However, carbon deposition and sintering can deactivate Ni catalysts. To mitigate this, alkali promoters (Mn, Ce) with basic properties can be added as inhibitors of deactivation [1-3].

Tests were conducted on catalysts prepared via SCS under atmospheric pressure, at 600-900°C in 50°C increments. The gas ratio of CH_4:CO_2:Ar was 1:1:1. XRD, BET and CHNS analyses were performed to characterize the catalysts.

Both catalysts exhibited high conversions of CH_4 and CO_2, reaching around 90%. The yield of CO was higher for 15NiCe20Al at 62% compared to 15Ni15Mn20Al at 54%, while the yield of H_2 was slightly higher for 15NiCe20Al. The lower carbon content in the 15Ni15Ce20Al (14%) in comparison with the 15Ni15Mn20Al (26%) indicated better carbon resistance during DRM. A decrease in surface area for both catalysts was due to pore blockage by carbon. Ni°, CeO_2, and $CeAlO_3$ phases were present in both fresh and spent catalysts. The 15Ni15Mn20Al also exhibited Ni° and $MnAl_2O_4$ phases, indicating the presence of active species even after the reaction.

In conclusion, the 15Ni15Ce20Al demonstrated higher H_2 and CO yields and better resistance to carbon deposition compared to the 15Ni15Mn20Al. The higher carbon content in the 15Ni15Mn20Al led to more severe pore blockage and a larger reduction in surface area. The presence of active species in both fresh and spent catalysts suggests the potential for catalyst regeneration and further optimization of the DRM process using these catalysts.

References:

1. Zhumabek, M., Kaumenova G., Augaliev, D., Alaidar, Y., Murzin, D., Tungatarova. S., Xanthopoulou, G., Kotov, S., Baizhumanova, T. Selective catalytic reforming of methane into synthesis gas. Chem. Eng. Techn., 2021, 44 (11), 2026 – 2033.

2. Ali, S., Khader, M.M., Almarri, M.J., Abdelmoneim, A.G. Ni-based nano-catalysts for the dry reforming of methane. Catal. Today, 2020, 343, 26 – 37.

3. Gili, A., Schlicker, L., Bekheet, M. F., Görke, O., Penner, S., Grünbacher, M., Götsch, T., Littlewood, P., Marks, T.J., Stair, P. C., Schomäcker, R., Doran, A., Selve, S., Simon, U., Gurlo, A. Surface carbon as a reactive intermediate in dry reforming of methane to syngas on a 5% Ni/MnOcatalyst. ACS Catal. 2018, 8739–8750.

PHOTOCATALYTIC DEGRADATION OF METHYLENE BLUE DYE USING HIGH-ENTROPY (CeGdHfPrZr)O2 OXIDE NANOPARTICLES

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In the current scientific research, high-entropy materials (HEMs) play a significant role because of their complexity, making them the next generation of nanomaterials [1-3]. Hydrothermal synthesis is used in this study to create high-entropy oxide nanoparticles whose composition is $(CeGdHfPrZr)O_2$. Different characterization techniques like X-ray diffraction (XRD), scanning electron microscopy (SEM), and UV-Visible spectroscopy were used to study the structural and optical properties. The results indicate the formation of a single-phase cubic fluorite high-entropy oxide system with a mean crystallite size of 5.2 nm possessing a bandgap of 2.01 eV. Using methylene blue (MB) dye as a model pollutant, oxide nanoparticles were evaluated for their photocatalytic properties. The current study examined and discussed how photocatalytic parameters affected MB dye degradation. Various parameters were found to affect the photocatalytic activity of $(CeGdHfPrZr)O_2$ nanoparticles [4, 5]. $(CeGdHfPrZr)O_2$ nanoparticles can be used as a promising catalyst for the photocatalytic degradation of organic pollutants.

References:

1. M. Anandkumar, E. Trofimov, Synthesis, Properties, and Applications of High-Entropy Oxide Ceramics: Current Progress and Future Perspectives, Journal of Alloys and Compounds, (2023) 170690.

2. M. Anandkumar, S. Bhattacharya, A.S. Deshpande, Low temperature synthesis and characterization of single phase multi-component fluorite oxide nanoparticle sols, RSC Advances, 9 (2019) 26825-26830.

3. V.R. Naganaboina, M. Anandkumar, A.S. Deshpande, S.G. Singh, Single-phase high-entropy oxide-based chemiresistor: Toward selective and sensitive detection of methane gas for real-time applications, Sensors and Actuators B: Chemical, 357 (2022) 131426.

4. A. Saravanan, V.C. Deivayanai, P.S. Kumar, G. Rangasamy, R.V. Hemavathy, T. Harshana, N. Gayathri, K. Alagumalai, A detailed review on advanced oxidation process in treatment of wastewater: Mechanism, challenges and future outlook, Chemosphere, 308 (2022) 136524.

5. M. Mishra, D.-M. Chun, α-Fe_2O_3 as a photocatalytic material: A review, Applied Catalysis A: General, 498 (2015) 126-141.

DIRECT ENERGY DEPOSITION OF Nb/Cu GRADIENT LAYERS FOR DISSIMILAR MATERIALS JOINING

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The use of Cu/Nb multilayer is an optimal transition for joining dissimilar materials [1] and preventing the formation of brittle phases Ti-Cu, Fe-Nb, Ni-Nb. In order to reduce the formation of intermetallic compound (IMC), the influence of inter-pass temperature on the formation of microstructure and mechanical properties of gradient joints was investigated.

The process of microstructure formation during layer-by-layer deposition of specimens is accompanied by high cooling rates, significantly limiting the development of diffusion processes. In the process of gradient transition synthesis, the specimen is exposed to repeated thermal effects associated with the formation of new material layers, which create favorable conditions for solid-phase diffusion and the formation of a metastable-type structure.

After depositing the first layer of niobium, the interpass temperature reaches 113 °C, 78 °C, and 50 °C for dwell times of 0 s, 10 s, and 30 s, respectively. When cladding the subsequent niobium layer, the interpass temperature does not change in the case of a pause of 30 s, increases slightly by 14 °C to 92 °C for a pause of 10 s, and without dwell time, increases by 1.3 times to 152 °C. The following tensile strength of Cp-Ti–316L joints was obtained: 0 s dwell time - 231 MPa; 10 s dwell time - 310 MPa; 30 s dwell time - 283 MPa. The tensile strength of Cp-Ti–Inc 718 joints was the following: 0 s dwell time - 365.5 MPa; 10 s dwell time - 356 MPa; 30 s dwell time - 370 MPa.

During the direct energy deposition (DED) process, IMC inclusions were formed in all samples; despite this, high mechanical properties were obtained. Partial melting of Nb powder particles has a positive effect on the formation of structure and mechanical properties due to the prevention of the formation of a large number of IMCs with 316L, as well as the formation of β-Ti. Under static tensile stress, fracture occurs in the area where most intermetallides (Fe_2Nb, FeNb) are formed in the Nb/bronze - 316L zone or less strong areas of Nb. In the process of DED gradient transition Cp-Ti–Inconel 718 IMC inclusions (Ni_5Nb, NiNb) are formed, despite this, high mechanical properties are obtained. In static tensile fracture occurs in the zone where the most Nb/bronze IMCs are formed - Inconel 718. The highest strength value was 387 MPa on the specimen at a pause of 0 s.

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References:

1. R.V. Mendagaliev, O.G. Klimova-Korsmik, G.A. Turichin, A.M. Vildanov, Direct energy deposition of Cu–Nb functionally graded layers for dissimilar joining titanium alloys and steels, Materials Letters. 324 (2022), Article 132721.

EXPERIMENTAL SCREENING OF NEW SINGLE-PHASE HIGH-ENTROPY STANNIDS

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High-entropy intermetallic compounds (HEICs) are a new class of high-entropy materials that recently attracted scientific interest and exhibited interesting mechanical properties and thermal stability. Considering the wide range of binary intermetallics and their applications, the expansion of the chemical diversity of HEICs to other group of elements is highly demanded. The goal of this study is to design and perform an experimental screening methodology to find single phase medium- and high-entropy stannides.

The samples were synthesized by a laboratory induction melting furnace under reducing atmosphere. Precursor metals consisting of powders or small pieces with a purity of at least 99.99 % were weighed according to the stoichiometric ratios, placed inside a corundum crucible, and loaded in an induction furnace lined with graphite.

Judging by the data of the chemical composition (from EDS analysis) and phase structure (from XRD analysis), multicomponent intermetallic compounds of other types (XSn_2, XSn, X_2Sn) occur only in the multiphase samples. Moreover, a significant part of the multiphase samples consists of a Sn based solid solution phase. Only sample with X_3Sn_2 stoichiometric composition indicated promising behavior to form single-phase stannide.

The obtained results were further employed to examine the stability criteria, the sublattices electronegativity differences and the atomic size polydispersity of the elements occupying high entropy sites.

Samples $(Fe,Co,Mn)Sn_2$, $(Fe,Co,Mn,Cr)Sn_2$ and $(Fe\ Co\ Mn\ Ni\ Cr)_3Sn_2$ exhibited a single-phase HEIC. However, $(FeCoMn)Sn_2$ and $(FeCoMnCr)Sn_2$ consist of mainly a Sn solid solution and a $MnSn_2$-type structure. For $(Fe,Co,Mn,Ni,Cr)_3Sn_2$, while the main phase is HEIC with hexagonal Co_3Sn_2 prototype structure, the precipitation of FeCr- and $MnSn_2$-type phases was observed.

By experimental screening of nine different compositions, a single phase $(Fe,Co,Ni,Mn)_3Sn_2$ stannide with hexagonal Co_3Sn_2 prototype structure is discovered. Entropy-stabilized intermetallic compounds of other types (XSn_2, XSn, X_2Sn) occur only in multiphase samples [1].

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References:

1. Evgeny Trofimov. Unraveling new single phase high entropy stannide by experimental screening of the as-cast samples / Evgeny Trofimov, Ahmad Ostovari Moghaddam, Olga Zaitseva, Rahele Fereidonnejad, Dmitry Mikhailov // Materials Letters. – 2023. – P. 4. https://doi.org/ 10.1016/j.matlet.2023.133861.

CALCULATION OF THE CHARACTERISTICS OF THE STRUCTURE OF REFRACTORY NONMETALLIC MATERIALS WITH A RIGID TRANSPORT PORE SYSTEM FORMED BY SINTERING FIBERS

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Application of porous materials on the basis of ceramic fibers as a basis of high-entropic and filtering materials is defined by possibilities of operation at high (over 15 MPa) pressures, temperatures (up to 700° C) with preservation of durability in a mode of long operation. In contrast to the known woven materials (fiber basalt plates) the size and configuration of the pores of the created porous materials remain constant during the operation due to the frame rigidity. This technical solution makes it possible to increase the stability of the characteristics.

In general, fibers made of refractory nonmetallic materials are superior to metallic ones in thermal, physical, electrical and acoustic characteristics, as well as in chemical resistance.

In [1] it is shown that during pressing the disperse medium changes its density only as a result of structural rearrangement of particles, which occurs quite uniformly in the entire volume of the pressed body. Due to this it is possible to form a technologically strong product of particles with a low plasticity resource. This feature of pressing makes it possible to obtain long porous fiber pipes based on refractory non-metallic materials with a length to diameter ratio of more than 35.

Prediction of characteristics of porous materials based on ceramic fibers with the help of polynomial model allowed to calculate the location of equal value planes D_{pores}, K (permeability coefficient), σ (material compressive strength) in coordinates D particles, T speckling, N(ratio of ceramic fiber volume to volume of porogen,%). The regression equation (1) has the form of polynomial of the second degree

$$P(X) = \sum_{\substack{i,j=1 \\ i \le j}}^{3} a_{ij} X_i X_j + \sum_{i=1}^{3} b_i X_i + c, \qquad (1)$$

where $P_k(X)$ *is* a polynomial for calculating the permeability coefficient;
$P_D(X)$ is a polynomial for the average pore size;
$P_\sigma(X)$ *is* a polynomial for compressive strength;
X_{1-3} – normalized values:
$X_1 = 3\left(\lg\left(D_{particle}\right) - 2{,}6\right)$;
$X_2 = \frac{\left(\mathrm{T_{sintering}} - 1200\right)}{50}$;
$X_3 = 0{,}2(E - 1{,}1)$;
a_{ij}, b_j, c – coefficients;
$E = \lg N$;
$D_{particle}$ is the diameter of the fiber;

Blanks consisting of basalt fiber, polystyrene, porcelain and vaporizer were used for the study. The formation of porous materials was studied at three temperatures 1050° C, 1075° C, 1100° C.

Calculations by the example of basalt fiber have shown that at a temperature of heat treatment of 1050 °C – 1100 °C, a material with a structure characterized by porosity 52 – 75 %, average pore size 10–18 μm, permeability coefficient (35–67) 10^{-12} $m^{2,}$ compressive strength 16–29 MPa can be formed from pressed fiber. The obtained results prove that the porous basalt fiber material is able to provide the specified characteristics when used as a base of high-entropic materials.

References:

1. Petushik, E.E. Fundamentals of deformation of wire winding bodies: monograph / E.E. Petushik, O.P. Reut, A.Ch. Jakubowski. - Mn.: "Tekhnoprint" UP, 2003. - 218 c.

STUDIES OF HIGH-ENTROPY ELECTRIC ARC COATING OF THE Al-Co-Cr-Fe-Mn SYSTEM

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In recent decades, the concept of high-entropy alloys (HEA) has been actively studied in the scientific community. This class materials is characterized by the presence of five and more components, each of which varies from 5 to 35 at. %. Due to this ratio of chemical elements, WEAs have unique microstructure and properties that distinguish them from traditional materials consisting of one or two main components.

The HEA manufacturing process also has a significant impact on the final properties products. The mechanical properties of an equimolar Al-Co-Cr-Fe-Mn alloy can vary as by varying manufacturing parameters, and depending on the technologies used for the production and subsequent processing. Therefore, for effective implementation and use of wind power plants in industry, it is necessary to choose a manufacturing method based on of the required properties.

Under the conditions of the SPC "Welding Processes and Technologies" of the Federal State Budgetary Educational Institution of Higher Education "SibSIU", the process of manufacturing flux-cored high-entropy wire was carried out on a laboratory installation using the technology with passing through dies. The diameter of the produced wire is 4.2 mm, the sheath is made of 08ps tape 14 × 0.6 mm in size. Various powdered materials have been used to produce high-entropy flux-cored wire.

Surfacing of the investigated composition was carried out under high-silicon manganese flux AN-348A according to GOST 9087-81, which provides good formation, low tendency to form pores and satisfactory separability of the slag crust from the deposited metal.

A plate made of steel 09G2S with a size of 20*70*500 mm was used as a substrate.

Surfacing of the studied samples was carried out using the surfacing mode recommended according to GOST 26101-84, current strength 450A, voltage 28V, surfacing speed 15 cm/min. After the surfacing process, samples of 40*20 mm in size were cut out.

Under laboratory conditions, the Center for Collective Use "Materials Science" determined the chemical composition of the deposited coating by the X-ray fluorescence method and the atomic emission method. The results of the chemical composition indicate that the deposited layer consists of 70% Fe and 23% alloying elements Al-5.27% Mn-6.47%, Cr-6.25%, Co-5.48%.

The next stage of the research work will be to study the microstructure and microhardness of the obtained material.

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HEAT TREATMENT OF INCONEL 718 OBTAINED BY WIRE ARC ADDITIVE MANUFACTURING WITH INTERLAYER FORGING

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The main manufacturing processes of structural components are machining and welding of billets produced by casting or forming. However, creep-resistant Ni-Cr-Fe alloys are prone to dendritic segregation during welding, which leads to the formation of Laves phase in fusion zones, microcracking in heat affected zones due to carbides and eutectic phases at grain boundaries, and porosity, which significantly reduces product performance [1]. At the same time, these alloys have low machinability, so there is an urgent need to develop new approaches to produce billets that fit the shape of the final part [2].

This research investigated the effect of heat treatment on the structure and properties of nickel-based superalloy Inconel 718 obtained by wire arc additive manufacturing using cold metal transfer and interlayer forging techniques. Interlayer forging was shown to prevent dendrite growth throughout the alloy's billet. Subsequent heat treatment led to dissolution of the brittle phases and precipitation of the strengthening γ'- and γ"- phases, which significantly improve the mechanical properties of the alloy.

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References:

1. Taylor P. Machining Science and Technology : An International machinability of nickel-based high temperature alloys // Mach. Sci. Technol. An Int. J. 2014. Vol. 4:1, № September. p. 37–41.

2. Sonar T. et al. An overview on welding of Inconel 718 alloy - Effect of welding processes on microstructural evolution and mechanical properties of joints // Mater. Charact. Elsevier Inc., 2021. Vol. 174, № February. P. 110997.

PROCESSING AND PROPERTIES OF HIGH-ENTROPY ULTRA-HIGH TEMPERATURE CARBIDES (TaTiNbZr)C and (TaTiNbZrX)C (X= Hf, W, Mo)

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High-entropy materials are one of the most popular areas of advanced materials science, substitution conventional approaches to creating new alloys that have practically exhausted their capabilities. High-entropy materials are defined as alloys or compounds consisting of five or more basic elements in the same molar ratios. Recently, the range of high-entropy materials has been expanded to include non-metallic and non-oxide elements and a class of high-entropy carbides, borides, nitrides and carbonitrides has been created.

In this work, carbides of equimolar compositions, (TaTiNbZr)C and (TaTiNbZrX)C (X= Hf, W, Mo) obtained by a combination of high-energy ball milling (HEBM), self-propagating high-temperature synthesis (SHS) and spark plasma sintering (SPS). The influence of HEBM modes on the morphology, structure and phase composition of powder mixtures has been studied. Optimization of the planetary ball mill process allowed to obtain two types of powder mixtures:
1) reaction powders Ta/Ti/Nb/Zr/Hf and (Ta/Ti/Nb/Zr/Hf)/C for subsequent SHS;
2) products of mechanochemical synthesis - (TaTiNbZrHf)C.

The obtained through SPS bulk ceramics were comprehensively characterized, mechanical properties, oxidative resistance in air and melting point were investigated.

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ALUMINUM ALLOY WIRE FOR ADDITIVE TECHNOLOGIES FROM LONG-LENGTH BILLETS OBTAINED BY ELECTROMAGNETIC CRYSTALLIZATION

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In recent years, the direction of additive technology has been developing, associated with the use of high-quality source material as wire for 3D printing, not powder. Studies conducted on the aluminum alloys creation for wire alloyed with transition metals have

shown that an effective way to obtain a dispersed structure of intermetallides is electromagnetic crystallization when casting a thin billet of Ø 8-12 mm of unlimited length.

The investigated wire's tensile strength from alloys Al-Mg-transition metals (TM) system was 453-485 MPa. When surfacing by the WAAM method, the microhardness increased by almost 1.5 times at 350 °C annealing temperature for 2 hours, apparently due to precipitation hardening.

A comparison of the 3D surfacing structure of L-DED and WAAM using wire obtained from billets with a diameter of 12mm of Al-Mg-TM alloys by electromagnetic crystallization shows that the crystallization conditions are significantly different. The surface quality of the laser-deposited sample is higher compared to the sample where the WAAM process was used as a source of welding arc heating. There are no pores in the microstructure in the zone of laser layers deposition, unlike the arc method. The conducted studies have shown that in both cases (when using the WAAM and L-DED method), the use of a wire more highly alloyed with transition metals will allow to obtain 3D component parts of a complex shape bionic design with a high strength level due to complex heat treatment: annealing for stress relief and precipitation hardening.

A technology is being developed to produce a billet of aluminum alloys with boron for drawing wire with a diameter of 1.2 mm and manufacturing transport package elements by the WAAM method for Rosatom. It is known that aluminum alloys doped with boron have a unique combination of properties such as strength, corrosion resistance, good thermal conductivity, low strength-weight ratio, as well as the ability to absorb thermal neutrons. This makes them indispensable as radiation-protective structural materials.

The casting billets with boron technology from AMG5 B5 and AK5B3 alloys based on Al5B alloyage, boron powder and boron carbide has been tested. The technology of putting powdered boron into the aluminum melt using a plasma torch was carried out, a prototype was obtained from a boron-containing aluminum alloy using powdered boron. It has been established that high-frequency plasma allows melting powdered boron and obtaining sufficiently dispersed and evenly distributed aluminum borides in a boron-containing aluminum alloy for the wire production for additive surfacing.

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STUDY OF THE EFFECT OF HIGH-TEMPERATURE ANNEALING ON THE CORROSION-FATIGUE STRENGTH OF FINE-GRAINED TITANIUM ALLOY PT-7M

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The object of study is the industrial titanium alloy PT-7M (Ti-2.2 wt.% Al-2.5 wt.% Zr), which is actively used in nuclear engineering. The ultrafine-grained (UFG) structure in the alloy was formed by the rotational swaging (RS) method. At present, this method is one of the promising ways to improve the physical and mechanical characteristics of metals and alloys. Fatigue tests were carried out on cylindrical specimens according to the "bending with rotation" scheme in a 3% NaCl aqueous solution. The loading frequency was 50 Hz. Short 30-minute high-temperature annealings were carried out at temperatures of 500, 550, 600, and 650°C. Long-term (500, 1000 h) high-temperature annealings were carried out at a temperature of 250°C.

Studies of the microstructure showed that, after rotational swaging, an UFG structure with an average fragment size of ~0.2–0.5 μm was formed in the PT-7M alloy. After long-term high-temperature annealing at 250°C and short annealing at temperatures of 500, 550°C, the structure of the alloys does not change; the first recrystallized grains ~1–3 μm in size are observed after annealing at 600°C.

Studies of mechanical properties have been carried out, it has been shown that at annealing temperatures of 500 and 550 °C, the microhardness does not change and amounts to ~ 2300 MPa. After annealing at temperatures of 600 °C and 700 °C, the microhardness of the alloy is 2080 MPa and 1715 MPa, respectively. The microhardness of the PT-7M alloy after long-term annealing at a temperature of 250°C remains unchanged and amounts to ~2600 MPa.

Carrying out corrosion-fatigue tests of fine-grained titanium alloy PT-7M showed that a significant drop in corrosion-fatigue strength is observed at annealing temperatures of 600 and 650°C, and is not observed at temperatures of 500 and 550°C.

Analysis of the results of corrosion-fatigue tests after long-term annealing at a temperature of 250 °C shows that there is a decrease in corrosion-fatigue strength compared to the original UFG titanium alloy PT-7M.

Fractographic analysis of specimen fractures after corrosion-fatigue tests has been carried out. The main stages of fatigue crack initiation and growth are revealed.

FORMATION OF NANODISPERSED PARTICLES UNDER DYNAMIC AGING DURING HIGH PRESSURE TORSION IN THE HIGH-ENTROPY ALLOY FeMnCrNiCo

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In the present study, an equiatomic face-centered cubic high-entropy FeMnCrNiCo alloy was subjected to high-pressure torsion (HPT) through 5 rotations at room temperature (300 K) and at 300˚C (580 K).

High-entropy alloys processed by HPT typically exhibit high strength but limited ductility due to their low strain rate hardening and sensitivity to strain rate [1, 2]. Therefore, short post-deformation annealing is often used to enhance ductility. However, annealing at too high temperatures leads to accelerated recovery and recrystallization processes and as a result to a decrease in strength [3].

In this work, HPT at 300˚C is considered instead of the traditional short post-deformation annealing. The application of HPT at 300˚C is focused on the study of solid solution decomposition and formation of dispersed particles of the second phase under dynamic aging conditions.

The microstructural changes after HPT at room temperature and 300 ˚C were examined using transmission electron microscopy (TEM). HPT at 20°C leads to a significant refinement of the structure of the studied HEA with areas of deformation twinning and the average grain size of 50 nm. Nanotwins were observed within the grain interiors, while no dispersed particles were detected. For comparative analysis, additional annealing of the HPT state at 20°C was conducted at 300°C for 1 hour. HPT at 300°C led to the formation of a larger ultrafine-grained microstructure with grain sizes up to 500 nm. TEM bright-field images revealed the presence of dispersed particles in individual grains, with a volume fraction of about 1-2% and dimensions of about 10 nm. These particles were identified to be a chromium-rich face-centered cubic phase and a tetragonal σ phase with high chromium content. The effects of ultrafine grains and nanoparticles on the strength properties of the alloy are discussed.

References:

1. R. Pippan, S. Scheriau, A. Hohenwarter, M. Hafok. Advantages and limitations of HPT: a review Mater. Sci. Forum, 584–586 (2008), pp. 16-21.

2.P.F. Yu, et al. Effects of high pressure torsion on microstructures and properties of an Al0.1CoCrFeNi highentropy alloy, Mater. Sci. Eng. A 655 (2016) 283-291.

3. Shahmir, H.; He, J.; Lu, Z.; Kawasaki, M.; Langdon, T.G. Effect of annealing on mechanical properties of a nanocrystalline CoCrFeNiMn high-entropy alloy processed by high-pressure torsion. Mater. Sci. Eng. A 2016, 676, 294–303.

ENHANCED STRENGTH-DUCTILITY SYNERGY OF FeCoNiMnV HIGH-ENTROPY ALLOYS VIA ULTRAFINE LAMELLAR STRUCTURES

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In the present study, the effect of severe cold rolling (SCR) process on the microstructure and mechanical characteristics of $X_{0.25}$FeCoNiMnV (X: Al, Ti) high-entropy alloys (HEAs) specimens was investigated. It was observed that the as-cast and homogenized specimens exhibited a two-phase microstructure consisting of face-centered cubic (FCC) and a minor body-centered cubic (BCC) structure. Electron backscattered diffraction (EBSD) analysis indicated that SCR could effectively induce a strong rolling texture with stretched grains along the rolling direction and lamellar deformation bands as the major microstructural features for all the HEAs specimens. Moreover, a large number of nano-scale grains are formed within the coarse-stretched microstructure of $Al_{0.25}$FeCoNiMnV and $Ti_{0.25}$FeCoNiMnV HEAs specimens due to local fragmentation, resulting in a bimodal grain structure. $Ti_{0.25}$FeCoNiMnV specimen exhibited the best combination of strength-ductility (tensile strength of 1225 MPa and elongation of 26%) compared to FeCoNiMnV (720 MPa and 15%) and $Al_{0.25}$FeCoNiMnV (970 MPa and 18%). Observations revealed that the failure mode of HEAs specimens was a ductile type fracture with a combination of deep and shallow dimples.

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POSSIBILITIES OF WIRE ARC ADDITIVE MANUFACTURING OF ALUMINUM ALLOYS

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The paper presents the results of experimental study of the possibility of realization of the process of wire arc additive manufacturing from aluminum alloy AMg5 in different spatial positions. Fronius TPS 500i welding source, Fanuc M 710iC robot manipulator and Fanuc two-axis positioner was used for manufacturing of prototypes. ER5356 welding wire (analog of AMg5) with a diameter of 1.2 mm was used as filler material. The technological parameters that have the most influence on the stability of the process in horizontal and vertical spatial positions have been determined. A series of preliminary experiments were carried out to limit the range of welding current, providing stable formation of samples in spatial positions other than the bottom position. The optimum values of inter-pass temperature and speed of movement of the

working tool which the molten material does not flow down have been determined. The waviness of the upper surface was evaluated by the standard deviation. The results of transferring the process parameters from horizontal to vertical position are presented. The possibility of growing in bottom-up and top-down directions is considered. A technology allowing to obtain stable formation in vertical spatial position with reversal of direction between layers is proposed. Micro-slides demonstrating the structure of samples obtained in bottom, horizontal and vertical spatial positions are presented. Demonstrator samples are fabricated.

The results of the research on the formation of angular elements in wire arc additive manufacturing in the lower spatial position are presented. Technological methods allowing to produce elements with change of growing direction up to 150 degrees without significant height difference between the wall body and the corner are proposed.

The possibility of cladding of inclined walls with inclination angles up to 60 degrees is considered. The influence of the welding torch inclination angle on the process stability is investigated.

The strategy of growing intersecting and adjoining elements, allowing to obtain cell structures with a regular height of the roll over the entire area of the specimen, is proposed.

KEYHOLE PLASMA ARC WELDING OF A Ti2AlNb-BASED ALLOY

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In order to obtain defect-free welded joints from a Ti_2AlNb-based alloy, plasma keyhole welding was proposed. Plasma keyhole welding was carried out using a PMI-350 AC/DC TL power source on an automated console-type portal. Plates of a VTI-4 alloy (σ_B = 1230 MPa, $\sigma_{0.2}$ = 1190 MPa, δ = 3.5 %) were welded without air gap and filler material. Welding modes were ranged as follows: keyhole current 150-160 A, base current 140-150 A, end current 15-20 A, plasma and main gas flow rate 3 l/min. Post-welding heat treatment (PWHT) was carried out using a vacuum muffle furnace according to the following regime: quenching at a temperature of 920°C with 2 hours soaking and air-cooling, followed by 6 h at a temperature of 800°C, cooling in air. As a result, welds were free of external pores and cracks. Furthermore, strength properties of the welded joint were ~80 % of the base metal (σ_B = 1020 MPa, $\sigma_{0.2}$ = 1010 MPa, δ = 0.5 %). However, there was the lack of ductility. After PWHT, strength properties of the welded joint were ~90 % of the base metal (σ_B = 1120 MPa, $\sigma_{0.2}$ = 1090 MPa, δ = 2.1 %).

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EFFECT OF Ni, Mn, Fe and Si ADDITIVES ON THE PHASE COMPOSITION AND STRUCTURE OF THE HYPEREUTECTIC ALUMINUM-CALCIUM ALLOYS

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Aluminum-calcium alloys are proposed as an alternative to hypereutectic silumins for the manufacture of heavy-loaded pistons operating at temperatures up to 300 °C.

Recent studies have shown that they are manufacturable, both in the process of obtaining castings and deformed semi-finished products. A large proportion of solid phases can provide increased wear resistance and hardness, combined with good ductility.

Using experimental and computational methods, including the construction of liquidus surfaces, the analysis of the phase composition and morphology of primary crystals in hypereutectic alloys Al—6%Ca—3%Ni—2%X, where X is Fe, was carried out Si, Mn.

Additional alloying of the base Al–6%Ca–3%Ni alloy with iron and silicon leads to the formation of coarse elongated primary crystals up to 100 μm in length. It was found that the addition of manganese, on the contrary, leads to the formation of relatively small (average size about 20 μm) compact primary crystals of two four-component phases. Presumably, these phases are based on ternary compounds Al_9CaNi and $Al_{10}CaMn_2$. The composition of eutectics in quaternary alloys has been determined. All aluminum-calcium eutectics are characterized by a higher proportion of the second phases, a thinner structure compared to the aluminum-silicon eutectic in AK18 silumin, and are also capable of spheroidization upon heating, starting at 500°C. The combination of compact and spherical particle morphologies after annealing in the 63-2Mn alloy appears to be favorable for deformation.

The alloy with nickel and manganese additives has the most favorable structure. It contains compact primary crystals combined with fine structure eutectic. Manganese is also part of the solid solution, strengthening it. To reduce the density of the 63-2Mn alloy, the concentration of calcium in it was increased to 8%, and nickel, on the contrary, was reduced to 1%, i.e., the total content of alloying elements remained the same — 11%. The density of the resulting alloy of optimized composition (81-2) was 2.51 g/cm3 versus 2.63 g/cm3 for silumin AK18.

Comparison of the manufacturability of the experimental alloy Al–8%Ca–1%Ni–2%Mn and the grade silumin AK18 showed the advantage of the former. In terms of the totality of its characteristics, the experimental alloy can be considered as the basis for the development of hypereutectic alloys of a new generation as an alternative to piston silumins of the AK18 type. The experimental alloy, whose microstructure is characterized by a compact morphology and small size of primary crystals and a fine structure of the eutectic, in contrast to hypereutectic silumins, does not require special modification.

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ELECTRODEPOSITION OF FeNiCoVW(Cr,Zr) and FeNiCoVW(Cr,Zr)/WC COATINGS

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Due to their high mechanical, physical and chemical properties, high entropy alloys are ideal for applications in various fields of technology, including coatings. There are various methods for applying HEA coatings. One of the possible ways to obtain coatings from HEA is galvanic deposition. Most often, HEA electroplating is applied from non-aqueous solutions (using, for example, dimethyl sulfoxide (DMSO) as an organic solvent). However, the use of aqueous solutions in this process has great and obvious advantages.

From the analysis of previous studies of the galvanic deposition of HEA coatings, it follows that their composition, morphology, and properties are determined by the deposition parameters, such as electrolyte composition, deposition potential, current density, stirring rate, and others. Thus, by varying the conditions of electrodeposition, it is possible to obtain the desired HEA properties.

The relevance of the work is associated with the need to develop new coatings for various purposes with improved performance. High entropy FeNiCoVW(Cr,Zr) alloys as well as composites based on HEA with the addition of WC carbide powder may have great potential for surface protection applications under extreme conditions such as high temperature, abrasion and corrosion.

The use of composite materials for the preparation of such coatings makes it possible to combine the mechanical characteristics of the matrix metal with the characteristics of the filler, which by itself may not have the necessary properties in order to independently form a strong coating with high adhesion to the surface to be coated and other required properties.

The purpose of this study is to develop scientific foundations for the synthesis of high-entropy coatings of new compositions of FeNiCoVW(Cr,Zr) and FeNiCoVW(Cr,Zr)/WC alloys by galvanic deposition from aqueous solutions of metal salts, as well as composite coatings based on these alloys with the addition of tungsten carbide particles. . The structure and properties of the resulting coatings are being studied. The results obtained will form the basis for the development of fundamental principles for the production, processing and operation of such coatings.

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FORMATION OF COATINGS WITH EQUIATOM RATIO FROM COMPOSITE POWDERS OF THE AL-NI-CO-FE-CR SYSTEM

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Since the 2000s, the unique physical and mechanical properties of high-entropy alloys (HEAs) have been in the focus of researchers attention. The processes of structure formation and phase formation, the mobility of atomic diffusion, the mechanisms of formation of physical and mechanical properties, and the thermal stability of HEAs differ significantly from similar processes in conventional alloys, and therefore attract attention as a special group. Of particular relevance for industrial applications are studies aimed at developing technologies for the formation of protective and wear-resistant coatings from HEA, as well as determining their set of properties. Despite the fact that since the first reports about this new type of alloys, interest in HEA has been steadily growing, no one has studied functional coatings from HEA for resistance to marine corrosion, and there are no publicly available publications on this topic. This work is devoted to establishing the possibility of forming coatings with the structure of high-entropy alloys by microplasma spraying from composite powders of the Al-Ni-Co-Fe-Cr system and studying their set of properties.

In the course of the work, a series of experiments on the mechanosynthesis of composite powders of the Al-Ni-Co-Fe-Cr system with variable processing modes was carried out. Their granulometric composition was studied by laser diffraction, morphology by scanning electron microscopy, and stability to phase transitions and oxidation under heating conditions up to 1000 °C was determined using a combined method of thermogravimetric analysis and differential scanning calorimetry. On the basis of which the most promising composite powder for subsequent deposition was determined.

The coating from the synthesized composite powder of the Al-Ni-Co-Fe-Cr system was deposited by the microplasma method using the UGNP-7/2250 installation, using the Kawasaki FS003N robotic arm.

Phase composition, microhardness, porosity, adhesion, corrosion potential in 3.5% NaCl solution and resistance to pitting corrosion in FeCl solution at room temperature for 5 hours were determined for sprayed coatings.Based on the results of the study, the most promising coatings for practical application on elements pipelines for various purposes, gate valves, control valves for ship systems. The use of the obtained results in further work will bring the technology to a level corresponding to the implementation at enterprises representing the real sector of the Russian economy.

CONTROL OF THE MICROSTRUCTURE, PROPERTIES, AND CHEMICAL COMPOSITION OF BLANKS DURING LAYERED GROWTH BY WAAM

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The possibility of obtaining multilayer blanks from steels 30CrMnSi and 307 Lsi by their simultaneous supply in different ratios by the method of additive layer-by-layer growth by means of wire-arc additive manufacturing (WAAM) has been studied.

For the manufacture of critical structures for various purposes, alloys from high-alloy steels and special structural alloys are increasingly used. Traditional alloys do not always provide the required combination of properties, such as high thermal and electrical conductivity with high strength properties, low ductility with high impact strength, low density and high strength, and others. One of the most accessible and relatively less expensive methods for obtaining layered metal materials is additive layer-by-layer growth by means of WAAM, the solution presented by the authors lies in the selection of a special proportion of wires, which is a significant advantage of additive layer-by-layer growth by means of WAAM for obtaining a different set of properties, which was quite difficult to do with the help of such technological operations as casting or forging.

To study the process of obtaining materials by this method, surfacing of 3 walls from steels 307 Lsi and 30CrMnSi was carried out, in modes with different proportions of the supplied materials. The fabrication was carried out by means of 3D surfacing along a given trajectory, using the arc wire additive technology. The process used two welding torches mounted on a bracket and two power sources with a hard current-voltage characteristic. Two arcs burned in one common weld pool, from consumable electrodes made of the above materials, the share of each of the materials was regulated by changing the wire feed speed.

In general, a defect-free structure is formed, the microstructure consists of martensite, austenite, and dark-colored inclusions. In general, the microstructure is dispersed, and with an increase in the carbon content in the samples, the amount of martensite increases.

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THE EFFECT OF MICROSTRUCTURE ON HYDROGEN EMBRITTLEMENT OF HIGH ENTROPY CANTOR ALLOY

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The influence of hydrogen charging on the mechanical properties and fracture mechanisms of a high-entropy alloy before and after microstructure design was investigated. A high-entropy Cantor alloy ($Co_{20}Cr_{20}Fe_{20}Mn_{20}Ni_{20}$) was chosen as an object for the study. The cast alloy was subjected to a thermomechanical treatment, including solid-solution treatment (SST, 1200 °C, 2 h), cold rolling (80% reduction) and final SST (1200 °C, 2 h). Some of the specimens were studied in the coarse-grained state after SST (C-HEA). Part of the specimens was subjected to an annealing at 950°C for 1 hour. After this treatment, a fine-grain specimens (F-HEA) were obtained. The other part was subjected to age-hardening at 900°C for 1 hour (A-HEA). Electrochemical hydrogen charging was carried out at a current density of $j_H = 10$ mA/cm^2 for 50 h at room temperature in a 3% aqueous NaCl solution in the presence of 3 g/l NH_4SCN as a recombination poison.

The results of X-ray diffraction analysis showed the formation of an austenitic phase structure in C-HEA, F-HEA and A-HEA specimens. However, electron microscopic studies have shown that age-hardening leads to the precipitation of the intermetallic σ-phase, enriched with chromium, along the grain boundaries in A-HEA specimens. An analysis of room temperature tensile properties shows close values of the yield strength ($\sigma_{0,2}$) and elongation to failure (δ) for C-HEA, F-HEA and A-HEA specimens. Hydrogen charging is accompanied with significant change in their mechanical properties. The yield strength increases ($\Delta\sigma_{0,2}$) in the hydrogen-charged specimens, which is caused by solid-solution hardening by hydrogen. The hydrogen embrittlement index (I_H), which describes the hydrogen-induced loss of elongation, for C-HEA specimens is 27%, that is 2 times higher than that for F-HEA and A-HEA specimens, $I_H^{F\text{-}HEA} = 13\%$ and $I_H^{A\text{-}HEA} = 12\%$.

All hydrogen-free specimens fractured via a ductile dimple micromechanism. Hydrogen-charging leads to the formation of brittle surface layers that undergo intensive cracking during tensile tests at room temperature. An analysis of the fracture surface showed that intergranular fracture of the hydrogen-assisted brittle layers occurred, but transgranular elements were also seen in C-HEA, F-HEA and A-HEA specimens. The thickness of hydrogen-assisted brittle layer (W_H) for F-HEA and A-HEA specimens ($W_H^{F\text{-}HEA} = 21.5 \pm 5.0$ μm, $W_H^{A\text{-}HEA} = 28.0 \pm 7.0$ μm) is much smaller than for the C-HEA specimens ($W_H = 69.5 \pm 20.5$ μm).

Therefore, specimens of the CoCrFeMnNi alloy after annealing at a temperature of 950°C for 1 hour and age-hardening at a 900°C for 1 hour are more resistant to hydrogen embrittlement as compared with the coarse-grain specimens.

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PLASMA DYNAMIC SYNTHESIS OF HIGH ENTROPY CARBIDES AND CARBINITRIDES Ti-Zr-Nb-Hf-Ta-C-(N)

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Ultra-high temperature ceramics (UHTCs), due to their extremely high melting temperatures, are considered the most promising class of materials for use in the aerospace sector, in particular, for creating a heat-shielding layer for hypersonic vehicles in harsh aerodynamic environments with ultra-high operating temperatures. UHTCs are based on metals of groups IV and V of the periodic table and their compounds with carbon, nitrogen, and boron. New opportunities in this area are opening up in connection with the discovery of high entropy ceramic materials [1], among which the most interesting are high entropy carbides, nitrides, and carbonitrides of transition metals [2].

Plasma dynamic synthesis is a universal way to obtain numerous compounds such as oxides, carbides, nitrides, borides. In this work, we study the possibility of synthesizing carbides and carbonitrides based on Ti, Zr, Nb, Hf, and Ta in a high-speed arc discharge plasma generated in a coaxial magnetoplasma accelerator. Using a graphite electrode system under the influence of a pulsed current of ~100 kA, a series of experiments was carried out to obtain high entropy carbide $TiZrNbHfTaC_5$ and carbonitride Ti-Zr-Nb-Hf-Ta-C-N in a dispersed form. Mixtures of the corresponding metals or their oxides can be used as precursors.

The synthesized products were studied by X-ray diffractometry, scanning and transmission electron microscopy, X-ray photoelectron spectroscopy, and Raman spectroscopy. It has been found that in the process of plasma dynamic synthesis, a cubic crystalline phase with the NaCl structure with the space group Fm3m is formed, mostly without any impurities. When using a carbon-free mixture of precursors and a gas of the reactor chamber as a source of nitrogen, it is possible to obtain materials containing up to 8 wt.% nitrogen. The resulting powders can be used to create UHTCs components.

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References:

1. C. Oses, C.Toher, S. Curtarolo. High-entropy ceramics. Nat Rev Mater. 5, (2020) 295-309.

2. A. Nisar, R. Hassan, A. Agarwal, K. Balani. Ultra-high temperature ceramics: Aspiration to overcome challenges in thermal protection systems. Cer Int,48 (7), (2022) 8852-8881.

EFFECT OF COPPER CONCENTRATION ON GRAIN STRUCTURE AND PROPERTIES OF HYPO-, HYPER- AND EUTECTOID TI6AL4V-CU ALLOYS IN ELECTRON-BEAM ADDITIVE MANUFACTURING

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Titanium alloys and composites based on them are increasingly used for special applications in the aerospace, biomedical, automotive and marine industries, due to their outstanding properties such as low specific gravity, high strength, high corrosion resistance and good fatigue properties. However, during additive manufacturing (AM) of titanium alloys, large primary columnar β-grains are formed. These grains are considered unfavorable because their presence leads to anisotropy of mechanical properties. The refinement of primary β-grains is associated both with an increase in the grain nucleation rate and with the effect of constitutional undercooling. The relative contribution of the solute to constitutional undercooling is estimated using the growth restriction factor Q. The addition of copper to the melt leads to the formation of a sufficiently large zone of constitutional undercooling, which can contribute to the refinement of primary columnar β-grains during the AM of Ti6Al4V alloy.

The purpose of this work is to study the effect of different Cu concentration on the formation of the grain structure, mechanical and tribological properties of Ti6Al4V alloy manufactured under conditions of non-stationary local metallurgy in two-wire electron beam additive manufacturing.

Alloys in the form of a vertical wall were obtained by admixing Ti6Al4V alloy with different concentrations of Cu (0.6, 1.6, 6, 9.7, 15, 19 and 25 wt.%) with the use of electron beam additive manufacturing. For each Cu concentration added into the Ti6Al4V alloy, the growth restriction factor was calculated, which was 11.9, 18.4, 47, 71, 105.5, 131.5, and 170.5 K, respectively. It was found that with an increase in the copper concentration 3 types of structure are formed: completely columnar (for Ti6Al4V-0.6Cu), mixed columnar-equiaxed grain structure (for Ti6Al4V-1.6Cu and Ti6Al4V-6Cu) and completely equiaxed one (for Ti6Al4V with a copper concentration from 9.7 to 25 wt.% Cu). With an increase in the Cu content from 6 to 19 wt.% in the middle part of the deposited Ti6Al4V-Cu, there is an improvement in ultimate tensile strength (UTS) to 875, 1146, 1142 and 929 MPa, respectively. When 25 wt.% Cu is added to Ti6Al4V, the UTS value is significantly reduced and becomes close to that of base Ti6Al4V. The linear wear value for alloys with 6 and 19 wt.% Cu decreased by ~46% and ~30%, respectively, compared to that of additively manufactured Ti6Al4V. Obviously, that the increase in UTS and wear resistance of Ti6Al4V alloys with a copper concentration from 6 to 9.7 wt.% is associated with the transition from columnar grains to equiaxed, solid solution hardening and dispersion hardening due to precipitation of Ti_2Cu particles in interlayers of α/β colonies.

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ELECTROCHEMICAL SYNTHESIS AND THERMODINAMIC PROPERTIES OF Pr-Ga-Pb ALLOYS IN LIQUID METAL/MOLTEN SALT SYSTEM

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The eco-destructive consumption of fossil fuels worldwide has resulted in growing concerns regarding the energy crisis and environmental pollution, warranting research on high efficiency and carbon free energy. Nuclear energy is deemed as the one of the most efficient clean and renewable energy to resolve such problems. However, the sustainable development of nuclear energy is seriously hampered by formation of fission products. Therefore, the reprocessing of spent nuclear fuel plays a key step in the process of nuclear energy waste recycling. Lanthanides is one of the most dangerous components of spent nuclear fuel and it is difficult to separate them by simple chemical methods on account of their chemical similarity to actinides. Electrolysis of molten salt using reaction electrode is one of the most important methods for recovering spent nuclear fuel, and lanthanide elements and other fission products can be successfully extracted due to depolarization reaction. Thus, the investigations in the field of electrochemical production of complex triple alloys and determining their principal thermodynamic characteristics in liquid metal/molten salt system are very important.

The reactions of Pr-Ga-Pb alloys formation by direct deposition of praseodymium (III) ions on reactive Ga-Pb electrodes and by co-deposition of Pr(III), Ga(III) and Pb(II) ions on inert electrodes have been investigated via different electrochemical technique. For calculation of the principal thermodynamic characteristics of the alloy formation processes open-circuit potentiometry was used. It was established that the process of alloy formation proceeds with depolarization, the value of which reaches 0.4–0.6 V. The effect of current density on the composition of the cathode product was investigated and the conditions for production of individual intermetallic compounds were found. The surface microstructure and micro-region composition of the alloy were also determined. The activity coefficients of praseodymium in three intermetallic compounds were calculated by Origin Pro 9.64 software:

$$\lg \gamma_{Pr-Ga} = 3.69 - \frac{13820}{T} \pm 0.48$$

$$\lg \gamma_{Pr-Ga-Pb} = 4.32 - \frac{13560}{T} \pm 0.46$$

$$\lg \gamma_{Pr-Pb} = 3.30 - \frac{10880}{T} \pm 1.10$$

Based on the electrochemical investigations the practical feasibility of electrochemical extraction of Pr(III) from molten NaCl–2CsCl eutectic was occurred. The separation rate of Pr on the three liquid electrodes was more than 90 %.

Analysis of the data obtained showed that the investigated system is the prospective media for application in partitioning technologies of spent nuclear fuels and nuclear wastes treatment.

EFFECT OF HEAT TREATMENT ON MICROSTRUCTURE AND MECHANICAL PROPERTIES OF THE VIT1 ALLOY

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Alloys based on orthorhombic titanium aluminide (Ti2AlNb) are promising structural materials in the field of aircraft engine building. This class of alloys exhibits an attractive combination of high specific strength and good machinability and oxidation resistance [1]. However, the search for a balance between the strength and plastic properties of these alloys is continues. It is known that one of the approaches to obtaining the required level of mechanical properties of alloys based on orthorhombic titanium aluminide is the formation of an optimal structural-phase state by quenching and subsequent aging [2]. In this work, we studied the effect of heat treatment on the evolution of the microstructure and mechanical alloys with the nominal composition Ti–25Al–19Nb-1,8Zr-0,8Mo-0,3Ta-0,2W-0,2Si (at. %). The material was subjected to stamping and subsequent quenching (900-1050 ºC, τ= 2 h, cooling in air). Aging was carried out at temperatures (750–850°C) and holding times (0,5–192 h). As a result of the study, it was shown that aging conditions have a significant effect on the microhardness of the quenched alloy. At all temperatures, a noticeable increase in hardness is found at the initial stage of aging, after which, with increasing holding time, the hardness decreases. The greatest hardness is noted at the lowest temperature. A study of the mechanical properties of the alloy in tension at room temperature showed that an increase in the aging temperature leads to an increase in the relative elongation and a decrease in the tensile strength. An analysis of the results of structural studies showed that, during aging, particles of the O-phase of various morphologies are released. At short exposures over the entire temperature range, the precipitation of a finely dispersed O-phase, of an acicular type, was observed, as well as the formation of layers of the O-phase along the boundaries of α_2 particles. An increase in temperature and exposure time contributed to the coarsening of the O-phase. The report discusses the relationship between structure evolution and hardness during aging.

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References:

1. Illarionov, A. G. "Alloys based on orthorombic intermetallic titanium Ti2AlNb: phase composition, alloying, structure, properties." Metallurg, 3 (2023): 42-54.

2. Kumpfert, J. "Intermetallic alloys based on orthorhombic titanium aluminide." Advanced Engineering Materials 3.11 (2001): 851-864.

SURFACING SPECIFICS IN MULTI COMPONENT ALLOYS CONTAINING REFRACTORY METALS

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One of the industry problems is the creation of parts with high performance properties. Laser surfacing is one of the methods for obtaining such products [1]. This coating method is widely used to reduce wear, improve mechanical properties and improve the corrosion resistance of the material surface. This process has many benefits. For example, it may be economically viable in manufacturing or repairing industries such as steel, oil, gas, etc. The development of surfacing methods has led to the development and study of highly efficient surfacing materials. The most important factor influencing the properties and performance of the deposited components is the coating alloy and base alloy.

This work considers the possibility of applying a refractory Al-Zr-V-Nb coating on a substrate made of steel 08H18N10 (AISI304, 1.4301). Refractory alloys containing zirconium, vanadium and niobium allow the coating to withstand loads at high temperatures and increase the mechanical and physical - chemical properties of the material [2].

The deposition was carried out using a laser complex consisting of an LS-5 laser radiation source and a KUKA KR-60 robot in a protective argon atmosphere. It is shown that the optimal mode of Al-Zr-V-Nb powder deposition on the base material corresponds to a power of 250 W at a processing speed of 0.5 m/s and a coating thickness of 0.6 mm, however, there is a need to further increase the number of passes to create a reliable coating with no discontinuities and islands. At the same time, the microhardness during surfacing of the Al-Zr-V-Nb coating increases by more than two times compared to the base material.

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References:

1. Chen J. Microstructure and wear properties of multicomponent alloy cladding formed by gas tungsten arc welding (GTAW)/ J. Chen, P. Chen, C. Lin, C. Chang, Y. Chang, W. Wu // Surf. Coat. Technol. 2009. V.203, №20. P.3231–3234.

2. Ripoll M. The role of niobium in improving toughness and corrosion resistance of high speed steel laser hardfacings / M. Ripoll, N. Ojala, C. Katsich, V. Totolin, C. Tomastik, K. Hradil // Mater. Des. 2016. V.99. P.509–520.

TENSILE PROPERTIES OF Ti-Zr-Nb ALLOY-BASED METAL-MATRIX COMPOSITES, REINFORCED WITH BORIDES

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The titanium alloys of the Ti-Zr-Nb system have a low elastic modulus, high specific strength, excellent corrosion resistance and biocompatibility, which determines their wide use in implantology, traumatology and orthopaedics. However, the use of these alloys is often limited by their other characteristics: relatively low strength, hardness and wear resistance. Their strength can be improved by a combination of hardening strategies, for example, by significantly modifying the chemical composition and moving to the so-called medium and high entropy compositions with high solidity solidification, and by making metal-matrix composites with ceramic reinforcing components, in particular boride particles. Samples of composite sizes (~60 g) were made by vacuum-arc melting in argon atmosphere using granules Ti, Nb and Zr (purity 99,9% weight in each case) with the introduction of reinforcing component in the form of metal powder TiB2 (purity 99.999%) In the original charge in quantity 0,2, 0,7, 2 and 4 weight. In all states, the ratio of Nb, Ti, and Zr was 1:1:1, which is an equiatomic proportion. The tensile test results showed that the alloy with the lowest TiB2 content of 0,2% showed the lowest yield point of 690 MPa and the highest relative elongation of ~ 20%. The NbTiZr matrix is likely to contribute the most to strength the presence of ω-phase practically does not increase strength. Increase the TiB2 content to 0,7 weight % leads to increase the yield limit to 750 MPa while reducing plasticity to 10%. Alloy with 2,0 weight. TiB2 showed a yield limit of 810 MPa and an elongation ratio of ~ 5%. The highest strength was achieved in the state of the composite with the maximum boride content, in which the yield limit reached 900 MPa with plasticity of 0,5%. The theoretical calculation of the strength of composites by summing the value of the friction stress of the grating and the deposits of various hardening mechanisms showed their proximity to experimental data. The most significant contribution is the calculated friction stress of the lattice - 684 MPa (68%), the toughening of the load transfer from the matrix to the striker turned out to be 236 MPa (23%), the value of sub-structural (dislocation) hardening and Hall-Petch was 56 and 34 MPa, respectively. Homogenizing annealing at a temperature of 1200° C within 24 hours did not significantly affect the microstructure and mechanical properties of the composites in all states. Morphology, size of borids, and distribution of chemical elements in borids and NbTiZr matrices varied within an error limit of 5%. The strength of composites decreased by 5-10% while maintaining plasticity.

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AN INSIGHT INTO SYNTHESIS OF HIGH ENTROPY HEUSLER INTERMETALLICS NANOPARTICLES

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Heusler alloys are ternary intermetallic compounds characterized by X2YZ and XYZ stoichiometry ratios for Full Heusler and Half-Heusler alloys, respectively, where X and Y are typically transition elements and Z is an element from group 13-15. There is a great deal of interest in these intermetallic compounds because of their multifunctional properties including magnetocaloric effect, half-metallic ferromagnetism, and thermoelectric effect [1-3].

It is known that magnetic and magnetocaloric properties of Heusler alloys are dependent on the atomic structure and lattice ordering, which can be modulated by partially substituting one or more elements within the crystal structure of the parent phase.

The new strategy of entropy stabilization in multi-principal elements alloys composed of five or more elements with equiatomic or near equiatomic ratios provides even better probability to tune functional properties Heusler alloys.

This study aims at unraveling and fabricating single phase Full Heusler-high entropy intermetallic compounds (FH-HEICs) with nano scale sizes by mechanical alloying. To this end, Co_2(FeNiMnMgZn)Al, Co_2(TiZrTaNbCr)Al and Cr_2(TiZrTaNbV)(AlSi) FH-HEICs are prepared by mechanical alloying for 20 h. All FH-HEICs crystallize in a mixture of partially ordered B2-type and disordered A2-type crystal structures, which exhibit higher degree of disordering compared to the ideal $L2_1$ structure. Co_2(FeNiMnMgZn)Al and Co_2(TiZrTaNbCr)Al exhibited semi hard magnetic behavior with magnetic saturation. Cr2(TiZrTaNbV)(AlSi) exhibited hard magnetic behavior with giant coercivity and low magnetic saturation.

FH-HEICs nanoparticles are introduced as a novel sub-class of HEICs for magnetic and catalytic applications, among others, where their crystal structure and functional properties can be tuned by alloying an appropriate set of elements.

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References:

1. A. Difalco, G. Barrera, M. Palumbo, A. Castellero, M. Baricco, P.M. Tiberto, et al., Journal of Alloys and Compounds (2022) 165464.

2. M. Gabor, M. Belmeguenai, T. Petrisor Jr, C. Ulhaq-Bouillet, S. Colis, C. Tiusan, Physical Review B 92 (2015) 054433.

3. Y.S. Koshkid'ko, E. Dilmieva, A. Kamantsev, J. Cwik, K. Rogacki, A. Mashirov, et al., Journal of Alloys and Compounds 904 (2022) 164051.

MICROSTRUCTURE AND MECHANICAL BEHAVIOR OF THE BORIDE-REINFORCED Al5Nb24Ti40V5Zr26-BASED METAL-MATRIX COMPOSITES

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Increasing the strength, hardness and wear resistance of beta titanium alloys while maintaining or reducing the elastic modulus is required to expand the scope of these materials. A radical improvement in the strength characteristics of titanium alloys can be achieved by using a combination of different hardening strategies, both through a significant modification of the chemical composition and the transition to the high-entropy compositions (high entropy alloys, HEAs), and through the creation of metal-matrix composites with ceramic reinforcing components, for example, particles of titanium carbides and borides. The best choice for titanium-based alloys is the use of TiB particles as a hardener. TiB adheres well to the titanium matrix without the formation of a transition region and has a similar coefficient of thermal expansion; in addition, due to its good thermal stability, TiB can provide strength even at elevated temperatures. The deformation characteristics of the HEA/TiB composites will be determined by the superposition of the properties of the ductile matrix, brittle TiB particles, and the matrix/TiB interface. To ensure the required balance of strength and plastic characteristics, it is necessary to understand the composite structure and the effect of various structural factors on the mechanical behavior of the material. This study is aimed at achieving high strength properties in a Ti40Zr26Nb24V5Al5 (in at. %) high-entropy alloy hardened with TiB particles by implementing most of the existing hardening mechanisms.

The $Al_5Nb_{24}Ti_{40}V_5Zr_{26}$ high entropy alloy-based metal-matrix composites with different amounts of TiB_2 (1, 2 and 3 wt. %) were produced vacuum arc melting in a high purity argon atmosphere. The initial microstructure of the synthesized composites was composed of bcc matrix and needle-like (Ti, Nb)B borides. A significant refinement of the microstructure was found with an increase in the proportion of borides. Alloying the base $Al_5Nb_{24}Ti_{40}V_5Zr_{26}$ alloy with 1 wt. % TiB_2 led to an increase in strength from 760 MPa (base alloy) to 840 MPa. Increasing the content of the reinforcing component TiB_2 to 2 and 3 wt. % led to a sharp drop in ductility (0.5 and 0 %, respectively) and a slight increase in strength to 890 and 900 MPa, respectively.

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ELECTRON BEAM ADDITIVE MANUFACTURING OF A NEW GAMMA TITANIUM ALUMINIDE ALLOY: COMPOSITION, MICROSTRUCTURE, POROSITY

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Metal powder composition (MPC) with particle size range of 40–100 μm was produced by crucible-free induction melting of cast electrode and inert gas atomization technique (EIGA) from a new six-component intermetallic β-solidifying gamma titanium aluminide (TiAl) based alloy Ti-44.5Al-2V-1Nb-2Cr-0.1Gd, at.% (Ti-31.0Al-2.5V-2.5Nb-2.5Cr-0.4Gd, wt.%) developed at VIAM [patent No. RU 2 606 368]. The distribution of the most light element – aluminum – along the cross-section of powder particles occurred to be homogeneous. A 1.5-fold increase of the oxygen content in the MPC was detected as a result of natural oxidation upon air environment due to developed specific surface of powder particles. All granules had dendritic structure; the room temperature phase composition differed from the equilibrium phase composition of the starting electrode ($\gamma+\alpha_2+\beta_0$/B2) and corresponded to pre-solidus *in-situ* rapidly solidified (quenched) metastable state ($\gamma+\alpha+\beta$), the latter being common for argon sprayed melt droplets after cooling with rate exceeding the critical one for the studied alloy. The raw MPC quality indicators (flowability of no more than 40 sec per 50 g of powder through a calibrated Hall funnel diam. 2.5 mm) satisfied the requirements for additive manufacturing of parts by selective electron beam melting (SEBM) technology.

The influence of the line energy input (E_L), varied from 120 to 300 J/m due to changing of the electron beam current (I) from 4 to 20 mA and the scanning speed (v) from 2 to 8 m/s, on residual porosity, content and local distribution of aluminum, and microstructure has been studied on 11×11×40 mm^3 samples produced from the TiAl-based alloy MPC by SEBM in the vertical building direction (Z). It has been found that layer-by-layer processing at $E_L \geq 250$ J/m makes it possible to obtain dense material with residual porosity of less than 1 vol.%. It has been revealed that an increase of E_L results in the average Al content reduction by ΔAl=1.7 at.% at E_L=300 J/m and distribution inhomogeneity thereof in Z cross-section of the samples, with the formation of layered structure consisting of Al-enriched and Al-depleted alternating layers. It has been shown that a fine-grained equiaxed microstructure is formed after processing at $E_L<200$ J/m and $I<8$ mA; increasing of E_L and I results in the formation of columnar grains, as well as their size and fraction growth, predominantly located in Al-depleted layers. After all studied SEBM parameters, both columnar and globular grains exhibit intragranular ($\gamma+\alpha_2$) lamellar colonies with some γ and β_0 (B2-ordered) phases at grain boundaries, which correspond to the sequence of phase transformations predicted by Thermo-Calc modeling. No areas of as-SEBM-built testpieces were identified with duplex or coarse-grained γ phase microstructures which are characteristic for the 2nd generation electron beam melted gamma alloy Ti-4822 (Ti-48Al-2Cr-2Nb, at.%).

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MICROSTRUCTURE, MECHANICAL PROPERTIES AND BIOCOMPATIBILITY OF MEDIUM-ENTROPY TINBZR ALLOY-BASED COMPOSITES, REINFORCED WITH BORIDES

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Medium-entropy alloys (MEAs) of the Ti-Nb-Zr system have undoubted advantages in the form of a low modulus of elasticity, high specific strength, excellent corrosion resistance and biocompatibility. However, the wider use of these alloys in industry and medicine is sharply limited due to their relatively low strength, hardness and wear resistance [1]. A significant increase in strength characteristics can be achieved by using an integrated approach due to a significant modification of the chemical composition, as well as by creating metal-matrix composites with high-strength reinforcing components. One of the most acceptable solutions for titanium-based alloys is the use of TiB particles as a hardener.

In this investigation the main attention was paid to the development and comprehensive study of the structure and properties of a new composite based on the medium-entropy alloy NbTiZr, strengthened by (NbTiZr)B particles. The structure of the matrix, the emerging borides, and the interface between the matrix and borides were studied by scanning and transmission electron microscopy (SEM and TEM), as well as X-ray diffraction analysis. The mechanical properties of the composite samples were studied using standard uniaxial tensile tests, microhardness and Young's modulus were also measured. To assess the biocompatibility of the composite, in vitro cytotoxicity studies were performed. The effect of homogenization annealing on the structure and mechanical properties of composites was determined.

Microstructure of the composite consisted of the TiNbZr matrix and boride particles, the fraction of which increased with an increase in the amount of TiB_2 in the charge mixture. The volume fraction of the borides in the structure of four conditions of the composites was found to be ~ 1.0, ~ 2.5 ~ 6.8 and ~ 12.4 % for states with 0.2, 0.7, 2, and 4 wt. %. TiB_2, respectively. The borides had a needle-like shape with the average diameter (cross-section size) ~ 0.2, ~ 0.4, ~ 0.9 and ~ 2.0 μm for 4 conditions of alloys, respectively. The homogeneity of distribution of the boride fibers in the NbTiZr matrix increases with an increase in the amount of the reinforcements. EBSD analysis suggested microstructure refinement with an increase in the amount of borides: 180 μm, 130 μm, 65 μm, and 50 μm for four variations of composites, respectively. Based on the results of microscopic studies, it can be concluded that during crystallization, borides (Ti, Nb) B with an orthorhombic crystal structure (oP8, Pnma) of the FeB type are formed in the composite. During tensile tests at room temperature the alloy with the lowest content of TiB_2 0.2 % showed the lowest value of the yield strength 690 MPa and the highest elongation ~ 20 %. An increase in the content of TiB_2 to 0.7 % wt. in the master alloy led to an increase in the yield stress up to 750 MPa with a decrease in ductility to 10 %. Alloy with 2.0 wt. % TiB_2 showed the yield strength of 810 MPa and elongation ~ 5%. The

highest strength properties were attained in the state of the composite with the maximum content of borides in which the yield strength reached 900 MPa with, however, ductility only 0.5%. The microhardness values were 231±5, 238±5, 267±7 and 319±8 HV for the four states, respectively.

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OXIDATION BEHAVIOUR OF REFRACTORY HIGH-ENTROPY ALLOYS WITH A BCC+B2 STRUCTURE

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With the development of aerospace, more stringent performance requirements are put forward for metal materials used at high temperatures. Refractory high entropy alloys (RHEAs) are the potential candidate for the hot parts of gas turbine engines due to their excellent strength at ultra-high temperatures and phase stability. Unfortunately, most refractory metals and alloys form volatile oxides that prevent the formation of a protective oxide layer. Although the oxidation resistance of some RHEAs is similarly inferior, certain refractory high-entropy alloys can withstand oxygen attack up to 1500 °C thanks to complex oxides. Recently, introduced series of $(NbMo)_x(CoHf)_{100-x}$ alloys demonstrated superior performance. In current work, we performed a comprehensive analysis of the oxidation kinetics and mechanisms, as well as the spallation/disintegration resistance, of the $(NbMo)_x(CoHf)_{100-x}$ RHEAs subjected to cyclic oxidation at 1000 °C.

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STRUCTURE, TEXTURE AND MECHANICAL PROPERTIES OF METASTABLE GRADIENT MATERIALS

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Metastable austenitic materials with gradient structure possess an attractive strength-ductility combination. The gradient structure might be defined via a gradual change in the size of structural elements, phase composition and texture along a cross-section or length of a workpiece. Within the framework of this study, mechanisms of the

gradient structure formation and mechanical behavior of metastable austenitic alloys with gradient structure are investigated. AISI 321 and 316Ti austenitic stainless steels, as well as a promising medium-entropy alloy Fe-30Mn-10Co-10Cr-0.5C (% wt.) are chosen as program materials. The deformation and subsequent heat treatment are applied for gradient structure formation. Firstly, to obtain a gradient structure, cold rotary swaging is carried out. Then, the final structure and mechanical properties are derived using post-deformation heat treatment. Apparently, cold rotary swaging with a reduction of 90-95% results in the formation of a pronounced gradient structure and texture. In the rod center, the strong axial austenitic texture with components <111> and <100> is enhanced that is weakened to the rod edge. It is worth noting that, in the AISI 321 steel, the gradient of the axial texture of α'-martensite with a component <110> is also observed. In the AISI 316Ti steel and Fe-30Mn-10Co-10Cr-0.5C alloy, the twin density gradient and non-uniform microstructure along the rod cross-section are observed. Due to the development of strain-induced martensitic transformation in the AISI 321 steel, the gradient of the α'-martensite volume fraction is also detected. Post-deformation low-temperature annealing causes the nanocarbide formation, polygonization, primary recrystallization and martensite-to-austenite reversion. The processing provokes partial structure transition, but the structure and texture gradient in the cross-section is still observed. Therefore, the obtained gradient materials perform anomalies of mechanical behavior under quasi-static and dynamic loadings that is associated with overcoming the strength-ductility/toughness trade-off.

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MICROSTRUCTURE EVOLUTION AND MECHANICAL BEHAVIOR OF THE BORIDE-REINFORCED Al5Nb24Ti40V5Zr26-BASED METAL-MATRIX COMPOSITES DURING HOT DEFORMATION

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Increasing the strength, hardness and wear resistance of beta titanium alloys while maintaining or reducing the elastic modulus is required to expand the scope of these materials. A radical improvement in the strength characteristics of titanium alloys can be achieved by using a combination of different hardening strategies, both through a significant modification of the chemical composition and the transition to the high-entropy compositions (high entropy alloys, HEAs), and through the creation of metal-matrix composites with ceramic reinforcing components, for example, particles of titanium carbides and borides. The best choice for titanium-based alloys is the use of TiB

particles as a hardener. TiB adheres well to the titanium matrix without the formation of a transition region and has a similar coefficient of thermal expansion; in addition, due to its good thermal stability, TiB can provide strength even at elevated temperatures. The deformation characteristics of the HEA/TiB composites will be determined by the superposition of the properties of the ductile matrix, brittle TiB particles, and the matrix/TiB interface. To ensure the required balance of strength and plastic characteristics, it is necessary to understand the composite structure and the effect of various structural factors on the mechanical behavior of the material. This study is aimed at achieving high strength properties in a Ti40Zr26Nb24V5Al5 (in at. %) high-entropy alloy hardened with TiB particles by implementing most of the existing hardening mechanisms.

The $Al_5Nb_{24}Ti_{40}V_5Zr_{26}$ high entropy alloy-based metal-matrix composites with different amounts of TiB_2 (1, 2 and 3 wt. %) were produced vacuum arc melting in a high purity argon atmosphere. The initial microstructure of the synthesized composites was composed of bcc matrix and needle-like (Ti, Nb)B borides. Microstructure evolution and mechanical behavior of the composite were studied during uniaxial compression at room temperature and in a temperature range of 400–950 °C. The microstructure evolution of the matrix was associated with the development of dynamic recovery at 400–700 °C and dynamic recrystallization at higher temperatures (≥800 C). The apparent activation energy of the plastic deformation was calculated and a processing map for the TMC was constructed using the obtained results.

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INVESTIGATION OF STRUCTURE AND MECHANICAL PROPERTIES OF MAGNESIUM ALLOY AZ31 BILLETS OBTAINED BY WIRE-ARC DEPOSITION

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The study presents the main regularities of structure formation and mechanical properties of billets from magnesium alloy AZ31 (alloying system Mg-Al-Zn) obtained by wire-arc deposition. Deposition was carried out using CMT (Cold Metal Transfer) technology on welding equipment for welding/surfacing in shielding gases Fronius TPS 320i installed on the robotic complex ARC MATE 100iC.

Analysis of the macro- and microstructure of the cross-section of the deposited sample has shown that equiaxed structure polyhedral shape with different dimensionality, without internal defects is formed during CMT cladding with oscillation. A finer grained structure is formed inside the layers. The microstructure of the layers in the upper part of the specimen is coarser grained than in the middle and lower parts. The largest grain size is observed in the central part of the sample, at the intersection of the layers. There are no

clear boundaries between the layers in the macrostructure, the fusion zone can be determined only from the microstructure at low magnifications. The microstructure of the layer is a solid solution of Mg-based alloying elements with finely dispersed strengthening phase $Mg_{17}Al_{12}$ inside the grains.

At the analysis of results of tests of the material of the billet from AZ31 alloy in the initial state after deposition it is revealed that the mechanical characteristics of the metal have an insignificant variation relative to the average values: UTS = 227±5 MPa; YS = 87±5 MPa; δ = 28±3 %; Ψ =28±5 %.

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STRUCTURE AND PROPERTIES OF THE BORIDE-REINFORCED Al5Nb24Ti40V5Zr26-BASED METAL-MATRIX COMPOSITES AFTER ISOTHERMAL MULTIAXIAL FORGING

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One of the best ways of the hardening for titanium-based alloys or titanium-based high-entropy alloys is the use of TiB particles as reinforcement. TiB adheres well to the titanium matrix without the formation of a transition region and has a similar coefficient of thermal expansion; in addition, due to its good thermal stability, TiB can provide strength even at elevated temperatures. The deformation characteristics of the HEA/TiB composites will be determined by the superposition of the properties of the ductile matrix, brittle TiB particles, and the matrix/TiB interface. To ensure the required balance of strength and plastic characteristics, it is necessary to understand the composite structure and the effect of various structural factors on the mechanical behavior of the material. This study is aimed at achieving high strength properties in a Ti40Zr26Nb24V5Al5 (in at. %) high-entropy alloy hardened with TiB particles by implementing most of the existing hardening mechanisms. The $Al_5Nb_{24}Ti_{40}V_5Zr_{26}$ high entropy alloy-based metal-matrix composites with different amounts of TiB_2 (1, 2 and 3 wt. %) were produced vacuum arc melting in a high purity argon atmosphere. The initial microstructure of the synthesized composites was composed of bcc matrix and needle-like (Ti, Nb)B borides. Microstructure and mechanical properties of composites after multiaxial forging (MAF) to the true strain ε = 5.2 were studied. Mechanical behavior in terms of aggregated σ-Σε curves during the multiaxial forging demonstrated a pronounced softening following by a steady-like flow stage. The length of (Ti, Nb)B whiskers considerably decreased after the first step of the multiaxial forging and then changed insignificantly. The microstructure after the MAF consisted of dislocation-free Ti matrix areas of ≈ 1-2 μm in diameter and areas with high density of borides and high dislocation density. The forging resulted in a increase in ductility of the composites at room and elevated temperatures without visible loss in strength.

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STRUCTURE AND MECHANICAL PROPERTIES OF MULTICOMPONENT ALLOYS OBTAINED BY MAGNETIC PULSE COMPACTION OF NANOPARTICLES

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Multicomponent alloys are a new object of fundamental and applied research. The active development of this direction is due to the possibility of obtaining materials with new or improved properties [1]. Multicomponent alloys with high values of strength and plasticity can be obtained as a result of relaxation of metastable states during heat treatment [2].

In this work, we studied the structure and mechanical properties of multicomponent alloys obtained by magnetic pulse pressing of powders based on nanoparticles [3]. Powders were obtained by joint electric explosion of wires of various metals/alloys in an argon atmosphere. The objects of study were alloys of the following compositions: $Ni_{34}Fe_{23}Cu_8Al_{13}Mo_6W_6Co_5Cr_5$ (1), $Mo_{29}Ni_{26}Fe_{25}Cu_{12}Co_8$ (2), $Ni_{30}Fe_{29}Cu_{20}Al_{12}Co_9$ (3), $Ni_{28}Fe_{27}Cu_{13}Al_{23}Co_9$ (4). The samples were subjected to vacuum heat treatment at 600, 800 and 1000 ℃ for 5 hours.

The results of X-ray diffraction analysis show that all the samples obtained are characterized by the formation of a structure based on the FCC or BCC phase with the presence of secondary phases with structures of the Ni_3Al and Co_7Mo_6 types. It has been established that for sample (1) an increase in the annealing temperature to 1000 ℃ leads to an increase in hardness and Young's modulus to 7.25 GPa and 202 GPa, respectively. For sample (2), an increase in the annealing temperature to 1000 ℃ leads to an increase in hardness and Young's modulus to 8.75 GPa and 212 GPa, respectively. For sample (4), an increase in the annealing temperature to 1000 ℃ leads to an increase in hardness and Young's modulus to 6.46 GPa and 171 GPa, respectively. For sample (3), the maximum value of hardness is observed at 800 ℃ (4.53 GPa) with a value of Young's modulus of 145 GPa.

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References:

1. M.R. Zamani, H. Mirzadeh, M. Malekan, S. C. Cao, J.-W. Yeh. Grain growth in high-entropy alloys (HEAs): A Review. High Entropy Alloys & Materials. (2022). https://doi.org/10.1007/s44210-022-00002-8

2. Z. Lyu, Z. Li, T. Sasaki, Y. Gao, K. An, Y. Chen, D. Yu, K. Hono, P.K. Liaw. Micromechanical origin for the wide range of strength-ductility trade-off in metastable high entropy alloys. Scripta Materialia. 231 (2023) 115439. https://doi.org/10.1016/j.scriptamat.2023.115439

3. A. Bokov, G. Boltachev, N. Volkov, S. Zayats, A. Il'ina, A. Nozdrin, S. Paranin, A. Olevskii. Uniaxial compaction of nanopowders on a magnetic-pulse press. Technical Physics. 58 (2013) 1459–1468. https://doi.org/10.1134/S106378421310006X

4. K. Suliz, A. Miller, K. Ivanov, A. Pervikov. Synthesizing multicomponent AlCrFeCuNi nanoparticles by joint electrical explosion of wires. Powder Technology. 404 (2022) 117491. https://doi.org/10.1016/j.powtec.2022.117491

AN OPTIMIZATION OF THE EFFECT OF LASER SHOCK PEENING ON FATIGUE PROPERTIES OF METALS

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The important highly loaded components of modern aircrafts require new techniques to extend their service life and prevent their expensive repair and replacement [1]. Among existing approaches, laser shock peening (LSP) have demonstrated remarkable efficiency in the aircraft industries for improvement fatigue life of components and fatigue crack growth slowdown. Despite the long history of the LSP study, this process still requires additional researches. For these purposes, an experimental setup was assembled in ICMM UB RAS, which includes Nd:YAG laser with pulse energy up to 10 J, pulse duration 10 ns and pulse frequency 5 Hz. The experimental setup is equipped with an original optical system that provides the formation of square and round shapes light spots with characteristic sizes of 1 mm and 3 mm. To measure a residual stress the setup was combined with a device MTS3000-Restan implementing the method of drilling holes.

The result of LSP treatment depends on many parameters, such as the laser power density, the shape of the laser spot, the overlap of the impact areas, the number of beam passes over the sample surface, the material of the ablative layer. Especially difficult in optimization of processing regime is taking into account the redistribution of residual stresses caused by the geometry of the part. To describe the LSP effect on the fatigue life of the part, it is necessary to solve four related physical problems. The first one is the development of a model for the formation of a plasma torch generating a stress wave in the processed material with an amplitude significantly exceeding the Hugoniot elastic limit. The second one is the simulation of an elastic-plastic wave propagation in a material, generating plastic deformation in the surface layer of the material. The third problem is calculation of the self–balanced residual stresses field in the sample caused by a plastically deformed surface layer. The fourth problem is development of a model of the effect of the residual stress field on the fatigue crack initiation and propagation processes.

As an example of optimization of LSP regime, a series of fatigue tests of flat samples with a stress concentrator made of Ti64 titanium alloy was carried out. Based on the simulation results, five different regimes are proposed, varying both the modes and the processing location. The samples tested under uniaxial cyclic deformation with R = 0.1. It is shown that for the selected geometry of the samples, the place of treatment on the sample surface plays an essential role. The samples processed in the optimal regime showed an 8-fold improvement in fatigue life compared to the samples without treatment.

References:

1. Zhang X, Yang M, Zhou C, Fu N, Huang W, Wang Z 2022. A comprehensive review of fatigue behavior of laser shock peened metallic materials Theoretical and Applied Fracture Mechanics 122:103642.

HIGHLY EFFICIENT PHOTOCATALYTIC COATINGS PRODUCED BY DETONATION SPRAY COATING METHOD ON BUILDING MATERIALS

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Biocorrosion is one of the main modern problems associated with a decrease in the operational life of equipment, building products and structures due to intense pollution of the human environment with organic waste and pathogenic microorganisms. A promising solution is the creation of photocatalytic coatings that can not only prevent the development of microorganisms on the surface, but also clean it from organic contaminants under the influence of ultraviolet radiation. A frequently used component of such coatings is titanium dioxide (TiO_2) in the anatase polymorph form. Among the many methods for creating coatings in recent years, one of the most promising is the detonation spray coating method [1, 2].

A TiO_2 coating was obtained using the detonation spray coating method on the following materials: structural steel grade St3, porcelain stoneware and B30 grade concrete. Three types of titanium metal powders were used for spraying: PTS-1 and PTM-1 produced by Polema JSC and PTN8-VT1.0 powder produced by Normin. The effect of the type of raw titanium powder used on the morphological features and phase composition of the coatings was assessed. The photocatalytic activity was evaluated by three methods: by decolorization of an organic dye (rhodamine B) according to the European standard UNI 11259, by changing the concentration of methylene blue in an aqueous solution in accordance with the recommendations of ISO 10678:2010 (E), which was determined using a two-beam spectrophotometer "PE-6100" (Promecolab) and by changing the contact angle in accordance with GOST R 57255-2016. All three methods confirm the high photocatalytic properties of TiO_2 coatings obtained by detonation spraying on substrates made of St3 steel, ceramic granite, and B30 grade concrete.

The results obtained make it possible to recommend such coatings for use as self-cleaning functional coatings on building materials operated under conditions of constant aggressive influence of physical, chemical and biological factors: hydraulic structures, slaughterhouses, paint and varnish industries, operating rooms, etc.

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References:

1. Kovaleva M. et al. Structure and microhardness of titanium-based coatings formed by multichamber detonation sprayer // Physics Research International. – 2015. – Vol. 1–2. 8 p.

2. Dudina D. V. et al. Detonation spraying behavior of TiCx–Ti powders and the role of reactive processes in the coating formation // Ceramics International. – 2016. – Vol. 42 (1). – P. 690–696.

HIGH ENTROPY THIN FILM ALLOY CoCrFeNiTix FOR ELECTRORESISTIVE ELEMENTS IN MICROELECTRONICS

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The main requirements for the resistive elements of microcircuits and other microelectronic devices include high accuracy of the electrical resistance value, which must depend in a controlled way on temperature [1] For pure metals, the temperature coefficient of electrical resistance (TCR) is positive and has a value of the order of $4 \cdot 10^{-3}$ K^{-1}. The search for alloys and compounds with a lower value of TCR is actively conducted. In recent years, the attention of researchers has attracted the high-entropy alloys [2], which are solid solutions of five or more metals taken in equal or comparable concentrations. The combination of atoms of dissimilar metals with different radii into a single crystal lattice (fcc or bcc) leads to strong distortions of the crystal structure and, as a result, to a relatively high electrical resistance and low TCR. The beginning of the rapid development of research in the field of thin-film high-entropy alloys was reflected in review [3].

Using the method of magnetron sputtering from a multicomponent target manufactured by hot pressing of a powder mixture, thin films of a high-entropy CoCrFeNiTix alloy on silicon substrates were first obtained. The microstructure and phase composition of these films have been studied. Resistive thin-film elements are made and their electrical resistance is measured at different temperatures. It is shown that the value of the electrical resistance of new resistive elements linearly depends on temperature with the temperature coefficient TCR = $4.66 \cdot 10^{-5}$ K^{-1}

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Rreferences:

1. Matsuda K., Sato K., Doi T., Ogata K., and Konishi K., "Super precision metal film resistors," National Technical Report, vol.26, pp. 283–288, 1980.

2. Rogachev A.S. Structure, stability, and properties of high-entropy alloys, Phys. Met. Metallogr. 121(8) (2020) 733–764. DOI: 10.1134/S0031918X20080098

3. Wang C., Li X., Li Z., Wang Q., Zheng Y., Ma Y., Bi L., Zhang Y., Yuan X., Zhang X., Dong C., Liaw P.K. The resistivity–temperature behavior of AlxCoCrFeNi high-entropy alloy films. Thin Solid Films. Vol. 700 (2020) 137895.

NANOSTRUCTURED BETA TITANIUM ALLOYS FOR MEDICAL APPLICATIONS

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Currently, the prospects of using β-titanium alloys in medicine are well known due to their high biocompatibility, corrosion resistance and low elastic modulus (40-80 GPa) close to the elastic modulus of bone in the single-phase β-state, which reduces bone tissue resorption due to the "stress-shielding" effect [1]. This is particularly important for applications in dentistry and osteosynthesis, where it is necessary to minimize the risk of repeated invasive interventions [2]. However, β-titanium alloys are characterized by low strength characteristics and low endurance limit (UTS≤800 MPa, σ_{-1}≤400 MPa) compared to steels and two-phase titanium alloys for medical use, which significantly reduces the range of their application to products of temporary fixation of fractures that do not require reliability and long-term durability [3].

The application of severe plastic deformation (SPD) of β-titanium alloys in the single-phase β-region is a solution to the indicated problem due to the formation of nanostructure in them with grain size less than 100 nm, which in turn, according to the Hall-Petch law, should lead to an extraordinary improvement of physical and mechanical properties [4,5].

In this work, the influence of nanostructuring by high-pressure torsion (HPT) on the structural-phase transformations and mechanical behavior of pseudo-β-titanium alloys Ti-15Mo and Ti-1023 is studied. Control of the structure parameters and phase composition (β, ω, α") of the studied materials by means of SPD methods allowed to significantly increase their strength characteristics (up to 1600 MPa) while maintaining low elastic modulus (up to 60 GPa).

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References:

1. Brunette, D. M. Titanium in Medicine / D. M. Brunette, P. Tengvall, M. Textor, P. Thomsen. – Berlin Heidelberg : Springer-Verlag, 2001. – 1019 p.

2. Teoh, S. H. Engineering Materials for Biomedical Applications, Biomaterials Engineering and Processing Series / ed. S. H. Teoh – World Scientific, 2004. – 352 p.

3. Pesode, P., Barve, S. J. Eng. Appl. Sci. 70, 25 (2023).

4. Valiev, R.Z.; Prokofiev, E.A.; Kazarinov, N.A.; Raab, G.I.; Minasov, T.B.; Stráský, J. Materials 2020, 13, 967.

5. Vishnu, J., Manivasagam, G. J. of Materi Eng and Perform 30, 4370–4379 (2021).

PHASE TRANSFORMATIONS IN MULTICOMPONENT TITANIUM ALLOYS

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Phase and structural transformations in multicomponent titanium alloys of various alloying are studied. It is shown that, depending on the alloy composition and the processing mode, it is possible to implement transformation processes both by heterogeneous and homogeneous transformation mechanisms. In this case, it is possible to form an identical phase composition, but having a different complex of physical and mechanical properties.

It is shown that in pseudo-α-titanium alloys, the formation of the Ti_3Al intermetallic phase is possible both by the mechanism of nucleation and growth, and by the ordering process in microvolumes, i.e. implementation of a homogeneous process of restructuring. A different complex of properties is formed, since various types of interphase boundaries are formed during these processes. The heterogeneous process provides increased strength properties, but low viscous-plastic characteristics, while as a result of a homogeneous transformation, it is possible to obtain higher viscosity and plasticity characteristics at sufficiently significant strength values.

The transformations occurring in highly alloyed alloys with a metastable β-phase are analyzed. It is shown that in addition to the known ω and α-phases, which are released from a supersaturated β-solid solution upon heating, the formation of highly dispersed O' and O" phases, which have rhombic lattices with different periods, is possible. The formation of such phases was found in alloys with β→ω transformation and they have a morphology close to that of ω precipitates. The transformation mechanisms and their role in the formation of material properties are discussed.

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INVESTIGATION OF A MELT BATH DURING OBTAINING INTERMETALLIC COATING OF THE FE-AL SYSTEM ON STEEL TO PROTECT AGAINST LIQUID METALLIC LEAD CORROSION

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The mechanism of liquid metal corrosion is the oxidation of grain boundaries in steel upon contact with liquid lead. The most resistant materials are considered to be intermetallic compounds and metal oxides. As an additional protection, the introduction of oxygen into the coolant is used. Oxygen forces the metal to passivate, creating an oxide film. The most resistant is aluminum oxide film. The creation of a structure from alloys resistant to liquid metal corrosion significantly increases the cost, however, it is possible to create a layer that can protect the material from contact with an aggressive environment. In particular, the Swedish company proposed the use of a Fechral coating, and in Russia, work is aimed at using the FeAl intermetallic layer. This paper presents a study on obtaining an intermetallic layer of the Fe-Al system.

To solve this problem, the method of complex laser alloying was used, which consists in applying a precursor aluminum coating by cold gas-dynamic spraying and subsequent laser processing. In the process of laser processing in a melt bath, an intermetallic layer is synthesized due to the mixing of the precursor coating with the substrate material and the formation of new chemical compounds.

In this work, the geometric characteristics of individual tracks are investigated, which allow us to give recommendations for the choice of the laser processing mode, as well as the compositions of the intermetallic coating.

The results of metallographic studies, studies of the chemical composition, microhardness are presented. It is shown that at a precursor coating thickness of 160 μm and a laser beam speed of 12 mm/s, a homogeneous structure is formed with an aluminum content of 17 wt.% and a microhardness of 579 HV. With an increase in the scanning speed, the structure is inhomogeneous, the microhardness is uneven. The effect of laser processing modes on the geometric characteristics of laser tracks is shown.

This work was carried out within the framework of the Russian Science Foundation, project no. 21-73-30019.

COMPLEX EFFECT OF Mn, Al AND V ON HARDNESS AND MICROHARDNESS OF HIGH-ENTROPY CrCoFeNi ALLOY

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High-entropy alloys are interesting because, by allowing variables such as the number, types and concentrations of alloying elements to be changed, they can be directly correlated with physical and mechanical properties such as elastic properties, diffusion coefficients, strength, hardness and ductility, corrosion and heat resistance.

The main purpose of the work is to study the hardness and microhardness of high-entropy alloys in Cr-Co-Fe-Ni-Mn-Al-V and Cr-Co-Fe-Ni systems.

A computer simulation of the single and complex effect of alloying elements V, Mn and Al on the high-entropy alloy of the CrCoFeNi system performed in the Thermo-Calc 2022b software package with the TCHEA5 database was carried out.1 (WES) [1,2]. The data obtained served to determine the parameters and the synthesis area of a high-entropy alloy of the CrCoFeNi-Mn-Al-V system for obtaining six alloys with different alloying element contents.

In the course of the research, a complex of modern research methods was used: scanning electron microscopy, radiography, microrentgenospectral analysis and others. The obtained data showed that the peak microhardness of the alloy with alloying elements Mn, Al and V is 30-35% higher compared to the alloy without substances (230 vs 170 HV).

References:

1. Popova V. S. et al. Computer modeling of thermodynamic processes of high-entropy alloys of the Fe-Ni-Cr-Co-Mn-A1-V system //Physics: fundamental and applied research, education. – 2022. – P. 115-120.

2. Popova V. S. Computer modeling of high-entropy alloys of the CrCoFeNi system with Mn-A1-V additives // Proceedings of the I regional Student Conference on the 65th anniversary of the TOGU. – 2023. – P. 132-136

HEAT TREATMENT OF MEDIUM-ENTROPY ALLOY OBTAINED BY SELECTIVE LASER SINTERING

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The intensive development of high- and medium-entropy alloys (HEAs and MEAs) requires modern methods of their production. One of the currently popular methods of fabricating metallic materials is additive manufacturing (AM), namely selective laser sintering/melting (SLS/SLM). The main advantage of SLS is the high cooling rate, which leads to a finer grain structure, so that high strength characteristics of the material can be achieved compared to conventional fabrication methods. It is known that more attractive mechanical properties can be achieved by additional heat treatment of HEAs/MEAs. This paper presents a study on the medium-entropy alloy of Fe-Co-Ni-Cr-C system obtained by the SLS method, annealed at temperatures ranging from 800 ℃ to 1100 ℃. It is found that the alloy annealed at 800 ℃ exhibits a set of preferable mechanical properties, including cryogenic properties. The effect of annealing temperature on the microstructure and mechanical properties of the $Fe_{65}(CoNi)_{25}Cr_{9.5}C_{0.5}$ alloy is discussed in detail.

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CAD/CAM TECHNOLOGY OF ADVANCED CERAMIC MATERIALS IN DENTISTRY

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The restoration of partially damaged or lost teeth has always had a personalized approach. Today, the precision and speed of fabrication of crowns, bridges and dentures is the highest since the 1980s. This is possible thanks to technologies based on the principle of computer-aided design and computer-aided manufacturing (CAD/CAM). The introduction of nanostructured ceramic materials based on zirconium dioxide has been a breakthrough in this field. These materials have excellent biocompatibility, excellent mechanical properties and aesthetics that fully replicate the anatomy of the tooth.

In the present work, performed within the Additive Technology Center of Tomsk State University, a full-cycle Russian technology for producing CAD/CAM disks from nanostructured ceramic materials based on zirconium dioxide has been developed.

A set of researches on optimization of initial powders for CAD/CAM discs production was carried out. Technological approaches for thermal treatment of disks were developed. Unique formulations were developed to match ceramic materials to VITA shades. The technology of obtaining multilayer (up to 12 layers) disks for the production of full anatomy products was developed. The milling modes of the obtained materials have been worked out and optimized. Regularities of formation of the structural-phase state and mechanical properties of ceramic materials for stomatological purposes have been studied. A scientific and technological basis for the production of import-substituting products in the form of CAD/CAM disks for dentistry was created.

The work was carried out within the framework of the project under the Priority 2030 program within the project №1.1.22 "Development of scientific bases and technological methods of creation of new composite and biomaterials with application of advanced additive technologies"

MULTIFUNCTIONAL CATALYSTS BASED ON SHS-HEA

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Despite the fact that HEAs open up unique opportunities for obtaining various combinations of catalytically active elements, there is a problem of increasing the specific surface area and providing easy access of reagents to the active sites of the catalyst. Various approaches to solving this problem are proposed. For example, alloy etching without changing its composition in order to obtain a porous structure [3], HEA synthesis directly on an oxide support [4], HEA synthesis on carbon nanotubes [2].

The catalysts studied in this work were based on HEAs obtained by the method of self-propagating high-temperature synthesis (SHS) containing aluminum [5]. Alloys FeCoNiCuAl, FeCoNiCuAlMo, FeCoNiCuAlMn, FeCoNiCuAlCr were investigated. Aluminum, unlike all other alloy components, reacts with alkalis. When it is removed from the HEA, a porous branched surface structure is formed. At the same time, the remaining metals also form HEA.

The activity of the obtained catalysts in the process of complete oxidation of CO and propane was studied. The complete oxidation of CO occurs at a temperature of 250-350°C, propane conversion is 36-100% at 450°C. In the CO_2 methanation reaction, the conversion ranges from 36 to 42%. The reaction products are methane, CO and water.

Thus, SHS-HEA open up great prospects for the creation of highly active multifunctional catalysts.

References:

1. Gromov V.E., et al. Application of high-entropy alloys. Izvestiya. Ferrous Metallurgy. 2021;64(10):747-754. https://doi.org/10.17073/0368-0797-2021-10-747-754

2. Zhang N., Chen X., Liu Sh., Meng J., Armbrüster M., Liang Ch. PtFeCoNiCu High-Entropy Alloy Catalyst for Aqueous-Phase Hydrogenation of Maleic Anhydride. ACS Applied Materials & Interfaces 2023 15 (19), 23276-23285 DOI: 10.1021/acsami.3c02810

3. Peng H., Xie Ya., Xie Z., Wu Y., Zhu W., Liang Sh., Wang L.. Large-scale and Facile Synthesis of Porous High-entropy Alloy CrMnFeCoNi as an Efficient Catalyst. August 2020Journal of Materials Chemistry A 8(35)DOI: 10.1039/D0TA04940A

4. Mori K., Hashimoto N., Kamiuchi N. et al. Hydrogen spillover-driven synthesis of high-entropy alloy nanoparticles as a robust catalyst for CO2 hydrogenation. Nat Commun 12, 3884 (2021). https://doi.org/10.1038/s41467-021-24228-z

5. Pugacheva, E.V., Zhuk, S.Y., Borshch, V.N. et al. Magnetic-Field-Assisted Preparation of Ferromagnetic Ni–Co–Mn Catalyst for Deep Oxidation/Hydrogenation from a Mixture of SHS-Produced Intermetallics. Int. J Self-Propag. High-Temp. Synth. 30, 106–110 (2021). https://doi.org/10.3103/S1061386221020114

LAWS OF FORMATION OF STRUCTURE OF MATERIALS BASED ON NANOPHERS OF Ti-Al SISTEMA NANOPOURS CREATED WITH THE APPLICATION OF ADDITIONAL TECHNOLOGIES

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The main requirement for materials used in the aerospace and transportation industry is their minimum density while maintaining the necessary mechanical properties. The density of intermetallides based on titanium and aluminum: Al-Ti (titanium aluminide), is 1.5 - 3 times less than alloys based on nickel and titanium, and their mechanical properties (tensile strength, yield strength, etc.) at room and elevated temperatures are comparable or superior to those of the latter. In addition, intermetallides of this class have increased resistance to oxidation and corrosion, which allows their use in aggressive environments at elevated temperatures. Titanium aluminides are successfully used in the production of turbine blades for aircraft engines, as well as disks for wheels and exhaust valves of car engines. The use of these materials allows to reduce up to 55% of the weight of the product relative to nickel alloys, increase the efficiency of fuel utilization, as well as reduce the amount of carbon dioxide emissions, which meets the development trends of modern ecological production.

In the presented study, bulk materials were obtained by additive molding by extrusion of a mixture of highly filled polymers and nanopowders of Ti-Al intermetallides followed by sintering at temperatures of 1100 ± 20 ℃, 1200 ± 20 ℃, and 1250 ± 20 ℃ (MEAM-HP method). Nanopowders of Ti-Al intermetallides were obtained by electrical explosion of aluminum and titanium wires twisted together. The structure of the materials was found to consist of an AlTi matrix and MAX-phase Ti2AlN particles distributed in it, which are surrounded by a Ti3Al-Ti2AlN composite layer. Increasing the sintering temperature leads to a change in the concentration of TiAl, Ti3Al, and Ti2AlN phases in the samples. In addition, aluminum oxide particles were found in the structure of the materials. The average microhardness of the samples was found to increase from 193 to 690 HV0.1 with increasing sintering temperature from 1100 ± 20 ℃ to 1250 ± 20 ℃.

The work was carried out within the framework of the RNF project No. 21-79-30006.

DEVELOPMENT OF A BRIDGE FRAMEWORK FROM Co-Cr-BASED ALLOY ON MULTI-UNITS WITH SCREW FIXATION PRODUCED BY SELECTIVE LASER SINTERING

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For more than three decades, bridge-based prosthetics have played an important role in the field of dentistry. The use of this type of restoration allows to restore the aesthetic data of the tooth row, its functionality, restore correct diction and full life to the patient. A bridge framework is a type of fixed dental prosthesis used to replace inclusion defects of the tooth rows. It is used in cases when several consecutive teeth are destroyed, so such a prosthesis can be attached to the healthy teeth that are separated from each other or covered with crowns. Most often all bridge frameworks are made by the following methods: soldering, casting, as well as modern CAD/CAM technologies. Today, one of the most promising fabrication methods is additive manufacturing, such as selective laser sintering (SLS). This study describes in detail the method of fabrication of a bridge framework from Co63Cr29Mn1Mo5W1C0.5 alloy powder by SLS.

The research was carried out with the financial support of the Ministry of Science and higher education of the Russian Federation under the agreement from "24" June 2021 No. 07511-2021-046 (IGK 000000S407521QLP0002) with SEZ JSC "VladMiVa" under the complex project "Organization of a high-tech production of export-oriented medical devices based on innovative structural materials for the purpose of import substitution for based on developed technologies", with the participation of the National Research University "BelSU" in part implementation of research, development and technological works using the equipment of the Center for Collective use "Technologies and Materials of NRU "BelSU".

MECHANICS AND STRUCTURAL FEATURES OF ASYMMETRIC ROLLING

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Asymmetric rolling has recently been actively investigated by metallurgists and materials scientists of advanced countries in order to create promising processes for obtaining sheet metal blanks with improved properties and increased manufacturability. The most important advantages of the process is the reduction of rolling force while increasing the one-time degree of deformation. The presented work systematizes information about deformation schemes implemented during asymmetric rolling and features of structural changes and physico-mechanical properties based on literature data and own research, for example, copper and aluminum alloys. It is established that the predominant scheme is the shear scheme, and the coefficient of asymmetry of the rotation speeds of the rolls actively affects the intensity of shear deformation. Due to the possibility of implementing large deformations in one pass, the thermal effect is actively manifested and the initial structure is noticeably transformed, and there is a gradient grinding of the structure and the distribution of mechanical and physical properties over the cross section of the deformed workpieces.

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AMORPHOUS GLASS-METAL COMPOSITE AS ELEMENT OF A CEMENT MORTAR REINFORCING

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Fibers made from various materials (metal, polymers, minerals, etc.) are a traditional alternative to metal reinforcement. They are used to reinforce concrete on Portland cement in order to improve its operational properties. Composite materials have a set of properties that exceed the properties of each component separately.

Therefore, the use of composite fiber as an innovative reinforcing additive for cement systems is a promising direction in building materials science.

The effect of fibers from an amorphous glass-metal composite (AGMC) on the complex of properties of a plasticized mortar based on Portland cement (C/S = 1/3, W/C = 1/2, P = 1 % of C) was studied in this work. These fibers are pieces of high-strength microwire made of a model corrosion-resistant Co69Fe4Cr4Si12B11 alloy in a glass shell. The influence of fiber parameters (length and diameter), its content and method of introduction into the cement mortar mixture was analyzed.

The possibility of using AGMC fiber for reinforcing cement systems (mortars) based on Portland cement has been proved as a result of these studies. It has been established that the effectiveness of increasing the strength during reinforcement significantly depends on the geometric sizes and uniformity of the distribution of the fiber.

It was shown that the use of AGMC fiber in an amount of 0,5 % by weight of cement makes it possible to increase the flexural strength of cement mortars by 1,5 times while maintaining of compressive strength values. The coefficient of crack resistance (the ratio of flexural strength to compressive strength) as a complex criterion characterizes the total resistance of the material structure to mechanical loads. It has been established that this coefficient is increased by 1,2-1,7 times depending on the geometric sizes, content and method of introducing the AGMC fiber.

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INVESTIGATION OF CERAMIC COATINGS OF YALO SYSTEM OBTAINED BY VACUUM-ARC DEPOSITION METHOD

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To increase the power and efficiency of gas turbine engines (GTE) it is necessary to increase the temperature of gases in front of the GTE turbine. Therefore, it is necessary to protect the GTE parts from high temperatures and gas flow. Thermal barrier coatings based on ZrO2-Y2O3 [1, 2, 3, 4] are used to protect the blade temperature reduction.

Currently, a widely used material for thermal barrier coatings (TBC) is zirconium dioxide partially stabilized by yttrium, i.e., ≈8 wt% Y2O3 (8YSZ) [6]. However, the working temperature of YSZ is limited at 1200°C and further temperature increase leads to a change in phase composition and increased thermal conductivity. Therefore, a worldwide search for new ceramic coatings capable of operating at higher temperatures is underway. Recent works show that yttrium aluminates are promising materials for TBCs due to their excellent stability at high temperatures as well as mechanical and

thermal properties [5,6]. In the YAlO system, Y3Al5O12 (YAG) and Y4Al2O9(YAM) are also the most stable compounds.

The paper presents the results of studies of YAlO system coatings deposited by vacuum-arc deposition method. The structure, chemical and phase composition, as well as the results of phase transformations during heating of samples in vacuum are investigated.

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References:

1. Riallant F., Cormier J., «High-Temperature Creep Degradation of the AM1/NiAlPt/EBPVD YSZ System», Metall Mater Trans A – 2014. V. 45. C. 351–360.

2. Kunal M., Luis N., Calvin M.D., «Thermal Barrier Coatings Overview: Design, Manufacturing, and Applications in High-Temperature Industries», Industrial & Engineering Chemistry Research – 2021. V.60. №.17. C. 6061-6077.

3. Zhang, C., Lv, P., Xia, H., Yang, Z., Konovalov, S., «The microstructure and properties of nanostructured Cr-Al alloying layer fabricated by high-current pulsed electron beam», Vacuum – 2019. V. 167. C. 263-270..

4. Alymov, M.I., Stolin, A.M., Bazhin, P.M., « Investigation of the structure and properties of protective coatings produced by the method of electric spar alloying with shs electrodes (review)», Industrial Laboratory. Materials Diagnostics. - 2022, V. 88. №. 2. C. 40–48.

5. Bin L, Yuchen L, Changhua Z., «Advances on strategies for searching for next generation thermal barrier coating materials», Journal of Materials Science & Technology. – 2019.V. 35. № 5. C 833-851.

6. Uwe S., Christoph L. Some recent trends in research and technology of advanced thermal barrier coatings», Aerospace Science and Technology. - 2003. V.7. №.1. C. 73-80.

HIGH TEMPERATURE MARTENSITIC TRANSFORMATION AND SHAPE MEMORY EFFECT IN HIGH-ENTROPY Ti9Hf39Zr4Ni30Cu9Co9 ALLOY

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High-temperature shape memory alloys are very promising for the application in engines. Usually, the high-temperature martensitic transformation and the shape memory effects are observed in NiTi-based alloys doped by Hf, Z or Pd. The addition of Hf and/or Zr atoms allowed one to increase the transformation temperature to 300 – 400 ºC. For further increase in transformation temperatures, the NiTi-based alloys should be doped by Pd atoms, but it was very expensive. That aim of this work was to show that the high-

temperature martensitic transformation and shape memory effect may be observed at temperatures over 400 ºC in Pd-free senary Ti-Hf-Zr-Ni-Cu-Co alloy.

The $Ti_9Hf_{39}Zr_4Ni_{30}Cu_9Co_9$ alloy was produced in a vacuum arc furnace under an argon atmosphere purified by Ti getter. The alloy consisted of main matrix which was in the martensite B19' phase at room temperature. Two secondary phase Ti_2Ni-type and Hf_2Ni-type were found in the interdendritic space with different morphology. It was shown that main matrix underwent the B2 ↔ B19' martensitic transformation on cooling and heating at temperatures of M_s = 408 ºC, M_f = 333 ºC, A_s = 500 ºC and A_f = 562 ºC. The strain variation was studied in two modes: on cooling and heating under a constant stress through a temperature range of the martensitic transformation and on cooling under a stress and heating without stress. It was found that if the heating was under a stress, a huge creep was observed that significantly decreased the recoverable strain which value was not larger than 0.7 %. If heating was realized at zero stress, the creep was partially depressed and the maximum recoverable strain was 3.5 % that was observed on heating after cooling under a stress of 510 MPa. It was shown that the temperatures of the martensitic transformation were hardly sensitive to stress acting on cooling. Thus, the results of the study showed that the ultra-high temperature shape memory effects might be observed in Ti-Hf-Zr-Ni-Cu-Co alloys which did not include an expensive Pd element.

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FABRICATION OF BIOCOMPATIBLE CO-CR-BASED ALLOY POWDER BY ULTRASONIC ATOMIZATION METHOD

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One of the most promising alloys for biomedical applications are Co-Cr-based alloys. Co-Cr-based alloys are used for manufacturing crowns, dental implants, artificial hip joints, etc. At the moment, approaches based on additive manufacturing (AM) technologies seem to be an actual way of manufacturing biomedical products from Co-Cr alloys. In turn, for the development of AP methods it is necessary to ensure the production of powder material of appropriate composition. However, there are certain difficulties in the production of powders associated with obtaining spheroidized finely dispersed particles while maintaining the concentration of elements in the composition corresponding to the initial state. These problems can be solved by using ultrasonic atomization, which makes it possible to produce high-quality powder of metal alloys.

In this study, the modes of powder production of a given fraction of an innovative structural material based on Co-Cr system by high-frequency ultrasonic atomization are investigated in detail. The most attractive mode of ultrasonic atomization, allowing to obtain powders of spherical shape with the smallest particle size and including a relatively

small proportion of agglomerated particles has the following parameters: gas supply - 65%, current - 160 A, amplitude of oscillations of the ultrasonic system - 75%. The work also discusses in detail the studies on the cytotoxicity of the powder.

The research was carried out with the financial support of the Ministry of Science and higher education of the Russian Federation under the agreement from "24" June 2021 No. 07511-2021-046 (IGK 000000S407521QLP0002) with SEZ JSC "VladMiVa" under the complex project "Organization of a high-tech production of export-oriented medical devices based on innovative structural materials for the purpose of import substitution for based on developed technologies", with the participation of the National Research University "BelSU" in part implementation of research, development and technological works using the equipment of the Center for Collective use "Technologies and Materials of NRU "BelSU".

THE EFFECT OF SOLID SOLUTION HARDENING WITH NITROGEN AND CARBON ON THE TEMPERATURE DEPENDENCE OF THE MECHANICAL PROPERTIES AND DEFORMATION MECHANISMS OF FeMnCrNiCo ALLOY

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The temperature dependence of the mechanical properties and deformation mechanisms in $Fe_{20.0}Mn_{20.0}Cr_{20.0}Ni_{20.0}Co_{20.0}$ (at. %, HEA-0NC), $Fe_{19.9}Mn_{20.0}Cr_{20.0}Ni_{20.0}Co_{19.0}C_{1.1}$ (HEA-1C) and $Fe_{20.2}Mn_{19.4}Cr_{20.1}Ni_{20.4}Co_{19.1}N_{0.8}$ (HEA-1N) high-entropy alloys have been investigated.

It has been found that nitrogen and carbon alloying of the HEA-0NC leads to strong effects of solid solution hardening. An analysis of the data obtained after uniaxial tensile tests shows that alloying with nitrogen and carbon of the HEA-0NC alloy leads to an increase in the yield strength (YS) and ultimate tensile strength (UTS) in the test temperature range from 77 K to 473 K. The elongation-to-failure (EL) of HEA-0NC alloy slightly decreases after solid solution hardening by nitrogen and carbon, however, the investigated alloys have a good plasticity in a wide temperature range. It is shown that all alloys under study have the same stages of plastic flow, but the rate of strain hardening, and the duration of each stage depend on the chemical composition of the alloys. Nitrogen and carbon alloying of the HEA-0NC alloy contributes to a significant increase in the strain hardening coefficient, the maximum value of which corresponds to the liquid nitrogen test temperature.

It was shown by transmission electron microscopy that the main mechanism of deformation of all investigated alloys is dislocation slip. The initial HEA-0NC alloy is characterized by the activation of mechanical twinning as an additional mode of plastic deformation. In the nitrogen-containing alloy, only rare twins were observed at late

degrees of plastic deformation. However, at low-temperature deformation (77 K) powerfull dislocation pile-ups in several slip systems, which form a regular net of the multipoles and high-dense-dislocation walls, are observed. Dense dislocation walls effectively prevent dislocation sliding in cross-slip planes, which leads to an increase in the strain hardening coefficient and an increase in the EL-value. Solid-solution hardening of the initial HEA-0NC alloy with carbon, as in the case of the nitrogen-containing HEA, contributes to an increase of the planarity of the dislocation structure at late degrees of plastic deformation, which causes the accumulation of dislocations and contributes to an increase in the strain hardening coefficient compared to the HEA-0NC alloy.

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INFLUENCE OF SI ON STRUCTURE AND MECHANICAL PROPERTIES OF CO-CR-BASED ALLOY

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Changes in the microstructure and mechanical properties of Co63.5Cr29Mo5Mn1W1C0.5 alloy due to addition of Si in the interval 0.5 - 1 at.% were examined in this work. The structure and mechanical properties of the alloys were studied in the cast state. The microstructure of Co63.5Cr29Mo5Mn1W1C0.5 alloy (without Si) consisted of FCC (face-centered cubic) matrix and 5% HCP (hexagonal closely packed) phase. The addition of Si leads to the formation of the C14 Lave phase. The alloy without Si has a high ultimate tensile strength (UTS) of 936 MPa and uniform elongation (UE) of 13%. The addition of Si in the amount from 0.5 at.% to 1 at.% leads to a decrease in mechanical properties in the range of 878 to 818 MPa (US), 9 to 7% (UE), respectively. The influence of Si content on the technological properties of the alloy is discussed.

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DENSITY, ELECTRICAL RESISTIVITY AND MAGNETIC SUSCEPTIBILITY OF AlNiCoCuZr HIGH-ENTROPY ALLOYS IN SOLID AND LIQUID STATES

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High-entropy alloys have attracted much attention nowadays due to their high mechanical and corrosion properties. Aluminum and transition metals-based alloys occupy a special place among the investigated compositions [1]. It is known that such alloys exhibit changes in mechanical properties during long-term annealing; at the same time, the study of their volumetric and electromagnetic properties may make it possible to determine specific features of the change in structure. Density, electrical resistivity and magnetic susceptibility of high entropy AlNiCoCuZr alloys in solid and liquid states are investigated in the present paper.

Alloys for research were obtained by arc melting in an argon atmosphere. Density was measured by gamma absorption method in a protective helium atmosphere at a heating/cooling rate of 2 K/min. Electrical resistivity was studied by contact-less method in rotating magnetic field. Magnetic susceptibility was measured by the Faraday method. All experiments were performed from room temperature to 1800 K.

The temperature dependencies of density in crystalline state are practically linear during heating and subsequent cooling. Electrical resistivity and magnetic susceptibility curves have a more complicated form, in particular, section (500–750 K) where resistivity of the alloy decreases with increasing temperature was found. The changes recorded on electrical resistivity and magnetic susceptibility temperature dependences can indicates changes occurring at the level of the electronic subsystem of the alloy without changes in the atomic structure of solid solutions.

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References:

1. B.A. Rusanov, S.A. Petrova, V.A. Bykov, J.K. Bukreeva, E.V. Sterkhov, V.E. Sidorov, A.I. Rusanova, L.D. Son. Experimental investigation of density, electrical resistivity and DSC of AlNiCoCuZr equiatomic alloy // Intermetallics, V. 161, 2023, 107975, https://doi.org/10.1016/j.intermet.2023.107975

INTERFACIAL TENSION AND DENSITY OF THE AlTiZrVNb ALLOYS, OBTAINED BY ALUMINOTHERMIC REDUCTION METHOD

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The process of aluminothermic reduction of high-entropy alloys is significantly influenced by interfacial interactions and, accordingly, the surface and interfacial tension and density of the products. They determine the formation of a monolithic metal ingot and contribute to a good separation of the metal and oxide phases.

The samples were obtained using aluminothermic reduction of Ti, Zr, V, Nb oxides in a resistance furnace with a carbon-graphite heater, CaO, CaF_2 were added to the system to obtain low-melting slag.

The surface tension of the oxide-fluoride melt was determined by the method of maximum pressure in a gas bubble [1,2] for slag with a mass % content of 48 Al_2O_3, 2 TiO_2, 10 ZrO_2, 1 V_2O_5, 1 Nb_2O_5, 3 CaO, 5 CaF_2. The slag was loaded into an alund crucible and heated until it melted, then the capillary was lowered until it touched the slag and purged with an inert argon gas. The maximum pressure in the gas bubble was recorded on an inclined pressure gauge.

To measure the surface tension of a high-entropy alloy with a mass % content of 16 Al, 17 Ti, 10 Zr, 22 V, 35 Nb, the lying drop method was used [1]. The metal sample was placed on an alund substrate in a resistance furnace with a tungsten heater in an argon atmosphere. The sample was heated until it melted and the wetting angle of the substrate was recorded using a digital camera.

The interfacial tension between metal and slag was calculated according to Antonov's rule [3] by the difference between the experimental values of the surface tension of metal and slag. The results showed that with the values of interfacial tension and density found, a metal ingot will form at the bottom of the crucible with its complete separation from the oxide phase.

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References:

1. Arsentiev, P.P. Metal melts and their properties. – M.: Metallurgy, 1976.— 376 p.

2. Lynchevsky, B.M. Technique of metallurgical experiment. – M.: Metallurgy, 1979. – 256 p.

3. Popel', S.I. Surface phenomena in melts. – M.: Metallurgy, 1994. – 440 p.

DEVELOPMENT OF THE GEOMETRY OF POROUS STRUCTURES TO BE PRODUCED BY ADDITIVE MANUFACTURING FOR MEDICAL APPLICATIONS

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The relevance of the development and use of porous structures is due to their wide application in medicine and biology. Porous materials can be used as bone implants, as well as a platform for localized drug delivery to affected tissues. 3D printing enables the creation of customized and complex structures, which enhances the treatment of various diseases.

We review the main 3D printing methods and technologies used to create porous medical structures, models and design methods, analyze the advantages and disadvantages of using 3D technology to create medical devices. Possible applications of porous structures in medicine, including osteoinductivity, drug delivery, and tissue engineering, are discussed, as well as the challenges associated with additive printing of porous structures to meet medical requirements are discussed.

3D modeling-based geometries of porous structures for 3D printing with different parameters of their configuration and porosity of the samples are developed, which can be used for medical applications. The obtained results are compared with the literature data in terms of efficiency and prospects of application of porous medical implants obtained by 3D printing.

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HIGH ENTROPY MATERIALS AND THEIR PRACTICAL APPLICATIONS

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High entropy alloys (HEA) are a new strategy for alloying alloys, which consists in creating a combination of several (usually ≥ 5) basic elements in equiatomic or close to it concentration. This determined their name, since the configurational entropy in alloys should increase in proportion to the number of their constituent elements. The main feature of this approach to alloying alloys is the creation of a multidimensional compositional space, and although several hundred alloys with properties that exceed those of conventional ones have been developed to date, only small areas of it have been studied. In essence, the composition of alloys with such alloying corresponds to the central part of the concentration triangle, i.e. part that has not been explored until recently.

The vast majority of alloys developed to date are formed by three main groups of elements: 3d transitional Co, Cr, Cu, Fe, Mn, Ni, Ti, V, etc., refractory Cr, Hf, Mo, Nb, Ta, Ti, V, W , Zr, rare-earth Dy, Gd, Ho, Tb, Y, etc. Within these groups, with a certain combination of elements, substitutional solid solutions can be created as the matrix base of alloys. These are alloys of the systems: Co-Cr-Fe-Mn-Ni, Hf-Nb-Ta-Ti-Zr or Nb-Ta-Mo-W, as well as, for example, the Dy-Gd-Ho-Tb-Y systems, respectively FCC, BCC and HCP structures. We also consider alloys based on only three main elements, such as CoCrNi (FCC), NbTiZr (BCC), etc., or two with additional elements of lower concentration. Alloys belonging to the Co-Cr-Fe-Mn-Ni system are close in structure and properties to austenitic steels, and those created based on refractory elements, due to the peculiarities of their characteristics, to heat-resistant alloys. Modification of the alloy composition of these systems, including alloying with additional elements, leads to the formation of, for example, TRIP/TWIP alloys, and dispersion hardened alloys due to the formation of carbides, nitrides, oxides and intermetallic compounds. In addition, due to the peculiarities of alloying and phase transformations, multiphase alloys, single- and two-phase intermetallic alloys can be created in these systems.

The results of numerous studies show the possibility of developing high-strength alloys based on HEA, alloys with special properties: cold-, corrosion-, wear-, radiation-, heat-resistant, magnetic, and catalytic. One of the main tasks in relation to HEA is the creation of alloys that compete with industrial ones in terms of cost. Approaches to the rational design of alloys are considered. Examples of alloys of practical interest are given.

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References:

*1. Miracle D B and Senkov O N 2017 A critical review of high entropy alloys and related concepts Acta Materialia **122** 448–511*

2. Li Z, Zhao S, Ritchie R O and Meyers M A 2019 Mechanical properties of high-entropy alloys with emphasis on face-centered cubic alloys Progress in Materials Science 102 296–345

*3. Cheng Z et al 2023 Irradiation effects in high-entropy alloys and their applications Journal of Alloys and Compounds **930** 166768*

*4. Law J and Franco V 2023 Review on magnetocaloric high-entropy alloys: Design and analysis methods Journal of Materials Research **38** 1 37-51*

*5. Cheng Z et al 2022 Tribological properties of high-entropy alloys: a review International Journal of Minerals, Metallurgy and Materials **29** 3 389-403*

HIGH-ENTROPIC MATERIALS: FROM ALLOYS TO HIGH-TEMPERATURE CERAMIC COMPOUNDS

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Starting from the first publications in 2004, high-entropy alloys (HEA) aroused great interest in the scientific world, since the formation of HEA was based on a fundamentally new concept for the creation of metallic materials. Initially, HEAs were defined as alloys with an equiatomic composition consisting of at least 5 constituent elements. Later, the determination criteria for HEA were expanded and formulated as multicomponent alloys with component concentrations from 5 to 35 at. %. It was assumed that, due to the high configurational entropy of mixing, the formation of disordered substitutional solid solutions in HEA would be more preferable than the formation of ordered phases (intermetallic) and, thus, the formed high-entropy solid solutions would have both high strength and sufficient plasticity. However, studies carried out somewhat later showed the absence of a clear correlation between the calculated values of the configurational entropy and the phase composition of the obtained experimental multicomponent alloys. It was found that the HEA phase composition is primarily determined not by the number of elements included in the composition, but by the characteristics of the atoms of these elements.

A distinctive feature of HEA, in addition to the multicomponent composition, is the formation of a predominantly single-phase thermodynamically stable substitutional solid solution, mainly with a face-centered cubic (fcc) or body-centered cubic (bcc) lattice. Then, by the intensive development of this scientific direction the compositions were continuously expanded, and in the structure of the HEA with the participation of active metals (Al, Ti, Zr, etc.), dispersion precipitates of the nanosized and micron range were already observed. The observed secondary phases were usually formed on the basis of intermetallides, Laves phases.

Experience in the development of high-strength steels and alloys based on Ni, Ti and Al shows that the use of only solid-solution hardening does not make it possible to achieve the desired set of physical and mechanical characteristics required for modern alloys. Increasing the strength of alloys can be realized by forming the desired structure and implementation of some of hardening mechanisms (solid-solution, dispersion, deformation).

Thus, a new approach to the formation of materials provides new opportunities for the development of new alloys with improved performance. In particular, one of the most attractive directions in the development of HEA-based materials has become the development of new compositions that are promising for high-temperature operation.

Of particular interest are poorly studied metal matrix materials based HEA with carbides, silicides and borides.

In the report will presented some of results in the field of HEAs and materials based on them, and gives a general conclusion about the prospects for research in the field of HEA, taking into account their practical application.

ORIENTATION DEPENDENCE OF THE SHAPE MEMORY EFFECT OF $Cr_{20}Mn_{20}Fe_{20}Co_{34.5}Ni_{5.5}$ HIGH-ENTROPY ALLOY SINGLE CRYSTALS WITH THE FCC-HCP MARTENSITE TRANSFORMATION

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The shape memory effect (SME) was investigated on single crystals of a non-equiatomic $Cr_{20}Mn_{20}Fe_{20}Co_{34.5}Ni_{5.5}$ (at. %) high-entropy alloy with FCC-HCP martensitic transformation (MT) oriented along three different directions [001], $[\bar{1}11]$ and $[\bar{1}44]$ under two conditions: at constant stress (isobaric) and at constant test temperature (isothermal) under tensile deformation. Using differential scanning calorimetry and the temperature dependence of the electrical resistance ρ(T), it was shown that the investigated alloy exhibits FCC-HCP MT, which is characterized by temperatures M_s=195K and A_f=375K and a wide thermal hysteresis $\Delta T_h=A_f-M_s$=180K.

Theoretical calculations of the transformation strain $\varepsilon_{theory}=\Gamma\cdot m$ for [001], $[\bar{1}11]$ and $[\bar{1}44]$ orientations (where $\Gamma=\sqrt{2}/4$ is the shift value at FCC-HCP MT, m=0.23, 0.31 and 0.5 is the Schmid factor for HCP martensite in [001], $[\bar{1}11]$ and $[\bar{1}44]$ orientations, respectively, under tension) are 8.26%, 11% and 17.5%, respectively. It has been experimentally established that the SME in the FCC-HCP MT depends on the crystal orientation and the conditions for SME studying: isobaric and isothermal deformation. Under isobaric deformation at close tensile stresses of 150 and 160MPa, the maximum SME of 15.7% was observed in $[\bar{1}44]$-oriented crystals, which is 90% of the theoretical deformation value of 17.5%, and in the [001] and $[\bar{1}11]$ orientations, the SME was equal to 1.73% and 2.5 % and amounted to 21% and 23%, respectively. Under isothermal deformation at Ms temperature, the maximum SME of 12% was observed in the $[\bar{1}44]$ orientation, which was similar in magnitude to the value under isobaric deformation, and in the [001] and $[\bar{1}11]$ orientations, oriented for the development of HCP martensite in several systems from the beginning of deformation, the SME exceeded the values at isobaric deformation and became equal to 3.6% and 6.8%, respectively.

The physical reasons that determine the large SME in the $[\bar{1}44]$ orientation are established: the high yield strength $\sigma_{0.1}$ of initial FCC-phase, the development of HCP-martensite predominantly in one system, the absence of the variant-variant interaction of HCP martensite and short-range order, which enhance the localization of slip deformation in one system simultaneously with the FCC–HCP MT and promotes the formation of thin HCP martensite.

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EFFECT OF NITROGEN ON STRUCTURE AND MECHANICAL BEHAVIOR OF HIGH ENTROPY ALLOYS WITH FCC STRUCTURE

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The best-known high-entropy alloy (HEA) is the so-called Cantor alloy (CoCrFeMnNi) with a face-centered cubic (fcc) structure that is currently considered as promising structural material. Cantor alloy and its derivatives have high ductility at room and cryogenic temperatures, excellent fracture and impact toughness, etc. The current approach in the development of HEAs involves varying the content of each element to achieve the desired properties and (possibly) reduce the concentration of expensive elements. One of such alloys based on Co-Cr-Fe-Ni-Mn system is $Fe_{40}Mn_{40}Co_{10}Cr_{10}$ (in at.%) alloy, the mechanical properties of which are similar to the equiatomic alloy with drastically reduced cost. However, fcc HEAs tend to have low strength at room temperature. It is known that doping with interstitial elements can lead to a significant strengthening of alloys. Thermomechanical processing can also be effectively used to tailor the microstructure and properties. Therefore, in present work we have studied the effect of nitrogen doping on the structure and mechanical property's evolution of the equiatomic CoCrFeMnNi and $Fe_{40}Mn_{40}Co_{10}Cr_{10}$ alloys.

The CoCrFeMnNi and $Fe_{40}Mn_{40}Co_{10}Cr_{10}$-based HEAs doped with the different amount of N (0.5, 1.0 and 2.0 at.%) were produced by vacuum induction melting. The alloys were studied in as-cast condition and after thermomechanical processing (cold rolling followed by annealing at different temperatures). In the as-cast state, alloys had single fcc phase structure. Thermomechanical treatment led to the development of static recrystallization and precipitation of nitrides (in the alloys doped with 2 at.% of N). The mechanical behavior of the alloys was quite sensitive both to chemical composition and to microstructure parameters, especially in cryogenic conditions. In particular, the $Fe_{40}Mn_{40}Co_{10}Cr_{10}$-based alloys demonstrate notably lower ductility at cryogenic temperatures. Meanwhile some of the program alloys can have very attractive properties at 77K.

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ALUMINIZING OF FE-NI-CO-CR-MO0.5 HIGH ENTROPY ALLOY

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Diffusion coatings have been used for more than half a century as a cost-effective method of improving the corrosion and wear resistance of a base alloys by enriching the surface in Al, Cr, Si, etc.

Aluminide diffusion coatings are routinely applied to enhance nickel-based superalloy resistance to high temperature oxidation and hot corrosion.

The application of this technique for high-entropy alloys may be as well expedient to prevent the formation of volatile oxides of Mo, W, Nb, Ta, etc. In addition, the addition of Al to the FeNiCoCr system with FCC structure leads to the formation of B2 phase of high hardness (700HV).

The purpose of this work was to study the microstructure of aluminide coatings on high-entropy FeNiCoCrMo0.5 alloy.

Aluminizing was performed in the pack composed of 79% Al2O3, 3% NH4Cl, and 18% Al at 800°C for 2 h. As a result, a 50±5 μm coating was obtained. Microhardness of the coating reached 750±5 HV (the substrate's microhardness was 250±5HV). Subsequent annealing at 900°C for 5 h in an air atmosphere did not lead to change of microhardness or thickness of the coating. No significant oxidation was found.

The results of the study may be useful for evaluating the possible application of the aluminizing technique applied to high entropy alloys.

SHS OF CAST REFRACTORY COMPOUNDS FOR REPROCESSING INTO MICRO GRANULES USED IN 3D ADDITIVE TECHNOLOGIES

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The quest of new heat-resistant materials with improved service parameters is a key problem of modern materials science [1] and high-tech production. For implementation in aerospace industry, nuclear power engineering, and defense applications, most promising seem to be intermetallic alloys [2] and metal matrix eutectic compositions (MMCs) based on refractory metals [3]. A main difficulty in designing the above materials is high sensitivity of their phase composition to the presence of alloying agents, impurities, process parameters, structural imperfections (e.g. liquation phenomena), sinterability, and ductility. The fabrication of complicated items by conventional methods including casting, machining, spark erosion and thermo-mechanical treatment is labor and material consuming process. The challenge here can be solve by the additive

technology (AT). The most promising kind of AT is selective laser smelting (SLM) that requires starting materials in the form of spherical granules (micro granules) with strictly defined size and morphology (spherical shape).

In this communication we will present some technological research aimed at obtaining raw materials by centrifugal SHS metallurgy [4] and their subsequent processing to obtain promising powder compositions used in AT.

Among the studied materials were the intermetallic compounds based on NiAl, multicomponent metal-matrix composites based on systems: Co–Nb(Cr,Mo,W))C; Nb–Nb(Mo,Ti,Hf)xSiy and Nb–NbC etc.

The details will be discussed at presentation including: testing of the roadmap for basic technological stages of SHS process for raw materials (precursors), formation of micro granular of the SHS precursors and the comparative data of the structural and phase composition study of raw materials and micro granules.

References:

1. Reed, R.C., The Superalloys: Fundamentals and Applications, Cambridge–New York: Cambridge University Press, 2006.

2. L.Y. Sheng, J.T. Guo, H.Q. Ye, Microstructure and mechanical properties of NiAl–Cr(Mo)/Nb eutectic alloy prepared by injection-casting, Mater. Design, 2009, vol. 30, no. 4, pp. 964–969.

3. Drawin Stefan, The European ULTMAT project: Properties of new Mo and Nb silicide based materials, Mater. Res. Soc. Symp. Proc., 2009, vol. 1128.

4. V.N. Sanin, D.M. Ikornikov, D.E. Andreev, V.I. Yukhvid, Centrifugal SHS metallurgy of nickel aluminide based eutectic alloys, Russ. J. Non-Ferr. Met., 2014, vol. 55, no. 6, pp. 613–619.

INVESTIGATION OF THE INFLUENCE OF ELEMENT CONCENTRATION ON THE STRUCTURE AND PROPERTIES OF FE-NI-CO-CR-MO0.5-AL2 HIGH ENTROPY ALLOY

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The high entropy alloy $FeNiCoCrMo_{0.5}Al_{2.13}$ attracts attention due to high hardness and thermal stability of B2 and BCC phases.

The aim of this work was to study the effect of the main element's ratios and the effect of additional alloying (Nb, W, Y, Ti, Cu and Si) on the phase composition and hardness of $FeNiCoCrMo_{0.5}Al_{2.13}$ high entropy alloy.

The alloys were prepared from elements with 99.94% purity using an induction furnace. Phase composition, microstructure and hardness were analyzed. Annealing in air at 900 ^{o}C was carried out to evaluate the heat resistance by weight gain.

It was found, that when Si, Co and Y are added, a large amount of the sigma phase appears, when alloying with W and Nb, the separation of the BCC solid solution into two is observed. The highest values of hardness were observed in the samples with the addition of Si (903±52 HV) and Y (877±12 HV). The lowest hardness was observed with

the addition of Ti (653±13 HV), in which the sigma phase was practically absent. W-alloyed sample has a high hardness (850±12 HV), despite of a small amount of sigma phase.

It was found that an increase in the Co and Ni content in $FeNiCoCrMo_{0.5}Al_{2.13}$ leads to the disappearance of the BCC separation and the appearance of a sigma phase. The sample with increased Co has the highest hardness (727±12 HV). The sample with a lower content of Fe and Co has a lower amount of sigma phase and the lowest hardness (577±22 HV). The $FeNiCoCr_{1.4}Mo_{0.9}Al_2$ alloy with a high content of Cr and Mo is eutectic, it has a sufficiently high hardness and the highest heat resistance.

These results can be used to predict alloys with the desired phase composition and properties in this system.

INVESTIGATION OF MECHANICAL PROPERTIES OF ALUMINUM ALLOYS WIRE Al-0.25Zr-(Si,Er,Hf,Nb)

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The thermal stability of a wire made of microalloyed aluminum alloys with a diameter of 0.3 mm has been studied. Alloy composition: type 1 — Al-0.25Zr-0.1Si-0.25Er-0.20Hf, type 2 — Al-0.25Zr-0.1Si-0.25Er, type 3 — Al-0.25Zr-0.1Si, type 4 — Al-0.25Zr-0.1Hf, type 5 — Al-0.25Zr-0.25Hf, type 6 — Al-0.25Zr-0.15Nb (wt.%).

The alloy specimens 22×22×150 mm in sizes were obtained by induction casting in INDUTHERM VNC-200 casting machine. Regime of deformation: 1. Equal Channel Angular Pressing (ECAP) (temperature 250°C, number of cycles N=4, ECAP regime – A); 2. Rotary Forging (RF); 3. Ageing at 450°C 1 h; 4. Wire drawing (ø 0.3 mm). Microhardness (HV) studies were carried out in the center of the wire cross section using a Qness A60+ hardness tester at a load of 20g. For tensile testing, a Lloyd Instruments LR5K Plus breaking machine was used (the traverse movement speed was 10 mm/min). During the tests, the stress – strain diagram was recorded, according to which the values of the tensile strength were determined. In order to obtain statistically reliable results, tests were carried out on at least three samples in each series. Fractographic study of fractures of wire samples after tensile tests was carried out using a scanning electron microscope (SEM) Jeol JSM-6490. The heat treatment of the samples was carried out in an air furnace of the SNOL type. The SIGMATEST 2.069 tester was used to measure electrical resistivity in cast alloys. To measure the electrical resistivity of the wire, an L-C-R meter was used. , tension tests and fractographic studies were carried out.

The minimum microhardness (400MPa) in the initial state is observed for a wire type 6. The microhardness values for wires type 1-5 lie in the rang from 485 MPa (type 5) to 555 MPa (type 1). For all alloys, the monotonically decreasing nature of the dependence of microhardness on the temperature of 30-minute annealing is observed.

In the initial state, wire type 6 have the lowest value of the tensile strength (160 MPa). The highest tensile strength in the initial state is observed in wire type 1 (290 MPa).

The results of the fractographic analysis wires show that a perimessentially viscous nature of the destruction.

The electrical resistivity in the initial state is about 3.3 μΩ·cm. After heat treatment (500°C, 30 min), the electrical resistivity drops to about 3.2 μΩ·cm.

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PECULIARITIES STRUCTURE FORMATION AUSTENITIC STEELS IN THE PROCESSES OF LASER POWDER BED FUSION AND DIRECT LASER DEPOSITION

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Corrosion-resistant steels have an optimal set of mechanical, physical and operational properties, are effective in conditions of corrosive environments and oxidation, including at elevated temperatures. Therefore, they are widely used in aerospace, nuclear, shipbuilding, chemical, food and many other industries. For the use of stainless steels manufactured by additive technologies in these industries, it is necessary to conduct thorough studies of structure formation at various scale levels, providing the necessary complex of mechanical and operational properties.

Additive manufacturing technologies for parts and products made of metal-powder compositions of austenitic stainless steels include two main methods of laser synthesis: laser powder bed fusion (LPBF) and direct laser deposition (DLD). The fundamental difference between these methods lies in the scale of formation of the deposited layer of steel powder. The dimensions of the melt bath are very different. The LPBF method is characterized by the width of the melt bath of about 100 microns and the thickness of the formed layer of about 40 microns. Whereas, with DLD, the metal is deposited with rollers with an average size of 2.5 mm wide and 1 mm thick. Accordingly, from the point of view of structure formation, these two methods create completely different conditions for the process of crystallization of austenitic steel and subsequent cooling.

This paper presents the results of studies of the influence of the main technological parameters of LPBF and DLD of austenitic stainless steels of type 18-10 on the processes of crystal structure formation. Studies have shown that differences in the geometry of the melt bath, as well as the intensity of heat removal due to the large-scale factor of the implementation of melting and crystallization processes, have a direct effect on the morphology of crystallites, which ultimately determines the difference in mechanical properties.

SYNTHESIS OF Cu/MoS2 COMPOSITE FROM WASTE PRINTED CIRCUIT BOARDS AS CATALYST FOR EFFECTIVE DEGRADATION OF ORGANIC POLLUTANTS

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There is a major concern on a global scale about the disposal of electronic waste (e-waste) [1]. The direct conversion of e-waste into valuable products helps to protect the resources and environmental effects from the conventional disposal of e-waste [2]. In the present study, Copper composite (Cu-composite) are used as a photocatalyst which was recovered from waste-printed circuit boards (WPCBs). Further, MOS_2 is combined with Cu-composite to produce a Cu/MoS_2 composite that is beneficial for the degradation of organic pollutants. Through the use of various characterization techniques such as FTIR, UV-visible, SEM-EDS, and XRD analysis, we examined the structure, optical properties, and elemental composition of the photocatalyst. The catalytic performance of Cu/MoS_2 composite was investigated with different parameters including the amount of catalyst, pH, concentration of organic pollutant, and time. Moreover, a UV-visible spectral analysis is used to identify possible mechanisms of organic pollutant degradation [4]. The recyclability of Cu/MoS_2 composite was also studied for four cycles. As a result of this work, we have developed a novel strategy for producing useful composites from the WPCBs thereby simplifying the management of harmful solid wastes and tidying chemical wastewater treatment.

References:

1. *Ghulam, S. T., & Abushammala, H. (2023). Challenges and Opportunities in the Management of Electronic Waste and Its Impact on Human Health and Environment. Sustainability, 15(3), 1837.*

2. *Takeda, S., Miki, H., Takeishi, H., & Takagi, T. (2017). Cu-based MoS_2-dispersed composite material formed by the compression shearing method at room temperature. Tribology Online, 12(2), 29-36.*

3. *Atacan, K., Güy, N., & Özacar, M. (2021). Design and synthesis of magnetically separable $CuFe_2O_4/MoS_2$ pn heterojunction for photocatalytic efficiency of Rhodamine B degradation. Colloid and Interface Science Communications, 40, 100359.*

4. *Jilani, A., & Melaibari, A. A. (2022). MoS_2-Cu/$CuO_@$ graphene heterogeneous photocatalysis for enhanced photocatalytic degradation of MB from water. Polymers, 14(16), 3259.*

STRUCTURE AND MECHANICAL PROPERTIES OF A MEDIUM-ENTROPY ALLOY PRODUCED BY ADDITIVE TECHNOLOGY

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Recently, multicomponent alloys (high-entropy and medium-entropy (HEAs and MEAs)) with close to equiatomic element abundances have attracted considerable attention from materials scientists. This interest is due to the unusual properties demonstrate by the MEAs. In particular, some medium-entropy alloys with a face-centered cubic (fcc) structure have a very good combination of strength and ductility at low temperatures [1, 2]. Consequently, these materials can be considered as potential candidates for application under cryogenic conditions.

However, most of the studies were devoted to the study of HEAs and MEAs obtained by the traditional method (i.e. casting). This approach provides stable result, but it requires additional and quite significant efforts for further deformability of blanks with a regulated structure and properties. Compared to traditional manufacturing methods, selective laser melting (SLM) makes it possible to obtain treat difficult parts directly from powder, with control over all production parameters. The formation of a fine-grained microstructure and a uniform chemical composition by the section of the part is provided, due to the high crystallization rate during SLM. It is contributing to the achievement of a high level of mechanical properties. Meanwhile, there are no systematic data on the effect of SLM on the structure and mechanical properties of carbon-containing MEAs with the TRIP effect.

In this work, we consider the structure and properties of a medium-entropy Fe65(CoNi)25Cr9.5C0.5 (in at.%) obtained by selective laser melting. The structure and mechanical behavior of the alloy were studied under tension at room and cryogenic temperatures. The microstructure of the alloy produced by SLM comprised an elongated substructure, inside which cells with a size of ~300 nm were observed. The as-produced alloy demonstrated high yield strength and ultimate tensile strength (YS = 680 MPa; UTS = 1800 MPa) along with good ductility (tensile elongation = 26%) at a cryogenic temperature (77 K) that was associated with the development of transformation-induced plasticity (TRIP) effect. The relationship between technology, structure and mechanical properties of the alloy is discussed.

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References:

1. *J.W. Bae and H.S. Kim / Scripta Materialia 186 (2020) 169–173.*
2. *J.W. Bae et al. / Acta Materialia 161 (2018) 388e399.*

FATIGUE FAILURE OF A5M, VT-1, M1 ALLOYS SUBJECTED TO MAGNETIC TREATMENT

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In recent decades, various energy flows such as laser radiation, electron and ion beams have been widely used to modify the structure and properties of metallic materials. Along with these methods, there is a promising, but less studied, method for changing the deformation characteristics of metals and alloys, namely, processing the material with constant magnetic fields. The study of the influence of constant and pulsed magnetic fields is an important area of modern science. The open effects of the influence of a magnetic field on the deformation characteristics of various materials are called magnetoplastic (MPE). To date, various research teams have established that the effect of a magnetic field on "non-magnetic" metallic materials (Ti, Pb, Zn, etc.) leads to a change in their deformation behavior [1, 2].

Alloys of titanium VT1-0, aluminum A5M, and copper M1 were used as the materials under study. Fatigue tests were carried out according to the scheme of cyclic asymmetric cantilever bending under fatigue conditions with a loading frequency of 3.3 s^{-1} and simultaneous exposure to a magnetic field. Specimens for fatigue testing had the shape of a parallelepiped with parameters 4x12x130 mm^3. The crack was simulated by two notches in the form of a semicircle with radii of 22 mm.

According to the results of fatigue testing of samples of titanium VT1-0 and aluminum A5M, it was revealed that exposure to a constant magnetic field of 0.3 T leads to a significant increase in fatigue life. It has been established that the use of a constant magnetic field of 0.3 T during fatigue testing of commercially pure aluminum A5M leads to an increase in the number of cycles to failure by a factor of 4. With commercially pure titanium VT1-0, a similar picture is observed, there is an increase in cycles to failure by 2.2 times, relative to tests without the use of a magnetic field. On samples of commercially pure copper grade M1, fatigue tests were carried out at a magnetic field induction of 0.1 T. The results showed that there was an increase in fatigue life. Copper samples M1 are destroyed on average at 263338 ± 20175 cycles, when a constant magnetic field of 0.1 T is connected - 292544 ± 45486, the increase is 11%.

References:

1. V.V. Shlyarova, K.V. Aksenova, D.V. Zaguliaeva, A.A. Serebryakova Evolution of the Fracture Surface of Commercially Pure VT1-0 Titanium Subjected to Multicycle Fatigue in a Constant Magnetic Field // Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques. 2023. – Vol. 17(1). – pp. 144-149..

2. A. A. Serebryakova, V. V. Shlyarov, D. V. Zaguliaev Mechanical characteristics and fracture surface of lead grade 2 destructed in a constant magnetic field // Materials in External Fields: Proceedings of the XII International Online Symposium. - 2023. - c.50-51.

A POROUS MATERIAL BASED ON TITANIUM CARBIDE POWDERS WITH A LAYERED STRUCTURE PRODUCED WITH THE USE OF A POROGEN

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Highly porous ceramics are used in various fields. For example, as fuel cell electrodes, as filters, catalyst carriers (1,2). The majority of porous materials are manufactured using a well-established powder technology, which makes it possible to implement a number of methods for the formation of porosity, such as partial sintering of powders, the template method, and the use of pore formers. In this case, materials with multimodal porosity are of particular interest. The combination of pores of different morphologies in one material allows the porous product to perform several functions, expanding the scope of its application. In this work, a study was carried out on obtaining a porous material from titanium carbide powders with a layered structure by powder metallurgy methods. To increase the efficiency of fluid filtration, a finely porous structure was created on a highly porous base. A highly porous structure in the base sample was obtained by adding a porogen to the submicron titanium carbide powder, which was completely removed at the heat treatment stage. Ammonium bicarbonate powder was used as a porogen. Heat treatment was carried out in a vacuum of at least 10^{-2} Pa at temperatures of 1200 -1500°C. The formation of a layered porous structure in the material was carried out by applying a suspension, which is an aqueous solution of polyvinyl alcohol (PVA) containing 20 wt.% of titanium carbide nanopowder, to a sintered porous sample of submicron titanium carbide powder. The layer was deposited by droplet flow of the suspension on one of the end surfaces of the sample.

The porous structure of the resulting material was studied by scanning electron microscopy. A large amount of agglomerates was observed after sintering in the layer where the PVA suspension with titanium carbide nanopowder was applied. The size of agglomerates reaches several tens of micrometers. Ultrasonic dispersion of the suspension before application made it possible to significantly reduce the size of the agglomerates. The study of the permeability of the obtained samples made it possible to establish that the application of such a layer increases the resistance to the flow of the technological medium in comparison with a single-layer highly porous material, which leads to a decrease in the permeability of the material by 1.6-4 times.

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References:

1. Shabri H.A., Othman M.H.D., Mohamed M.A., Kurniawan T.A., Jamil S.M., 2021. Recent progress in metal-ceramic anode of solid oxide fuel cell for direct hydrocarbon fuel utilization: A review. Fuel Processing Technology, 212, p.106626.

2. Kuo T., Rueschhoff L.M., Dickerson M.B., Patel T.A., Faber K.T., 2021. Hierarchical porous SiOC via freeze casting and self-assembly of block copolymers. Scripta Materialia, 191, pp.204-209.

HIGH-ENTROPY CANTOR ALLOYS CoCrFeNiMn AND CoCrFeNiAr: METHODS FOR IMPROVING PROPERTIES

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The highly entropic five-component alloys CoCrFeNiMn (Cantor alloy) and CoCrFeNiAl, created among the first and studied more than 20 years ago, continue to attract the attention of materials physicists because of their possible application in various industries due to successful combination of strength and plastic properties. To date, a lot of experimental data have been accumulated on ways to control the properties of these alloys.

In previous reviews [1], methods for improving the mechanical properties of high-entropy CoCrFeNiAl and CoCrFeNiMn alloys were analyzed from the point of view of their possible industrial use. The solution to this problem involved strengthening of grain-boundary hardening, solid-solution hardening, generation of a nanocrystalline state, hardening by precipitations, partial amorphization, use of hardening surface treatments, development of new methods for obtaining HEA, etc., ultrasonic exposure, formation of structure gradients, etc. Such approaches can stimulate a significant expansion of the application areas for these HEA.

In this paper, we review the publications of Russian and foreign authors in two directions of improving the properties of these alloys: alloying, isolation and heat treatment and the use of Calphad phase diagrams. Within the first direction, the role of alloying with B, Vi, Al, V, Si, Nb was analyzed; γ and γ′with nano precipitations, various modes of thermal and deformation treatment. It was concluded that it is necessary to conduct experiments on the HEA alloying with Zr and Nb, which have proven themselves well in the hardening of steels. Creation and modification of properties of five-component HEAs is possible using Calphad computer programs designed to calculate transformation diagrams. The analyzed results of publications on the thermodynamic description of five-component alloys are confirmed by comparing phase diagrams with available experimental data. In one of the analyzed works on the phase formation of five-component HEA consisting of Co, Cr, Fe, Ni, Al, Mn, Cu, 2436 compositions were considered, which made it possible to determine 1761 variants of reliable prediction of the formation of BCC/B2 and FCC phases, bypassing amorphous phases and intermetallides, thereby constructing a certain level of mechanical properties. It is shown that the design of a new generation of HEA is possible on the basis of Calphad phase diagrams calculation.

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References:

1. Gromov V.E., Ivanov Yu.F., Osintsev K.A., Shlyarova Yu.A., Panchenko I.A. Structure and properties of high-entropy alloys. Ru. Science Moscow; 2021: 203.

ADDITIVE MANUFACTURING OF BIMETALLIC JOINT WITH HIGH CORROSION RESISTANCE

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The development of bimetallic parts is a perspective field, because one of the advantages of bimetals is their application in the nuclear industry, electrochemistry and aircraft construction. Bimetallic compounds are a type of functionally graded multi-component structure to obtain properties such as strength and corrosion resistance. Obtaining a heterogeneous compound is focused on improving the quality and reliability of vessels for low-power nuclear reactors, as well as the introduction of technology for obtaining bimetallic compounds by direct laser deposition for the needs of the nuclear power industry. To achieve high corrosion resistance on the one hand and high heat and radiation resistance on the other hand, stainless steel AISI 321 is used as the inner wall material and heat and radiation resistant steel 15Cr2MoV as the outer one.

Manufacturing of specimens by the DLD method was performed using the following process parameters: laser power P = 2600 W, travel speed V = 20 mm/s, powder flow rate G = 22 g/min. As a result of the analysis of macro-surfaces of technological samples it was revealed that at laser power less than 2000 W non-melting is formed in the bases between lack of fusion. At powers ≥ 2200 W no defects were found.

Post-heat treatment has a positive effect on the formation of structure, increase in strength properties and impact toughness due to the formation of equilibrium structure and formation of carbide phases. The impact toughness before heat treatment was 95 J/cm^2, and after heat treatment 227 J/cm^2. Post-heat treatment has a positive effect on the formation of structure, increase in strength properties and impact toughness due to the formation of equilibrium structure and formation of carbide phases. Microstructure of steel AISI 321 represents cellular subgrains with a directed crystallization front. The structure of 15Cr2MoV steel consists of bainite and a small proportion of martensite. The transition boundary of the two materials has a small mixing area of the two steels which is up to 1 mm. When analyzing the electrochemical studies of the bimetallic joint it was found that cladding of AISI 321 steel has a positive effect on the protection of the base material 15Cr2MoV. Post-heat treatment increases mechanical properties and slightly improves corrosion resistance.

MAGNETIC PROPERTIES AND ELECTRIC RESISTIVITY OF REFRACTORY HIGH-ENTROPY ALLOYS

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Multicomponent high-entropy alloys are expected to be one of the emerging advanced structural materials [1]. Samples of the TiZrHfTa, TiHfNbTa, TiZrHfNbTa alloys with equiatomic composition were synthesised by arc melting. Structure characterization of the alloys was performed by means of the X-ray phase analysis, metallographic and scanning electron microscopy examination. Magnetization of the as-cast HEA samples was explored by vibrating sample magnetometry using a Cryogenic CFS-9T-CVTI measurement system in a temperature interval of 300–3 K. Both electrical resistivity and magnetization temperature dependencies were measured during continuous cooling at a rate of 1 K/min. The electrical resistivity measurements at the temperature 3 K were made up to ±8 T. The new data about magnetization and electrical resistivity of the TiZrHfTa, TiHfNbTa, TiZrHfNbTa alloys were obtained.

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References:

1. B.R. Gelchinski, I.A. Balyakin, A.A. Yuryev, A.A. Rempel, High-entropy alloys: properties and prospects of application as protective coatings, RUSS. CHEM. REV., 2022, 91 (6), RCR5023, DOI: doi:10.1070/RCR5023

HIGH-ENTROPY FeCoCrNiMn AND FeCoNiCrAl ALLOYS COATINGS: STRUCTURE AND PROPERTIES

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The aim of this work is to analyse the structure and properties of FeCoCrNiMn and FeCoNiCrAl Cantor HEA coatings deposited on 5083 alloy.

The coating was high-entropy alloys of non-equiatomic elemental composition FeCoNiCrAl and FeCoCrNiMn applied to the substrate by the method of wire arc additive manufacture (WAAM).

Studies of mechanical properties of microhardness profile showed that the microhardness values vary within (2.5–3.5) GPa and increase almost to 9.9 GPa at the boundary with the substrate in the volume of coating composed of high-entropy alloy FeCoCrNiMn. The hardness of the substrate at the boundary with the coating reaches 8 GPa and quickly (at a distance of 300 μm) decreases to 1.1 GPa, almost corresponding to the substrate hardness (1.0 GPa).

The phase composition and defective substructure analysis conducted in this work makes it possible to assume about the physical mechanisms of the increase of material hardness in the zone of FeCoCrNiAl coating and substrate contact. Namely, (1) strengthening of the substrate is due to the formation of iron aluminides of lamellar morphology; (2) hardening in the high-entropy alloy is a result of the formation of grain-subgrain structure with submicron sizes, at the boundaries and in the volume of which nanosized particles of the second phase are observed; (3) mutual alloying of the substrate and coating indicates solid-solution hardening of the material of the contact zone; (4) the formation of internal stress fields in the contact zone should not be excluded due to the difference in the thermophysical characteristics of the contacting materials.

The cross-section of the coating composed of FeCoNiCrAl HEA has a structure typical for a two-phase material, in which inclusions of the second phase are present in the volume of the main phase. Inclusions of the second phase are rounded (globular) and are located along the grain boundaries of the main phase. The sizes of inclusions of the second phase vary from 2 μm to 9 μm. The microcracks in the coating are also present.

The substrate layer adjacent to the coating has a lamellar structure as in FeCoCrNiMn HEA. The latter indicates that the substrate is alloyed with chemical elements of the coating followed by phase transformations in the substrate. Obviously, this explains the increase in the microhardness of this substrate layer.

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DIFFUSION-HARDENING COMPOSITE MATERIAL Ga-Sn-Zn-Cu-W

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The integral connection of dissimilar materials is an urgent task, for this purpose several composite solders with low melting points have been developed [1], including those based on low-melting gallium alloys [2]. Dissimilar materials usually have different coefficients of thermal expansion and in order to reduce the stress at the junction, the connecting solder layer must have an intermediate coefficient of thermal expansion. It can be adjusted by introducing various fillers into the solder [1]. Tungsten has a small coefficient of thermal expansion of $4.1 \cdot 10^{-6}$ K^{-1} [3], and it practically does not interact with liquid gallium [2], which makes it possible to use tungsten for additive reduction of the coefficient of thermal expansion of copper- and gallium-based solders, in which different phases have a coefficient of thermal expansion in the region of $20.0 \cdot 10^{-6}$ K^{-1} [4]. Tungsten metal powders are well wetted with gallium-based liquid alloys, while it does

not interact with gallium and other solder components, thereby additively reducing the coefficient of thermal expansion, and increasing the mechanical strength of composite diffusion-hardening solders. The results of measuring the microhardness of the obtained compositions, depending on the composition, are shown in the table.

Table – Microhardness of samples

№	Composite alloy, %	Microhardness, HV, MPa.
1	24.6Ga–6.85Sn–1.8Zn–61.75Cu–5W	630
2	24.6Ga–6.6Sn–1.8Zn–57Cu–10W	660
3	24.6Ga–6.35Sn–1.8Zn–52.25Cu–15W	710

The work was carried out in accordance with the state task and plans of the ISSC UB RAS (№ AAAA-A19-119031890028-0).

References:

1. Yatsenko S.P., Hayak V.G. Kompozicionnye pripoi na osnove legkoplavkih splavov [Composite solders based on low-melting alloys]. Ekaterinburg, Ural Branch of RAS Publ., 1997, 186 p. (In Russian).

2. Yatsenko S.P., Pasechnik L.A., Skachkov V.M., Rubinshtein G.V. Gallii: Tehnologii polucheniy I primenenie zidkih splavov [Technologies for the production and application of liquid alloys]. Moscow, RAS Publ., 2020, 344 p. (In Russian).

3. Zelikman A.N., Nikitina L.S. Wolfram [Tungsten]. Moscow, Metallurgy, 1978. 272 p. (In Russian).

4. Ershov V.M. Termicheskoe rasshirenie intermetallidnich faz sistemi med`-gallii [Thermal expansion of intermetallic phases of the copper-gallium system], Sbornik nauchnich trudov Donbasskogo gosudarstvennogo tehnicheskogo universiteta [Collection of scientific papers of the Donbass State Technical University]. Alichevsk, 2008, issue 27, pp. 242-247. (In Russian).

STRENGTHENING TITANIUM ALLOYS VIA IN-SITU ALLOYING IN A NITROGEN ENVIRONMENT

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Additive manufacturing holds great promise for the production of intricate parts while minimizing material waste. Gradient printing is an innovative technique that enables the creation of materials with different physical properties through the manipulation of printing parameters and material selection throughout the manufacturing process. This method entails the gradual replacement or blending of materials in a layer-

by-layer fashion, resulting in meticulously crafted objects with varying properties across their entire volume.

In this paper, we present a demonstration of the in-situ strengthening mechanism of Ti_6Al_4V by utilizing Ar-N_2 environments in the direct energy deposition process (DED). The printing process involved the alteration of the environment by introducing a reactive atmosphere with and without N_2 to fabricate a multilayer structure. We conducted an investigation to assess the influence of the reaction atmosphere on the mechanical properties of the produced materials.

Three types of samples were printed: first type was built in pure Ar, second in mixture of Ar and N_2, and the last was built during alternation of Ar and N_2. Structure of printed material were observed with SEM, XRD and EBSD. The measurements of nitrogen content in the samples were performed by the elemental analyzer. The microhardness was measured with the Vickers hardness tester.

The nitrogen content increased significantly, from 90 ppm to 9200 ppm, when N_2 was introduced into the reactive atmosphere. The resulting sample structure exhibited a needle-like morphology, with the size of the lamellae being dependent on the N_2 content. Specifically, the addition of nitrogen to the reaction atmosphere led to an increase in lamella size. Among the samples, the smallest lamellae were observed in those printed with pure Ar, while the largest lamellae were found in the structures with alternating Ar and Ar + N_2 environments. Microhardness analysis revealed average values of 554 HV for the "N_2+Ar" section, 348 HV for the "Ar" section, and 727 HV for the "alternation of Ar and Ar+N_2" section. EBSD and TEM analysis detected the presence of nitrides in the structure, with the highest concentration observed in the alternating sample. However, X-ray diffraction did not detect any nitride peaks.

Overall, microstructural analysis established a direct correlation between the lamellae size and the nitrogen content in the samples. Higher nitrogen percentages resulted in larger lamellae sizes, which in turn influenced the microhardness. Consequently, the alternating samples exhibited the largest lamella size and highest microhardness values.

DEFORMATION BEHAVIOR AND EVOLUTION STRUCTURE BELOW THE EUTECTOID TRANSFORMATION TEMPERATURE OF (α2+γ)/(α2+β+γ) γ-TiAl BASED ALLOYS WITH A METASTABLE STRUCTURE

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In the last few decades, there has been an active study of β- solidified γ-TiAl based alloys [1]. Such alloys have a high possibility for use as gas turbine engine blades in high-pressure compressors and low-pressure turbines [1]. The low ductility in a wide temperature range significantly complicates processing [2]. An improvement in mechanical properties, in particular strength and ductility, can be achieved with a decrease in the size of lamellar colonies [3]. Hot deformation makes it possible to significant refine the structure. However, hot deformation accompanied by high flow

stresses and localization of deformation, which does not allow for a high volume fraction of recrystallized/spheroidized structure. One of the ways to reduce stresses and increase the proportion of volume fraction of recrystallized/spheroidized structure is pre-heat treatment. The occurrence of a phase transformation and/or structure transformation during deformation can have a positive effect on structure. In β-solidified γ-TiAl based alloys, it is possible to obtain a metastable structure represented by α_2-phase grains at room temperature by quenching from the α/(α+β)-phase field. With further heating and deformation, $\alpha_2 \rightarrow (\alpha_2+\gamma)/(\alpha_2+\beta+\gamma) \rightarrow (\beta+\gamma)$ phase transformations occur in the upper part of the $(\alpha_2+\gamma)/(\alpha_2+\beta+\gamma)$-phase fields, depending on phase composition of the alloy. During heating, a thin lamellar structure is formed, which will be unstable in the upper part $(\alpha_2+\gamma)/(\alpha_2+\beta+\gamma)$-phase field due to the high grain boundary energy and the nonequilibrium chemical composition of the phases. In β-solidified γ-TiAl based alloys under such conditions, a cellular reaction is possible [4]. As a result, new $\alpha_2+\gamma/(\beta+\gamma)$-lamellar colonies are formed with a larger interlamellar spacing. During hot deformation of an alloy with this type of structure, active dynamic recrystallization and spheroidization occur in colonies with a larger interlamellar spacing, which leads to a decrease in flow stresses and a significant increase in the recrystallized volume. The use of pre-heat treatment makes it possible to exclude surface cracks and increase the volume fraction of recrystallized/spheroidized structure.

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References:

1. Gamma Titanium Aluminide Alloys: Science and Technology / F. Appel – Wiley-VCH Verlag & Co. KGaA, Weinheim, 2011. – 745 p.

2. Y-W. Kim: in Gamma Titanium Aluminides, Y.-W. Kim, R. Wagner, and M. Yamaguchi, eds. TMS, Warrendale, PA, 1995, pp. 637-54.

3. Cao G., Fu L., Lin J., Zhang Y., Chen C. The relationships of microstructure and properties of a fully lamellar TiAl alloy // Intermetallics 8 (2000) 647-653.

4. G.W. QIN at. all / Metallurgical And Materials Transactions A. Volume 32a, August 2001, p. 1927

MINIMIZING LAVES PHASE EVOLUTION AND ENHANCING PRECIPITATION STRENGTHENING OF SUPERALLOY-718 JOINTS

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The techniques of InterPulse magnetic constriction and high frequency pulsation of arc in gas tungsten arc welding (GTAW) were deployed to minimize intermetallic laves phase evolvement in fusion zone (FZ) of Superalloy-718 welds and enhance the precipitation strengthening of joints. The Superalloy-718 joints were developed by deploying an advanced variant of GTAW popularly known as InterPulse gas tungsten compressed arc welding (IP-GTCAW). The joints were subjected to the post weld heat treatment (PWHT) cycles of direct aging (DA), solution annealing at 980oC and 1065oC followed by aging (980STA and 1065STA) respectively. The tensile properties and hardness of joints were evaluated. The microstructures of joints were analyzed using optical (OM) and scanning electron microscopy (SEM). The elemental analysis of Laves phase and dendrite core of FZ of joints was performed by energy dispersive spectroscopy (EDS). The tensile fractured surfaces were analyzed using SEM. Results showed that the Superalloy-718 joints developed using IP-GTCAW showed better response to PWHT than GTAW joints because of the greater refining of FZ and evolvement of finer and discrete Laves phase in FZ. The 980STA joints exhibited superior tensile properties than DA and 1065STA joints. It is correlated to the greater dissolution of Laves phase in nickel austenitic (γ) matrix resulting in more niobium (Nb) accessible for the precipitation strengthening of FZ. The 1065STA joints showed slightly higher hardness of FZ than 980STA joints because of the almost complete dissolution of Laves phase in FZ. However, the tensile properties of 1065STA joints are lower than 980STA joints because of severe grain growth in FZ and BM. The evolvement of microvoids at the interface of Laves phase/weld matrix leading to development and coalescence of microcracks in FZ on tensile loading is main mechanism responsible for the premature fracture of joints.

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THE MANUFACTURING TECHNOLOGY OF THE LEADING PROTECTIVE EDGE BY DIFFUSION WELDING AND SUPERPLASTIC FORMING

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One of the promising directions in the development of turbofan engines is the use of carbon fiber fan blades with a protective cover of the inlet edge made of titanium alloy. Among the many technologies for the manufacture of protective linings , the method stands out (patent US20050278950) diffusion welding followed by superplastic forming (DW/SPF), having a disadvantage in the form of a characteristic sharpening in the inner cavity of the edge. In the development of the method DW/SPF by the firm «FormTech» a technology has been proposed that increases the resistance of the lining itself from erosion wear by introducing an intermediate layer of an intermetallic alloy with increased hardness (Patent Nr. 10 2010 032 097.8). Combining and developing both ideas, a new method of obtaining a protective lining is proposed.

This method involves pre-milling of the initial blanks of the back of the trough, installing an alloy layer between them VTI-4 and steel wire, which ensures the formation of the inner radius during the diffusion welding operation. A barrier coating is applied to surfaces that are not subject to diffusion welding. After sealing operations of the assembled package and DW/SPF, at the stage of trimming the overlays, the wire is removed.

Diffusion welding of alloys VT6 и VTI-4 it is accompanied by mutual penetration of redundant components with the formation of intermediate layers according to the law of increasing the entropy of the system.

The shape of the blanks is optimized by finite element analysis, the efficiency of the method is verified by field experiments.

References:

1. Karimbaev T.D., Luppov *A.A., Petrov Yu.A., Ezhov Yu.A., Afanas'ev D.V. Turbomachine composite material blade. Patent for an invention RU № 2350757, 27.03.2009. Application: 2007134993/06, 21.09.2007.*

2. Jean-Louis Despreaux, Jean-Michel Franchet, Philippe Joffroy, Gilles Klein, Stephane Leveque, Daniel Lhomme, Alain Lorieux. Process for manufacturing a reinforcing leading or trailing edge for a fan blade. Patent for an invention US20050278950A1, 22.12.2005.

3. Astanin V.V., Berdin N.V., Lukyanov V.V., Starovojtov S.V., Utkin A.Yu., Karimbaev T.D., Chernyshov A.A. Manufacturing method of leading protective edge for fan blade. Patent for an invention RU № 2711697, 21.01.2020. Application: 2019111210, 15.04.2019.

STRUCTURE AND MECHANICAL PROPERTIES OF Co-Cr-Fe-Mn-Ni-(Al, C) and Nb-Ti-Zr-(Al, Cr, Hf, Ta, V) HIGH ENTROPY ALLOYS

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The so-called high entropy alloys (HEAs) are widely considered as promising materials for a variety of structural and functional applications. However, there are still plenty of questions regarding nearly all aspects of behavior, including the dependence of phase composition on chemistry, the phase stability, strengthening mechanisms (especially solid solution strengthening), etc. In addition, there is a huge interest in detailed comparison of the properties of HEAs with their state-of-art competitors from "conventional" alloys.

Here, we first briefly overview the landscape of the available structures in different HEAs depending on their chemical composition and presented a tentative classification. The classification separates 2 main classes of the alloys depending on their chemical composition, namely the alloys based on transition metals of 3d group and refractory metals, respectively. In terms of structure, the following classes are proposed: (i) single substitutional solid solution alloys, (ii) precipitation and dispersion-hardened alloys, (iii) multiphase alloys, (iv) single intermetallic phase alloys, (v) multiple intermetallic phase alloys.

Then we focus on the mechanical behavior of the single solid solution phase alloys with fcc (Co-Cr-Fe-Mn-Ni system) and bcc (Hf-Nb-Ta-Ti-Zr) structures. We demonstrate that the strength variations in such alloys can be associated with the solid solution hardening and the variation of the well-known Labush approach can be extended to predict solid solution hardening in multicomponent solid solutions. We also reveal the manifestation of the so-called stress equivalence in such alloys. We show that, in addition to dislocation slide, the plastic deformation is associated with the mechanical twinning and shear band formation in fcc alloys and kink bands formation – in bcc alloys.

Then, we focus on the stability of the solid solutions in the fcc CoCrFeMnNi and bcc HfNbTaTiZr and the approaches to predict the phase transformations in HEAs. We show that single phase structure of both CoCrFeMnNi and HfNbTaTiZr is thermodynamically unstable under certain conditions and formation of multiple secondary phases can be anticipated. We emphasize the validity of the CALPHAD predictions of phase transformations in both alloys.

Finally, we show applicability of CALPHAD approach for the design of new HEAs with promising properties, including (i) fine-grained fcc Co-Cr-Fe-Mn-Ni-C alloys, reinforced with carbides, for cryogenic applications; (ii) bcc+B2 structured Al-Cr-Fe-Mn-Ni alloys for intermediate (≤600˚C) applications; low-density Al-Cr-Nb-Ti-V-Zr alloy with B2 or eutectic B2+Laves structure for high-temperature applications. Extensive comparison of the developed HEAs with commercial alloys is presented.

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HOT DEFORMATION BEHAVIOR AND MICROSTRUCTURE EVOLUTION OF TI-6.5AL-2ZR-1MO-1V/TIB METAL-MATRIX COMPOSITES

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High specific strength, technological plasticity and corrosion resistance allow titanium alloys to occupy a special place in the aviation and shipbuilding industries [1]. Maximum operating temperature of titanium alloys does not exceed 550-600 ºC due to a noticeable decrease in strength. Ti-6.5Al-2Zr-1Mo-1V belongs to the pseudo-alpha class; this alloy is used for the manufacture of hull structures operating temperature up to 500 ºC [2]. Increasing the heat resistance to ~600°C of this alloy would significantly expand the scope of these materials by replacing heavier steels and nickel alloys [1–3]. The influence of alloying TiB (2.0, 6.0 and 10.0 vol. %) on the microstructure and mechanical properties of the Ti-6.5Al-2Zr-1Mo-1V alloy has been studied. The alloy was obtained by vacuum-arc melting. The addition of TiB led to the formation of boride particles in the two-phase α+β structure. The mechanical properties of the alloys were obtained in the temperature range 400-950°C. With an increase in the TiB content, an increase in strength and a slight decrease in ductility were observed at its maximum content. During hot deformation, intensive refinement of the structure occurred. A twofold increase in strength was achieved at a temperature of 950°C for an alloy with vol. 10 % of TiB compared to the base alloy.

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References:

1. C. Leyens, M. Peters, Titanium and Titanium Alloys: Fundamentals and Applications, WileyVCH: Weinheim, Germany, 2003. https://doi.org/10.1002/3527602119

2. Q.J. Sun, X. Xie, Microstructure and mechanical properties of TA15 alloy after 433 thermomechanical processing, Mater. Sci. Eng. A 724 (2018) 493-501. https://doi.org/10.1016/j.msea.2018.03.109

3. Z. Sun, H. Yang, Microstructure and mechanical properties of TA15 titanium alloy 436 under multi-step local loading forming, Mater. Sci. Eng. A 523(1-2) (2009) 184-192. https://doi.org/10.1016/j.msea.2009.05.058

HIGH-ENTROPY CARBONITRIDE CERAMICS: POWDER SYNTHESIS AND SPARK PLASMA SINTERING

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The interest in nitrides and carbonitrides of transition metals (Ti, Zr, Hf, V, Nb, Ta) is due to an exceptional set of their properties: high melting point, hardness, wear resistance, chemical stability, and oxidation resistance [1]. The emergence of their high-entropy (HE) modifications, which exhibit superior properties due to entropy stabilization, is viewed as a promising alternative to binary compounds [2]. Such materials can be used in the manufacture of various heat-loaded elements and structures that operate at extreme temperatures and intense oxidation, as well as thermal insulation and fuel elements. At present, few works have been devoted to the study of refractory high-entropy carbonitrides [3, 4]. The most common method for their production involves the long-term sintering of a mixture of carbides and nitrides from individual compounds in a spark plasma sintering unit.

In this work, the single-phase (Hf,Ta,Nb)(C,N), (Hf,Ta,Nb,Zr)(C,N), and (Hf,Ta,Nb,Ti)(C,N) powders and bulk carbonitride ceramics were obtained by mechanically activated combustion synthesis combined with a spark plasma sintering process. The mechanical properties of HE carbonitrides, including high-temperature compressive strength, were studied. The values varied from 300 to 420 MPa at 1600 °C and from 220 to 280 MPa at 1800 °C depending on the composition of the sample.

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References:

1. Sengupta P., Manna I. Advanced high-temperature structural materials for aerospace and power sectors: a critical review //Transactions of the Indian Institute of Metals. – 2019. – T. 72. – №. 8. – C. 2043-2059.

2. Zhang R. Z., Reece M. J. Review of high entropy ceramics: design, synthesis, structure and properties //Journal of Materials Chemistry A. – 2019. – T. 7. – №. 39. – C. 22148-22162.

3. Peng Z. et al. Novel refractory high-entropy ceramics: Transition metal carbonitrides with superior ablation resistance //Corrosion Science. – 2021. – T. 184. – C. 109359.

4. Wang Y. et al. Synthesis, microstructure, and mechanical properties of novel high entropy carbonitrides //Acta Materialia. – 2022. – T. 231. – C. 117887.

PROMISING RESEARCH DIRECTIONS IN THE FIELD OF HIGH-ENTROPY MATERIALS

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The report is devoted to the current state of theoretical and experimental research in the field of synthesis and application of high-entropy phases in various groups of materials.

The authors present and analyze their own and literature data on the synthesis methods, structural analysis, properties, and potential applications of different high-entropy materials. This report is mainly focused on the new and most promising research areas in the field of high-entropy materials.

In particular, new achievements in the field of synthesis and properties of high-entropy non-metallic materials with the aim of obtaining new structural and functional materials, as well as highly efficient catalysts are considered.

The results of the preparation and investigation of composite materials composed of high-entropy phases as matrix or reinforcement phase, as well as the preparation and study of coatings based on such materials, are presented.

The possibilities of using severe plastic deformation for modification of the structure and properties of high-entropy alloys are demonstrated.

Moreover, the development of welding processes for high-entropy alloys are also considered.

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INVESTIGATION OF THE EFFECT OF MAGNESIUM AND ZINC ON THE STRUCTURE AND MECHANICAL PROPERTIES OF Al–2%Cu–1.5%Mn ALLOY SHEETS

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The latest developments in the automotive industry, the rapid growth of cities, the use of aluminum as a substitute for copper in the energy sector – these and many other trends will allow aluminum to consolidate its leading position as a key material of our time [1-3]. Therefore, increasing the mechanical characteristics of deformable aluminum alloys is an important task.

In this study, the influence of magnesium and zinc on the mechanical properties and structure of a heat-resistant alloy of the Al-2Cu-1.5Mn system was studied using the example of cold-rolled sheets. Initially, ingots of 5 compositions were obtained by casting

into a graphite mold with dimensions of 10x40x180 mm. Ingots of experimental alloys were subjected to hot rolling to a thickness of 2 mm at a temperature of 400 °C. Then the hot-rolled sheets were annealed at a temperature of 350 °C for 3 hours, after which cold rolling was carried out to a thickness of 0.5 mm. The microstructure of the samples cut from ingots and sheets was studied using light and electron scanning microscopes. To assess the contribution of heat treatment to the structure and physico-mechanical properties, multistage annealing of sheets and ingots of experimental alloys was carried out. After each annealing stage, the hardness and electrical conductivity of the samples were measured. The tensile strength, yield strength and elongation of cold-rolled sheets were determined by the method of tensile testing on a universal machine.

It was found that in the cast state, zinc is completely contained in an aluminum solid solution, magnesium partially enters the eutectic particles of the Al_2CuMg phase, and after annealing at temperatures above 400 °C completely dissolves in (Al). Magnesium and zinc practically do not affect the amount of the $Al_{20}Cu_2Mn_3$ phase, which is formed during deformation and heat treatment in the form of nanoscale dispersoids. It was found that the addition of 1% magnesium increases the strength of cold-rolled sheets of the base alloy by 15% after 3-hour annealing at 400 °C, without reducing the plasticity.

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References:

1. Ashkenazi D. How aluminum changed the world: A metallurgical revolution through technological and cultural perspectives. Technol. Forecast. Soc. Chang. 2019, 143, 101–113.

2. Pedneault, J., Majeau-Bettez, G., Pauliuk, S., Margni, M. Sector-specific scenarios for future stocks and flows of aluminum: An analysis based on shared socioeconomic pathways. J. Ind. Eco. 2022, 26, 1728–1746.

3. Zheng, K., Politis, D. J., Wang, L., Lin, J.A. review on forming techniques for manufacturing lightweight complex—shaped aluminum panel components. Int. J Light. Mater. Manuf. 2018, 1, 55-80.

THERMAL STABILITY OF A REFRACTORY Al7.5(NbTiZr)92.5 MEDIUM-ENTROPY ALLOY WITH A BCC+B2 STRUCTURE

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One of the new directions in the development of high-performance refractory high/medium-entropy alloys is controlling the degree of B2 ordering through appropriate alloying. Previous studies have shown that certain additions of Al to the well-known single-phase bcc (body-centered cubic) refractory NbTiZr medium-entropy alloy can simultaneously enhance its strength and uniform elongation up to 40 % due to B2 (an ordered variant of the bcc phase) nanodomain strengthening and changing dislocation glide character. However, it is worth mentioning that prolonged use of the material at potential operation temperatures can cause alterations of its phase composition, resulting

in the degradation of mechanical properties. Unfortunately, there is almost no data revealing thermal stability of refractory high/medium entropy alloys with tensile ductility.

The purpose of this study was to investigate the phase stability of a ductile refractory $Al_{7.5}(NbTiZr)_{92.5}$ (at.%) medium-entropy alloy, which initially possessed a structure comprising of a bcc matrix and homogeneously distributed B2 nanodomains. Additionally, the study aimed to analyse the evolution of the mechanical properties as a result of long-term annealing at different temperatures. The effect of the annealing temperature on the mechanical properties and structure of the alloy was thoroughly discussed.

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LASER AND ADDITIVE TECHNOLOGIES FOR INDUSTRY

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Laser and additive manufacturing technologies are revolutionizing the industrial landscape. These techniques offer unparalleled precision, efficiency, and flexibility in creating complex components. Laser technology is widely used for cutting, welding, and engraving materials, while additive manufacturing, commonly known as 3D printing, builds objects layer by layer from a digital model. The integration of these technologies allows for rapid prototyping and the production of custom parts in small batches. Industries such as aerospace, automotive, and healthcare are increasingly adopting these methods for their high-quality output and cost-effectiveness. Moreover, the use of lasers in additive manufacturing enables the creation of intricate geometries that are otherwise difficult to achieve. The combination of laser and additive technologies is paving the way for Industry 4.0, characterized by automation, data exchange, and smart manufacturing systems.

Here, we show experience in the use of direct laser deposition technology in real sectors of production, as well as experience in the implementation of equipment for laser and additive manufacturing technologies in industry. We also show applicability of laser and additive manufacturing technologies for production of large-scale items. We demonstrate the latest advances in laser technology development, in particular, in the field of obtaining new materials with unique structures and properties.

USE OF THE MONTE-CARLO METHOD TO CALCULATE THE PERCENTAGE RATIO OF METALS IN ION-PLASMA COATINGS OF THE TiAlVZrCr SYSTEM DEPOSITED ON Ti-6Al-4V TITANIUM ALLOY WITH UFG STRUCTURE

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In aircraft engine building, titanium alloys with high mechanical properties are used for the manufacture of critical parts. However, high loads and erosive wear lead to the need to use methods that increase the strength properties of both the base material of the product and the surface.

In the last decade, ultrafine-grained titanium alloys obtained by methods of severe plastic deformation are of particular interest due to their enhanced physical and mechanical properties [1]. A promising direction for improving the properties of protective coatings is the use of high-entropy alloys (HEA) in them, consisting of at least 5 basic elements, the mixing of which leads to an increase in performance, in view of the features of structural-phase transformations of HEA [2].

To develop the optimal coating architecture, there are a number of methods for calculating the thickness and percentage composition of the applied ion-plasma coating - geometric, simulation (including Monte-Carlo) and based on the laws of thermal radiation. All three approaches demonstrated satisfactory results in comparison with experimental data, however, in the considered works, the number of metals does not exceed three. In this regard, the assessment of the possibility of using Monte Carlo models to calculate the composition of the applied coating is of scientific interest.

In this work, we used the previously described [3] approach to constructing a computational model, and as a sample for the experiment, we chose a simulator of a blade, on which an ion-plasma coating of the TiAlVZrCr system was deposited in an NNV-6,6-I1 vacuum unit.

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References:

1. Valiev R. Z., Zhilyaev A. P., Langdon T. G. Bulk nanostructured materials: fundamentals and applications. – John Wiley & Sons, 2013.

2. George, E.P. et al. High-entropy alloys. Nat. Rev. Mater. 2019, 4, 515–534.

3. Oleinik A.V., Ramazanov K.N., Determination of the dependence of the non-uniformity of the thickness of the coating from the vacuum-arc discharge plasma on the geometric parameters of the interblade channel // Problems of mechanical engineering and automation, 2022, No. 4, P. 71-77.

HIGH-STRENGTH STATES IN ULTRAFINE-GRAINED HIGH-ENTROPY ALLOYS PROCESSED BY SEVERE PLASTIC DEFORMATION

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Over recent years, much attention has been focused on achieving ultrahigh strength in metallic materials using severe plastic deformation (SPD) techniques. Such techniques allow the formation of ultrafine-grained (UFG) structure in various materials and alloys, and lead to the precipitation of nanoparticles and segregations of alloying elements at grain boundaries [1].

In the present report, these approaches are applied to engineer high-strength states in high-entropy materials. Based on the literature data and our own research results, the microstructural states determining the strength enhancement in these alloys are considered, the strength mechanisms are discussed, and the prospects for application of such unusual materials are discussed.

References:

1. R.Z. Valiev, B. Straumal, T.G. Langdon, Using severe plastic deformation to produce nanostructured materials with superior properties, Annual Review of Materials Research 52 (2022) 357

LOW-TEMPERATURE SYNTHESIS OF HIGH-ENTROPY CARBIDE IN MOLTEN SALTS

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The low temperature synthesis of high-entropy carbide $(Ti_{0.2}Zr_{0.2}Nb_{0.2}Hf_{0.2}Ta_{0.2})C$ was performed in the ionic melt. The method is based on the phenomenon of currentless transfer of metal to carbide of another metal through the molten salt [1].

In a series of standard electrode potentials relative to the reference chlorine electrode in the NaCl-KCl melt (1:1 mol.) at 1000 K [2], niobium and tantalum take the places of the most electropositive metals, zirconium and hafnium are the most electronegative ones. Titanium takes a position between these pairs. Thus, it is possible to create conditions, described in [3], for the step-by-step transfer to titanium carbide first of niobium and tantalum, and then of zirconium and hafnium. In order to receive one phase material the powder obtained during the synthesis was heated twice in a vacuum furnace to a temperature of 1733K.

Bulk pellets were made out from the XH77TUR alloy powder with the additions of 2, 5. 10, 20% high-entropy carbide powder. Vacuum sintering of pressed mixed powders was performed at a temperature of 1473K. Sintered samples was studied by microhardness measurements.

References:

1. Varaksin A.V., Petrova S.A., Rempel A.A. Method for obtaining high-entropy carbide in an ionic melt // Melts. - 2023. - №4. - P. 396-405.(in Russian).

2. M. V. Smirnov, Electrode Potentials in Fused Chlorides (Nauka, Moscow, 1973), pp. 109–110 (in Russian).

3. N. G. Ilyushchenko, Interaction of metals in ionic melts (Nauka, Moscow, 1991), pp 12-15 (in Russian).

THE WAY OF INCREASING PRODUCTION OF HIGH-ENTROPY CARBIDE TiZrNbHfTaC5 BY VACUUM-FREE ELECTRIC ARC METHOD

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In recent years, we see the interest of new materials with properties that meet the growing demand for strength, durability and resistance to aggressive operating conditions. One of the promising directions is obtaining high-entropy ceramics. High-entropy ceramics is a solid solution of four or more major transition metal carbide components in nearly equiatomic ratios or at least with the content of each element from 5 to 35 at. % in a single-phase structure. High-entropy metal carbides (HEC) have attracted tremendous attention for potential applications in various fields such as aerospace, cutting tools, microelectronics and nuclear reactors. There are several methods of obtaining high-entropy ceramics. Predominantly, the synthesis is performed by ball milling followed by sintering in spark plasma or by reactive high-energy ball milling [1].

Vacuum-free electric arc method is considered promising for synthesis of different carbides and borides [2-3]. This method provides the synthesis of materials in electric arc plasma in the open-air environment, which is possible as a result of the self-shielding effect of the reaction zone by the emitted carbon monoxide and carbon dioxide gases. So, there is no need to use a sealed chamber, vacuum equipment and other additional systems for providing an inert environment, which allows simplifying the arc reactor and synthesis methodology, and increasing energy efficiency.

In this work we successfully carried out experiments to scale up the process of vacuum-free electric arc synthesis of high-entropy carbide $TiZrNbHfTaC_5$. For this purpose, we modernized electric arc reactor, namely, increased the power supply and changed discharge circuit. After modernization we can process up to 5 g of initial powder, which is more than in our previous experiments in 10 times [4]. At the same time, the yield of powder containing HEC phase was 95 ± 2 %. The increase in the production of high-entropy carbides by the vacuum-free electric arc method is an important step towards scaling up this method to industry.

The research was funded by the Russian Science Foundation project number 21–79-10030.

References:

1. Oses C., Toher C., Curtarolo S. High-entropy ceramics // Nature Reviews Materials. – 2020. – V. 5. – №. 4. – P. 295-309.

2. Pak A. Y. et al. Vacuumless synthesis of tungsten carbide in a self-shielding atmospheric plasma of DC arc discharge // International Journal of Refractory Metals and Hard Materials. – 2020. – V. 93. – P. 105343.

4. Pak A. Y. et al. Efficient Synthesis of WB5–x–WB2 Powders with Selectivity for WB_{5-x} Content // Inorganic Chemistry. – 2022. – V. 61. – №. 18. – P. 6773-6784.

5. Pak A. Y. et al. Machine learning-driven synthesis of $TiZrNbHfTaC_5$ high-entropy carbide // npj Computational Materials. – 2023. – V. 9. – №. 1. – P. 7.

AN INSIGHT INTO OXIDATION RESISTANCE OF HIGH-ENTROPY ALLOYS

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High-entropy alloys (HEA) have a unique set of mechanical and technological High-entropy alloys (HEAs) typically exhibit a unique set of mechanical properties such as a combination of high strength and ductility, high mechanical properties at elevated temperatures, increased fatigue resistance, high hardness/wear resistance, and high thermal stability [1-2]. The complex of HEAs properties makes it possible to consider them as materials suitable for manufacturing of parts operating at difficult conditions - parts of gas turbines, turbojet and jet engines, etc. These possible high-temperature applications of HEAs makes it relevant to assess the resistance of HEAs against high-temperature oxidation.

The paper studies the oxidation behavior of five alloys belonging to the systems AlxCoCrFeNiM (where M = Cu, Ti, V, Mn and Si) at temperatures between 700 to1000 °C in air atmosphere. In addition to experimental studies, the possibility of thermodynamic modeling of the processes occurring during oxidation is discussed in order to predict the composition of the resulting oxide products. The microstructures of the alloys were experimentally studied before and after the samples were oxidized for 10 hours at 700-1000°C. The compositions of the resulting oxide products and the kinetic of the oxidation process have been studied. The results of the study show that among the materials studied, Al0.45CoCrFeNiSi0.45 HEA exhibits the highest resistance to high-temperature oxidation due to the formation of protective oxide layers based on Al2O3, SiO2 and mulite (2Al2O3 · SiO2). At the same time, Al0.25CoCrFeNiCu HEA also showed high resistance to high-temperature oxidation. Alloys with additions of Ti, V, and especially Mn showed a rather low resistance to oxidation at elevated temperatures. This is probably due to the fact that during the oxidation process, protective films based on aluminum oxide could not be formed, and instead loose layers of transitions metal oxides are formed on the surface of the samples.

References:

1. Shaburova, N.A. High-temperature oxidation behavior of AlxCoCrFeNiM (M=Cu, Ti, V) high-entropy alloys / N.A. Shaburova, A. Ostovari Moghaddam, S.N. Veselkov, M.V. Sudarikov, O.V. Samoilova, E.A. Trofimov // Physical Mesomechanics. – 2021. – V. 24, № 6. – P. 653-662.

2. Ostovari Moghaddam, A. High temperature oxidation resistance of $Al_{0.25}$CoCrFeNiMn and $Al_{0.45}$CoCrFeNi$Si_{0.45}$ high entropy alloys // Vacuum. – 2021. – V. 192, № 5 – 110412.

PREDICTION OF ELONGATION TO FRACTURE OF HIGH-ENTROPY ALLOYS USING NEURAL NETWORK

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High-entropy alloys, also known as multi-element alloys, were originally discovered by Ye [1] and Cantor [2]. Unlike traditional alloys based on one basic element, high-entropy alloys contain five or more basic elements in equal or almost equal atomic percentages (5-35 at.%). Such alloys are characterized by increased mixing entropy values compared to traditional multicomponent alloys. In this regard, instead of forming complex phases, simple solid solutions with FCC or BCC lattices are formed. This class of materials has increased mechanical properties, such as high strength, hardness, corrosion resistance[3].

Deep learning approaches (artificial neural networks) are promising techniques for the development of new high-entropy alloys with given mechanical characteristics. An artificial neural network approach was used to predict the elongation in compression test of high-entropy alloys. A data set of 153 alloys was used to train an artificial neural network of various configurations. Among the various configurations, the model with 2 hidden layers of 14 neurons in each layer showed the best accuracy. The error of this model was 6%. In order to improve accuracy, optimization of hyperparameters of the network was used. The algorithm showed an accuracy of 4%.

This work was carried out using equipment of the Joint Research Center of Belgorod State National Research University «Technology and Materials».

References:

1. Yeh J. W. et al. Nanostructured high entropy alloys with multiple principal elements: novel alloy design concepts and outcomes //Advanced Engineering Materials. – 2004. – T. 6. – №.5. – C. 299–303.

2. B. Cantor, I.T.H. Chang, P. Knight, A.J.B. Vincent, Microstructural development in equiatomic multicomponent alloys, Mater. Sci. Eng. A. 375–377 (2004) 213–218. https://doi.org/10.1016/j.msea.2003.10.257.

3. T.S. Srivatsan, Manoj Gupta High Entropy Alloys: Innovations, Advances, and Applications. - 2020 – 758 p.

ALUMINUM ALLOYS IN ADDITIVE MANUFACTURING. HEAT TREATMENT OF ALUMINUM ALLOYS

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Reducing the weight of structures used in aircraft and space industry, mechanical engineering and shipbuilding is an important problem of modern industry. In this connection, light alloys based on aluminum are of particular interest. Additive manufacturing with aluminum alloys is of even greater interest, as it offers almost unlimited design freedom, which is especially important for weight reduction applications. However, additive materials have a number of structural features that have a negative impact on mechanical properties. As a result, additively manufactured products may have poor mechanical properties. The microhardness value in the initial state is 47 HV. The yield strength, tensile strength, as well as the relative elongation of the sample in the initial state are 122 MPa, 246 MPa and 18%, respectively. The tensile strength of additively manufactured samples is on average 4-5% (12-14 MPa) less than the values regulated by GOST 17232-99.

One of the simplest and most common methods for improving mechanical properties is heat treatment. In the work, various modes of hardening and aging of the AMg5 aluminum alloy obtained by wire arc additive manufacturing were tested. The mode of 480 ºC for 120 min was chosen as the optimal mode of hardening. This mode contributes, on the one hand, to some homogenization of the alloy at the boundary of the welding beads; on the other hand, this mode provides a slight grain increase by 13% (10 μm), the optimal microhardness value is 64 HV, exceeding the microhardness value in the initial state by 36% (17 HV). Subsequently, the alloy quenched at 480°C for 120 min was subjected to aging. The maximum obtained microhardness value is 67 HV for aging at a temperature of 210 ºC for 20 hours. Moreover, as a result of aging at a temperature of 210 ºC for 20 hours, it was possible to increase the tensile strength by 10% and the relative elongation by 38% compared to the initial state material. The maximum value of the tensile strength was 271 MPa, relative elongation - 25%. The obtained values exceed the corresponding values presented in GOST 17232-99 by 4% (11 MPa) and 108%, respectively. The considered regimes of aging and hardening do not lead to grain enlargement or to the formation of coarse brittle intermetallic compounds of irregular morphology.

SYNTHESIS, PHASE STABILITY, AND MAGNETIZATION BEHAVIOR OF NEW HIGH-ENTROPY HEXAFERRITES

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The polycrystalline $SrFe_{12}O_{19}$ samples deeply substituted up to at. 67% by Al^{3+}, Ga^{3+}, In^{3+}, Co^{3+}, and Cr^{3+} cations with a high configurational mixing entropy were prepared by solid-phase synthesis. Phase purity and unit cell parameters were obtained from XRD and analyzed versus the average ionic radius of the iron sublattice. The crystallite size varied around 4.5 μm. A comprehensive study of the magnetization was realized in various fields and temperatures. The saturation magnetization was calculated using the Law of Approach to Saturation. The accompanying magnetic parameters were determined. The magnetic crystallographic anisotropy coefficient and the anisotropy field were calculated. All investigated magnetization curves turned out to be nonmonotonic. The magnetic ordering and freezing temperatures were extracted from the ZFC and FC curves. The average size of magnetic clusters varied around 350 nm. The high values of the configurational mixing entropy and the phenomenon of magnetic dilution were taken into account [1].

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References:

1. Zhivulin, V.E., Trofimov, E.A., Zaitseva, O.V., Sherstyuk, D.P., Cherkasova, N.A., Taskaev, S.V., Vinnik, D.A., Alekhina, Y.A., Perov, N.S., Naidu, K.C.B., Elsaeedy, H.I., Khandaker, M.U., Tishkevich, D.I., Zubar, T.I., Trukhanov, A.V., Trukhanov, S.V. Preparation, phase stability, and magnetization behavior of high entropy hexaferrites (2023) iScience, 26 (7), № 107077, DOI: 10.1016/j.isci.2023.107077

ORIENTATION DEPENDENCE OF MECHANICAL BEHAVIOR OF THE (COCRFENI)96MO4 HIGH-ENTROPY ALLOY SINGLE CRYSTALS

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Temperature dependence of the critical resolved shear stresses (CRSS) τ_{cr}, the deformation mechanism (slip and twinning), the strain hardening coefficient θ and plasticity δ were studied on [001]-, $[\bar{1}11]$ and $[\bar{1}44]$- oriented crystals of the fcc $Co_{24}Cr_{24}Fe_{24}Ni_{24}Mo_4$ ($(CoCrFeNi)_{96}Mo_4$) (at.%) high-entropy alloy (HEA) under tension.

The $(CoCrFeNi)_{96}Mo_4$ (at.%) HEA was obtained by alloying with Mo atoms up to 4 at.% by reducing the concentration of each element of the fcc equiatomic CoCrFeNi HEA in equal atomic percentages. Alloyed with Mo atoms up to 4 at.% of the $(CoCrFeNi)_{96}Mo_4$ (at.%) HEA was characterized by the stacking fault energy γ_0=0.027 J/m^2 and slight increase in τ_{cr} relative of the equiatomic CoCrFeNiMn HEA: by 15 MPa at T=77 K and by 11 MPa at T=296 K. The onset of plastic flow (0.1 % offset yield stress $\sigma_{0.1}$) along studied orientations of the $(CoCrFeNi)_{96}Mo_4$ (at.%) HEA was associated by slip, the CRSS for slip τ_{cr}^{sl} were independent on crystal orientation and the Boas-Schmid law was fulfilled.

The influence of the crystal orientation on the strain hardening coefficient θ and plasticity ε, which are determined by the deformation mechanism (slip/twinning) and the number of active slip or twinning systems, was established. At T=296 K, in the $(CoCrFeNi)_{96}Mo_4$ (at.%) HEA, the main deformation mechanism that determines the mechanical behavior, orientation dependence θ and plasticity ε is slip. The maximum θ = 1300 and 1950 MPa was found in [001] and $[\bar{1}11]$ orientations, respectively, oriented for multiple shear. The maximum plasticity δ=70 % was found in $[\bar{1}44]$-crystals oriented for shear in one system. At T=77 K, the orientation dependence of mechanical behavior were determined by slip and twinning. With the development of twinning in several systems in $[\bar{1}11]$-crystals, the maximum θ = 1900 MPa was observed, whereas the development of twinning in one system at the same time with slip in $[\bar{1}44]$-crystals led to decrease in θ = 1050 MPa and an increase in plasticity ε = 106%. Plasticity in $[\bar{1}11]$-crystals was 52 %. Twinning was not detected in [001]-crystals and the mechanical behavior was determined by slip. In this case the strain hardening coefficient θ=1300 MPa and plasticity δ = 30 % did not depend on the test temperature.

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QUASI-HIGH-ENTROPY ALLOYS FOR HYDROGEN ABSORPTION

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High-entropy alloys (HEA) based on refractory transitional metals (Ti, Zr, Hf, V, Nb, and Ta) may become promising materials for gas absorption (getters) owing to that they contain elements which actively interact with hydrogen and other gases (O, N). HEAs based on such metals possess a BCC lattice where hydrogen can dissolve immensely.

It can be proposed that if we manufacture a multi-phase structure of such HEA consisting of the sequence of BCC lattices with different lattice parameters and, therefore, of various compositions, this HEA might have the fastest absorption rate among others. That assumption is based on two things: 1) phases with a large cell parameter, obviously, will be enriched with Zr, Hf, and Ti, which have high affinity for hydrogen and possess large tetrahedral interstices; therefore, hydrogen should dissolve into these BCC metals actively and in large quantities without strong cell distortions; 2) on account of quantum tunnel effect, hydrogen can rapidly diffuse in a BCC lattice with a small lattice parameter due to small distance between tetrahedral interstices. Consequently, some BCC lattices (large cell parameter) accumulate hydrogen actively, and others (small lattice parameter) provide hydrogen mobility within the structure.

In the framework of the current research, quasi-high-entropy TiZrHfNbTa alloy has been synthesized through the metallothermic (calcium-hydride) method with the application of metals oxides and calcium hydride (CaH_2). The alloy has four BCC lattices with parameters 3.320, 3.336, 3.379, and 3.419 Å. It has been established that the alloy starts to absorb hydrogen when the temperature approaches 200 °C. The interaction rate of the powder and hydrogen follows the second-order chemical reaction, and appeared activation energy was estimated as ~102 kJ/mol.

It has been shown that during absorption, hydrogen preferably dissolves in BCC phases with cell parameters of 3.379 and 3.419 Å, and hydrogen concentration riches $H/M \approx 0.5$ (33.3 % at.).

Also, an important characteristic of the new quasi-high-entropy getter is the activation temperature, which is 400 ºC. In comparison, traditional Ti-V-based getters have an activation temperature of over 500 ºC.

The study was carried out with the financial support of the Moscow Polytechnic University within the framework of the Kapitsa's grant program

EFFECT OF CHEMICAL COMPLEXITY ON THE STRUCTURE, MECHANICAL PROPERTIES, AND OXIDATION RESISTANCE OF REFRACTORY Nb-Ti-Zr-Cr ALLOYS

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Since the inception of the high-entropy alloys (HEAs) concept, a strong belief has emerged that chemical complexity inevitably led to exceptional properties. Specifically, single-phase refractory HEAs (RHEAs) with a multicomponent bcc/B2 matrix appear to be much stronger compared to conventional refractory alloys, while multiphase RHEAs containing large volume fraction of intermetallics can outperform nickel-based superalloys in specific strength. Oxidation resistance, one of the most important features for potential high-temperature service, also benefits from the chemical complexity. However, studies revealing the systematic changes in the structure, mechanical properties, and oxidation resistance due to the increasing number of constitutive elements have not been performed yet.

In this study, we accomplished a comprehensive analysis of the structure, mechanical properties, and oxidation resistance of binary Nb-Cr, ternary NbTi-Cr, and quaternary NbTiZr-Cr alloys depending on the Cr content. Quaternary alloys were found to have the highest strength at room-temperature and decent oxidation resistance at 1000 °C. Simultaneously, binary alloys were stronger at 800 °C yet could not withstand the oxygen attack and disintegrated rapidly. Ternary alloys showed the best oxidation resistance and the 800 °C-strength comparable to quaternary counterparts. Composition-structure-property relationships were thoroughly discussed.

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STRUCTURE AND PROPERTIES OF A COMPOSITE COATING BASED ON A HIGH-ENTROPY ALLOY REINFORCED WITH CrB PARTICLES

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One of the effective methods of extending the service life of the materials is the formation of surface protective coatings from alloys with the necessary complex of operational properties on a cheaper base material. In this paper, the structure and properties of protective coatings based on the high-entropy alloy CoCrFeMnNi,

reinforced with chromium boride particles obtained by non-vacuum electron beam surfacing, were investigated.

The surfacing was carried out on an industrial electron accelerator ELV-6 (INP SB RAS). Particles of CrB is added in the amount of 0 % ... 30 % from the mass of the equiatomic mixture of the elements Co, Cr, Ni, Mn. Fe entered the melt bath during the melting of the steel base (plates with a size of 100×50×10 mm^3). CaF_2 powder (30% of the total weight) was used as a flux. The density of the powder mixture was 0.8 g/cm^2, the speed of the workpiece was 15 mm/sec, the electron beam current was 25 mA, the accelerating voltage was 1.4 MV.

The thickness of the deposited layers was ~ 1 mm. Dendritic inhomogeneity is clearly revealed in the structure of all coatings, and with an increase in the concentration of chromium boride, the structure of coatings consists of a matrix of a high-entropy alloy and a large number of grains of primary and secondary borides of various shapes and sizes.

The results of X-ray phase analysis confirm the formation of a solid solution with an FCC crystal lattice in all samples. With an increase in the number of hardening particles, peaks of boride phases with the space group Fddd (Cr_2B, Mn_2B, $(Cr,Fe)_2B$, $(Cr,Mn)_2B$), Cmcm (CrB), I4/mcm (Mn_2B) are registered on x-ray patterns.

The mechanical properties of the coatings were evaluated by measuring the microhardness with Vickers method. The average microhardness of the coating without the addition of CrB was 192 HV. The introduction of 5% led to an increase in hardness to 263 HV. A further increase in the concentration of borides leads to linear growth of value up to 1141 HV at 30%.

In order to study the effect of hardening on the wear resistance of coatings, a wear test was carried out according to the ball-on-flat test scheme during the reciprocating movement of the counterbody. Coatings with 5 % and 10 % hardening particles demonstrate a lower level of wear resistance compared to the non-hardened composition. An increase in the proportion of CrB particles to 20 % leads to a sharp decrease in the volume of worn material by 3 times: from 0.61 mm^3 to 0.17 mm^3.

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Al-CONTAINING REFRACTORY MEDIUM-ENTROPY ALLOYS: STRUCTURE, MECHANICAL PROPERTIES, DEFORMATION BEHAVIOUR AND MECHANISMS

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Introduced in 2010, so-called refractory high/medium-entropy alloys (RH/MEAs) became a hot topic theme in materials science community due to their exceptional strength at temperatures, where state-of-art Ni-based superalloys melt. In the pursuit of the weight-saving goals, RH/MEAs were massively alloyed with Al. Indeed, Al-containing RH/MEAs attained higher specific strength, yet at a cost of plasticity. The origin for that was a B2-ordered structure that restricted the dislocation motion abruptly.

In this comprehensive study resulted from two years of extensive and fruitful investigations, we show that the B2 ordering is a tuneable parameter, which can be tailored to break the strength-ductility dilemma.

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PECULIARITIES OF REPAIR OF GAS TURBINE COMPONENTS BY LASER POWDER CLADDING METHOD

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Gas turbines are currently one of the most widespread types of power plants. They have found their application in air, land, water transportation, and are also widely used in power engineering. From the experience of domestic and foreign engine building, the creation of a new engine model takes a long time and is very expensive. Taking into account these facts, increase of resource of existing GTU is the most important technical and economic task.

One of the most important conditions of GTU technical resource increase is maintainability of its components. The key factor in determining repairability is a compromise between repair technology and repairable part: its material and geometrical forms. Speaking about modern power plants it is necessary to take into account that as materials for parts and assemblies complex alloyed multicomponent systems are used, repair of which by traditional methods is not possible.

Laser powder cladding is one of the most promising methods of repairing parts of gas turbine units. The peculiarities of metallurgical processes along with wide variability

of technological parameters of laser powder surfacing method makes it possible to work with groups of materials that are traditionally referred to non-weldable. In addition, the possibility to repair complex parts of different thicknesses with high accuracy and quality of the restored surface allows to increase the productivity of the repair process, reducing the downtime of the equipment.

To fulfill the work, theoretical and experimental studies aimed at studying the peculiarities of the process of laser powder cladding of GTU components have been carried out. Metallographic studies aimed at studying the micro-, macrostructure and properties of the restored parts were carried out.

The results of the conducted researches show technological possibility of application of laser cladding method for repair of GTU components.

NEW INTERMETALLIC COMPOUNDS WITH ONE MEDIUM- OR HIGH-ENTROPY SUBLATTICE OCCUPIED BY P-BLOCK ELEMENTS

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The use of p-block elements to form a high-entropy sublattice in the chemically complex intermetallic compounds (CCICs) is justified. The results suggest that the possibility of mutual compensation of the characteristics (i.e. electronegativity and atomic radius) should be considered when developing new criteria to predict the stability of CCICs.

The use of p-block elements to stabilize a multicomponent sublattice was verified in Cu_3(InSnSb), Cu_3(InSnSbGa), Cu_3(InSnSbGe), and Cu_3(InSnSbGaGe) CCICs.

Cu_3(InSnSb) exhibited a single orthorhombic Cu_3Sn type structure (space group Pmmn), while the samples with four or five elements occupying the high entropy sublattice site mainly exhibited a hexagonal $Cu_{10}Sn_3$ type structure (space group P 63/m). Moreover, when Si was introduced to Cu_3(InSnSbGeSi), a clear phase segregation occurred.

Cu_3(InSnSb), Cu_3(InSnSbGa), Cu_3(InSnSbGe), and Cu_3(InSnSbGaGe) CCICs remained stable after annealing at 600 °C for 4 h, while Cu_3(InSnSbGeSi) underwent a partial phase transition from hexagonal $Cu_{10}Sn_3$ prototype to orthorhombic Cu_3Sn prototype structure during annealing.

Mutual compensation of the materials characteristics is an important phenomenon to be considered for developing new criteria that predict the formation of single-phase CCICs.

The intrinsic nature of the elements filling the multicomponent site and their deviation from stoichiometric chemical composition lead to stabilization of distinct crystal structures [1].

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References:

1. Trofimov, E., Ostovari Moghaddam, A., Zaitseva, O., Fereidonnejad, R., Naseri, M., Shaburova, N., & Mikhailov, D. (2023). Synthesis and characterization of intermetallic compounds with one medium- or high-entropy sublattice occupied by p-block elements. Materials Chemistry and Physics, 301 doi:10.1016/j.matchemphys.2023.127596.

PRODUCTION OF NEW CAST COBALT-BASED ALLOYS WITH DIFFERENT CR AND NB RATIO IN THE COMPOSITION

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The authors of the research carried out a series of experiments on production new alloys by the centrifugal SHS method [1]. The reactant chaφrge blanks were mixtures of Co_3O4, Nb_2O5, Cr_2O3, WO_3, MoO_3, C, and Al; the ratio of Cr_2O_3 and Nb_2O_5 mutually changed in each experiment. At the preliminary stage of the work, two separate mixtures were prepared, where only Cr_2O_3 and only Nb_2O_5 were present, then these mixtures were again mixed in the required proportions for each point of a series of experiments.

The ratio of variable oxides Cr_2O_3 to Nb_2O_5 is taken as parameter α. Mixtures weighing 150 g were burnt in alundum molds in a centrifugal installation using overload a=200g. The combustion products had the form of a two-layer cylinder with a clear separation of slag (oxides) from the metal phase. The obtained CoCrNbWMoCAl alloys had different proportions of Cr and Nb elements in the composition, respectively. During the further study of the obtained alloys using SEM, the influence of the ratio of the parameter α on the content of elements in the alloy was determined.

With an increase in α from 0 to 100%, the content of Cr in the alloy increases from 0 to 29%, W - from 3.0 to 3.7%, Mo - from 1.7% to 2.0%. The content of Nb decreases from 35% to 0%, the content of Al - from 2.2 to 1.5%. The Co content practically does not change.

References:

1. Yukhvid, V. I. SHS-metallurgy: fundamental and applied research / V. I. Yukhvid // Advanced Materials and Technologies. - 2016. - No. 4. - S. 23-34. – DOI 10.17277/amt.2016.04.pp.023-034. – EDN XESSQF.

DIRECT LASER DEPOSITION: TECHNOLOGY, EQUIPMENT, AND IMPLEMENTATION EXAMPLES

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Direct Laser Deposition (DLD) is an advanced form of additive manufacturing that utilizes a laser beam to fuse powdered material onto a substrate, layer by layer. This technology is particularly useful for repairing damaged components or adding features to existing parts. The equipment required for DLD includes a high-power laser source, a nozzle for material delivery, and a motion control system. One of the most notable examples of DLD implementation is in the aerospace industry, where it is used to repair turbine blades. The technology allows for the deposition of specialized alloys, thereby extending the lifespan of critical components. DLD is also making inroads in the medical field for the creation of custom implants. The technology offers the advantage of reduced waste, shorter lead times, and the ability to produce complex structures.

The report is devoted to the ongoing research and development in the field of direct laser deposition at the Institute of Laser and Welding Technologies (ILWT) of SMTU. Principle schemes of realization and technological possibilities of the process are shown. The results of a series of mechanical tests of deposited and heat-treated samples from powders of nickel, titanium and aluminum alloys and steels confirm the compliance of strength characteristics of deposited samples with the characteristics of similar materials in the rolled state.

The paper presents a model range of technological equipment for direct laser deposition technology developed at ILWT. Samples of high-precision blanks of products manufactured by direct laser deposition technology by order of industrial enterprises are demonstrated. The directions of further development of technology and equipment for direct laser deposition of large-size complex metal blanks are highlighted. Particular attention is paid to the issues of quality assurance of blanks and the need for end-to-end control of key operations of the technological process.

DEFORMATION OF Ti-BASED METAL-MATRIX COMPOSITES

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One of the attractive ways to improve the strength-related properties of metallic materials is associated with the creation of metal-matrix composites (MMC) via inserting ceramic particles or fibers into the metallic matrix. The combination of a Ti-based matrix reinforced by boride particles (TiB) is a very promising example since this reinforcement has excellent thermodynamic stability, thermal expansion coefficients similar to the Ti

matrix, a clean interface and excellent interface bonding between the TiB whiskers and the Ti matrix. The MMCs can be obtained using various methods, including traditional casting and various powder metallurgy techniques (e.g. spark plasma sintering or selective laser melting). Usually the composite preforms do not considered as an object for further thermomechanical treatment, however MMCs, along with the increased strength, demonstrate sometime poor room-temperature ductility. Thermo-mechanical treatment of short fibers reinforced composites can improve their mechanical properties however the effect of such treatment is not quite well known.

In present work the effect of thermomechanical treatment on structure and properties of Ti-based MMCs reinforced by boride particles is discussed. The mechanisms that control the mechanical behavior and factors contributing to strengthening are analyzed.

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INVESTIGATION OF THE EFFECT OF OXYGEN ON THE MECHANICAL PROPERTIES OF THE REFRACTORY Al7.5(NbTiZr)92.5 MEDIUM-ENTROPY ALLOY

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Refractory medium/high-entropy alloys have attracted special attention for their stability and excellent mechanical properties at high temperatures. However, most of these alloys face the dilemma of a compromise between strength and ductility, which leads to a limitation of their use.

One of the options for improving mechanical properties is alloying alloys with oxygen. Early studies have demonstrated [1-4] an improvement in mechanical characteristics in comparison with the initial alloys. However, such studies are still insufficient.

In this work, we found that the addition of oxygen to the refractory $Al_{7.5}(NbTiZr)_{92.5}$ medium-entropy alloy led to an increase in strength and a slight reduction in ductility in a wide temperature interval. Relationships between the mechanical properties and microstructure were thoroughly discussed.

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References:

1. Lei Z., et al. Enhanced strength and ductility in a high-entropy alloy via ordered oxygen complexes // Nature, 2018. Vol. 563. P. 546-550.

2. Iroc L.K., et al. Design of oxygen-doped TiZrHfNbTa refractory high entropy alloys with enhanced strength and ductility // Materials and Design, 2022. Vol. 223. P. 111239.

3. Wu L., et al. Achieving superior mechanical properties and biocompatibility in an O-doping TiZrNb medium entropy alloy // Intermetallics, 2023. Vol. 161. P. 107991.

4. Jin C. et al. Effect of interstitial oxygen /nitrogen on mechanical and wear properties of TiZrHfNb refractory high-entropy alloy // Journal of Alloys and Compounds. 2023. Vol. 960. P. 170863.

SYNTHESIS OF HIGH-ENTROPY BORIDES OF TRANSITION METALS IV AND VI GROUP

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At present, an important task is to obtain materials for operation in an oxidizing environment at temperatures above 1500°C under mechanical loads. High-entropy materials show higher mechanical characteristics (high thermal conductivity, hardness, strength) compared to individual components. The range of modern ceramic materials based on high-entropy materials is constantly expanding through the use of borides, carbides, nitrides, and silicides.

In the course of the work, the synthesis of high-entropy borides of transition metals of groups IV and VI (Ti, Zr, Hf, Cr, Mo, W) of a given stoichiometric composition was worked out. Part of the experiment was carried out using the shock wave treatment (SWT) method, which is necessary to activate the interaction between individual compounds by accumulating structural defects in the crystal lattice.

Products were obtained by high-temperature sintering and their physical and mechanical properties, such as density, ultimate strength in bending, modulus of elasticity, were studied. X-ray phase analysis (XRD) of the obtained samples and analysis of the structure of the samples by scanning electron microscopy (SEM) were performed.

X-ray phase analysis established the formation of solid solutions of stoichiometric composition, which is confirmed by the results of energy dispersive analysis using SEM.

The characteristics of high-entropy transition metal borides of groups IV and VI are as follows: average flexural strength (230–270 MPa); the value of the density of borides approximately corresponds to the density of steel - 7800 kg/m3, which makes the high-entropy material more in demand; as well as a high modulus of elasticity (280 - 450 GPa).

It is observed that the use of shock wave treatment accelerates diffusion mass transfer, which makes it possible to obtain qualitatively dissolved components in each other.

When determining the melting points of the samples, it was found that at a temperature of 3000 °C and above, the solid solution decomposes into 2 types: (4-5) component, and also (2-3) component based on group VI borides.

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