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Application of High-Entropy Alloys

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Abstract—From the accumulated data on the structure, properties, stability, methods for obtaining high-entropy alloys (HEAs), created at the beginning of the 21st century, a whole range of useful properties were discovered, which allows for promising usages in various industries. A brief review of the literature from the last five years on the analysis of using HEAs in specific knowledge-intensive industries is carried out. In biomedicine, protective coatings made of HEAs (TiZrNbHfTa)N and (TiZrNbHfTa)O possess biocompatibility, a high level of mechanical properties, high wear and corrosion resistance in physiological environments, and excellent adhesion. $(MoTa)_x$NbTiZr products have successfully passed clinical trials when implanted in living muscle tissue. The developed HEAs based on rare earth elements and metals of the Fe group of the YbTbDyAl*Me* type (*Me* = Fe, Co, Ni) have a magnetocaloric effect, have the Curie point close to room temperature, and can be used in modern refrigeration devices. By changing the stoichiometric composition of the CoCrFeNiTi HES, alloying them and conducting heat treatment, it is possible to obtain soft magnetic materials. The application fields of HEAs as catalysts for ammonia oxidation (PtPdRhRuCe), decomposition of ammonia (RuRhCoNiIr), oxidation of aromatic alcohols ($Co_{0.2}Ni_{0.2}Cu_{0.2}Mg_{0.2}Zn_{0.2}$), electrocatalysts for the evolution of hydrogen ($Ni_{20}Fe_{20}Mo_{10}Cr_{15}$CutPi, redox reactions (AlCuNiPtMn and AlNiCuPtPdAu), and methanol/ethanol oxidation are considered. HEAs can be used as electrodes-anodes and cathodes for Li-ion and Na-ion batteries. Synthesized nanoporous AlCoCrFeNi HES have a high bulk density (up to 700 F/cm^3) and cyclic stability (>3000 cycles) and are used in supercapacitors. High-entropy oxides of the $(MgNiCoCuZn)_{0.9}5Li_{0.05}O$ type with high dielectric properties in a wide frequency range can be used in electronic converters. Examples of HEAs application as coatings for parts of watercrafts operating in sea water, dissimilar welded joints—parts of nuclear reactors—are given. Prospects for expanding the areas of HEAs application are noted.

Keywords: high-entropy alloys, application, biomedicine, energy, catalysts, magnetocaloric effect

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INTRODUCTION

High-entropy alloys (HEAs) as a class of new materials appeared at the beginning of the 21st century. They contain up to five to six elements at a concentration of 5–35% [1, 2]. By changing the elemental composition, it is possible to form a high level of such useful properties as high-temperature strength, superparamagnetism, corrosion resistance, and high hardness (along with plasticity and many other properties) [3–6]. If we consider that there are about 80 metals in nature, more than 107 combinations of 5-element HEAs can be made. Then, the set of useful properties of such HEAs is very large. Unique characteristics will significantly expand the scope of HEAs [7]. This is, first of all, the use of HEAs for the production of cutting tools, dies, magnetron sputtering targets, diffusion barriers in microelectronics, parts of nuclear power equipment, cryogenic technology, aerospace industry, etc. [8–17]. However, the results presented in these works are, at most, five years old. In the last five years, there has been an even more intensive accumulation of information about the structure, stability, methods for obtaining, and the prospects for the practical application of HEAs. It is still too early to talk about the real global practical use of HEAs, but an analysis of the latest literature data indicates a positive trend in the possible use of HEAs in various science intensive industries.

In this work, a brief review of recent domestic and foreign studies of the possibilities of practical HEAs application is carried out.

BIOMEDICINE

Biomedicine is one of the promising fields of HEA application for nitride- and carbide-based coatings [7]. If the main requirements for HEAs are biocompatibility and high mechanical properties, then protective coatings must additionally have high chemical stability, wear and corrosion resistance in physiological environments, and strong adhesion to a deposited surface. (TiZrNbHfTa)N and (TiZrNbHfTa)O coatings [18] have similar properties, which do not cause cytotoxic reactions on osteoblasts. Studies of medium-entropy TiZrNbMo alloys with titanium content up to 65% made it possible to successfully test them [19].

A comprehensive study of the $(MoTa)_x NbTiZr$ alloy has shown that products made from it have excellent plastic, strength and anti-corrosion properties. In the carried-out vivo tests (tests inside a living organism) of products from this alloy, they were implanted in muscle tissue for four weeks. A marked passive behavior in the phosphate buffered saline and a mild, non-toxic response of muscle tissue were revealed [20].

HEAS WITH SPECIAL MAGNETIC PROPERTIES

Varying alloying, stoichiometric composition (ratio of Co/Cr, Fe/Cr, Ni/Cr) and heat treatment (annealing for 2–10 h at 200 and 700°C) of HEAs ($Co_{35}Cr_5Fe_{20}Ni_{20}Ti_{20}$, $Co_{20}Cr_5Fe_{20}Ni_{35}Ti_{20}$) allows the development of soft magnetic-based materials [21, 22]. In this case, HEAs with an fcc lattice have a high saturation magnetization, in contrast to alloys with a bcc lattice [7], which is due to a higher atomic packing density and a high content of ferromagnetic elements (Fe, Co, Ni).

Of special interest are HEAs based on rare earth elements and metals of the iron group, such as YbTbDyAl*Me* (*Me* = Fe, Co, Ni) with a magnetocaloric effect [23], which manifests itself in a reversible change in the temperature of the magnetic material with a change in the magnetic field. Magnetic cooling is based on this effect. For HEAs of transition metals of the $Mn_xCr_{0.3}Fe_{0.5}Co_{0.2}Ni_{0.5}Al_{0.3}$ ($20.8 < x < 1.1$) types with a magnetocaloric effect, the Curie temperature approaches room temperature, which makes them extremely efficient in modern refrigeration units [24].

HEAS IN THE POWER INDUSTRY

In works from Chinese researchers [25], theoretical and experimental results on the structure, properties, methods of obtaining HEAs with an emphasis on energy are analyzed. The results are summarized in Table 1. Let us take a look at some of the highlights.

Catalysis

Decomposition of ammonia. Compared with traditional Co–Mo and Ru catalysts $Co_xMo_yFe_{10}Ni_{10}Cu_{10}$ ($x + y = 70$) and RuRhCoNiIr catalysts have more than tenfold efficiency. Such outstanding catalytic performance and high stability are due to the synergistic effect of ultrafine particle size, uniform dispersion, multi-element composition and fcc structure.

Oxidation of aromatic alcohols. A mesoporous HEA $Co_{0.2}Ni_{0.2}Cu_{0.2}Mg_{0.2}Zn_{0.2}O$ provides ultra-high catalytic activity of aerobic oxidation of benzyl alcohol with 98% conversion, achieved in 2 h.

H_2 evolution reaction (HER). Compared to two-phase catalysts, HEAs have increased corrosion resistance. In addition to those listed in Table 1, it should be noted the highly efficient highly entropic oxide $(FeMgCoNi)O_x$ ($x \approx 1.2$) with a complex structure from a mixture of a simple cubic lattice and spinel.

O_2 evolution reaction (OER). Nanoporous catalysts made of HEAs AlNiCoFe*Me* (*Me* = Mo, Nb, Cr), developed from NiFe or NiCoFe nanoalloys, have high electrochemical stability.

In recent years, there has been an intensive study of the possibilities of creating electrocatalysts from double and ternary alloys without the use of noble metals. However, the further use of such electrocatalysts is limited due to their poor corrosion resistance. The authors of [26] obtained a highly efficient porous HEA CoCrFeNiMo by a fundamentally new microwave sintering method: the excess potential reaches 220 mV with a current density of 10 mA/cm^2. This is due to the ability of the porous structure to provide electronic transfer. High entropy oxide films $(FeCrCoNiAl_{0.1})O_x$ obtained by magnetron sputtering provided an excess potential of 381 mV and electrolytic stability for 120 h in an alkaline solution at a current density of 10 mA/cm^2 [27].

Oxidation-reduction reaction (ORR). Nanoporous platinum-based catalysts (AlCuNiPtMn and AlNiCuPtPdAu) have high temperature stability (up to 600°C) and redox activity up to ten times higher than the characteristics of Pt/C catalysts.

Methanol/ethanol oxidation reaction. Synthesized HEAs ($Ir_{0.19}Os_{0.22}Re_{0.21}Rh_{0.20}Ru_{0.19}$ and $Ir_{0.2}6Os_{0.05}Pt_{0.31}Rh_{0.23}Ru_{0.15}$) have exceptional activity and demonstrate high thermal stability at 1500 K.

Energy Storage

Electrode materials for lithium and sodium ion batteries. For lithium-ion batteries, materials based on high-entropy oxides can be used as anodes and cathodes. A cell of the anode $(Co_{0.2}Cu_{0.2}Mg_{0.2}Ni_{0.2}Zn_{0.2})O$ and $LiNi_{1/3}C0_{1/3}Mn_{1/3}O_2$ cathode provided an initial

Table 1. Scopes of HEA application in power engineering [25]

Application	Compound	Structure
Oxidation of ammonia	PtPdRhRuCe, PtCoNiFeCuAu, PtPdCoNiCuAu, PtPdCoNiFeCuAuSn	FCC
Decomposition of ammonia	$Co_xMo_yFe_{10}Ni_{10}Cu_{10}$ ($x + y = 70$)	FCC
H_2 evolution reaction (HER)	CoFeLaNiPt	FCC
	PtAuPdRhRu	FCC
	IrPdPtRhRu	FCC
	AlMoCuPdAu	FCC
	FeCoPdIrPt	FCC
	$Cr_{15}Fe_{20}Co_{35}Ni_{20}Mo_{10}$	FCC
	$(FeMnCoNi)_xO$	Cubic + Spinel
	$(CrMnFeCoNi)_xP$	Hexagonal
O_2 evolution reaction (OER)	CrMnFeCoNi	FCC
	AlMoCuPdAu	FCC
	CoFeLaNiPt	FCC
	AlMoCoIrMo	FCC
	$(FeMnCoNi)O_x$ (x ~ 1.2)	Cubic + Spinel
	FeMnCoNi + $(FeMnCoNi)O_x$	FCC
	$(CrMnFeCoNi)_xP$	Hexagonal
	$K(MgMnFeCoNi)F_3$, $K(MgMnCoNiZn)F_3$	Perovskite
Reduction oxidation reaction (ORR)	CrMnFeCoNiNb, CrMnFeCoNiMo	FCC
	AlNiCuPtPdAu	FCC
	AlCuNiPtMn	FCC
Methanol oxidation reaction	$Ir_{0.19}Os_{0.22}Re_{0.21}Rh_{0.20}Ru_{0.19}$	FCC
	AlMoCuPdAu	FCC
Ethanol oxidation reaction	RuRhPdOsIrPt	FCC
Water oxidation	$(Co,Cu,Fe,Mn,Ni)_3O_4$	Spinel
Oxidation of aromatic alcohols	$(Mg_{0.2}Co_{0.2}Ni_{0.2}Cu_{0.2}Zn_{0.2})O$	Cubic
Li-ion battery	$(Co_{0.2}Cu_{0.2}Mg_{0.2}Ni_{0.2}Zn_{0.2})O$	Cubic
	$(MgCoNiZn)_{1x}Li_xO$ ($x = 0.05; 0.15; 0.25; 0.35$)	Cubic
	$(Mg_{0.2}Ti_{0.2}Zn_{0.2}Cu_{0.2}Fe_{0.2})_3O_4$	Spinel
	$(Mg, Ti, Zn, Cu, Fe)_3O_4$	Spinel
	$[(Bi, Na)_{1/5}(La, Li)_{1/5}(Ce, K)_{1/5}Ca_{1/5}Sr_{1/5}]TiO_3$	Perovskite
Sodium-ion battery	$NaNi_{0.12}Cu_{0.12}Mg_{0.12}Fe_{0.15}Co_{0.15}Mn_{0.1}Ti_{0.1}Sn_{0.1}Sb_{0.04}O_2$	O3
Supercapacitors	FeNiCoMnMg	FCC
	AlCoCrFeNi	FCC
	(TiNbTaZrHf)C	FCC
	(CrMoVZrNb)N	FCC
Strong dielectric	$(Mg,Co,Ni,Cu,Zn)_{1x}Li_xO$	Cubic

capacity of 446 (mA/h)/g and 256 (mA/h)/g after 100 cycles. Sodium-ion batteries showed 83% capacity retention after 500 cycles.

Supercapacitors. A synthesized nanoporous HEA AlCoCrFeNi, used as an electrode, has a high capacity (700 F/cm^3) and cyclic stability (>3000 cycles).

Dielectric materials. Due to polarization in an external electric field, high-entropy dielectrics can be used in capacitors and powerful electronic converters. Highly entropy oxides of the $(MgNiCoCuZn)_{0.95}Li_{0.05}O$ type have high dielectric properties in a wide (100 Hz–2.3 MHz) frequency range.

One of the promising areas of HEA application is the shipbuilding industry [28]. Valves, pumps, shafts, screws and other mechanisms operating in seawater are subject to corrosion and wear. Polymeric and ceramic materials are used as protective coatings, which are not perfect, in particular, ceramic coatings are fragile, and polymer ones have unstable dimensions. The developed and tested coating made of an $AlCrFeNiW_{0.2}Ti_{0.5}$ HEA has a high hardness (~692 HV) and increased tribological properties [28]. HEAs AlCoCrFeNiCu and AlCoCrFeNiTi, which have increased tribological properties at high temperatures, have prospects for application in the aerospace industry [29].

Welding production also falls into a wide range of HEA applications. In modern nuclear reactors, there are a significant number of welded joints made of dissimilar materials. They are subject to high requirements for high-temperature (up to 1025 K) structural stability, anti-corrosion and mechanical properties. In the opinion of the authors of [30], the solution to the problem is possible when using joints made of a Cantor HEA (CoCrFeMnNi) and duplex stainless steel obtained by laser welding. There were attempts made to create high-entropy refractory superconductors [31, 32], superconductors based on rare-earth elements [33]. Other areas of possible use of HEAs are summarized in monographs and reviews [2, 23, 34–36]. There is every reason to believe that the fields of HEAs application will expand along with the development and creation of new compositions and the study of their properties.

CONCLUSIONS

The brief review of the works of domestic and foreign researchers over the past five years on the use of HEAs in various science-intensive industries was carried out. The promising areas of application are: biomedicine; materials with special magnetic properties, including those with a magnetocaloric effect; shipbuilding; aerospace industry; welding; and superconductors. The application of HEAs in the energy-related industries was analyzed in detail. The forecast is made for the expansion of HEAs along with the creation of new alloys and their research.

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REFERENCES

1. Cantor, B., Chang, I.T.H., Knight, P., and Vincent, A.J.B., Microstructural development in equiatomic multicomponent alloys, *Mater. Sci. Eng., A*, 2004, vols. 375–377, pp. 213–218. https://doi.org/10.1016/j.msea.2003.10.257
2. Gromov, V.E., Konovalov, S.V., Ivanov, Yu.F., Osintsev, K.A., Rubannikova, Yu.A., Peregudov, O.A., and Semin, A.P., *Vysokoentropiinye splavy* (High-Entropy Alloys), Novokuznetsk: Poligrafist, 2021.
3. Huang, Y.S., Chen, L., Lui, H.W., Cai, M.H., and Yeh, J.W. Microstructure, hardness, resistivity and thermal stability of sputtered oxide films of AlCoCrCu0.5NiFe high-entropy alloy, *Mater. Sci. Eng., A*, 2007, vol. 457, nos. 1–2, pp. 77–83. https://doi.org/10.1016/j.msea.2006.12.001
4. Tung, C.C., Yeh, J.W., Shun, T.T., Chen, S.K., Huang, Y.S., and Chen, H.C., On the elemental effect of AlCoCrCuFeNi high-entropy alloy system, *Mater. Lett.*, 2007, vol. 61, no. 1, pp. 1–5. https://doi.org/10.1016/j.matlet.2006.03.140
5. Zhou, Y.J., Zhang, Y., Kim, T.N., and Chen, G.L., Microstructure characterizations and strengthening mechanism of multi-principal component $AlCoCrFeNiTi_{0.5}$ solid solution alloy with excellent mechanical properties, *Mater. Lett.*, 2008, vol. 62, nos. 17–18, pp. 2673–2676. https://doi.org/10.1016/j.matlet.2008.01.011
6. Chang, H.W., Huang, P.K., Yeh, J.W., Davison, A., Tsau, C.H., and Yang, C.C., Influence of substrate bias, deposition temperature and post-deposition annealing on the structure and properties of multi-principal-component (AlCrMoSiTi)N coatings, *Surf. Coat. Technol.*, 2008, vol. 202, no. 14, pp. 3360–3366. https://doi.org/10.1016/j.surfcoat.2007.12.014
7. Pogrebnjak, A.D., Bagdasaryan, A.A., Yakushchenko, I.V., and Beresnev, V.M., The structure and properties of high-entropy alloys and nitride coatings based on them, *Russ. Chem. Rev.*, 2014, vol. 83, no. 11, pp. 1027–1061. https://doi.org/10.1070/RCR4407
8. Huang, P.K., Yeh, J.W., Shun, T.T., and Chen, S.K., Multi-principal-element alloys with improved oxidation and wear resistance for thermal spray coating, *Adv. Eng. Mater.*, 2004, vol. 6, nos. 1–2, pp. 74–78. https://doi.org/10.1002/adem.200300507
9. Hsu, C.Y., Yeh, J.W., Chen, S.K., and Shun, T.T., Wear resistance and high-temperature compression strength of Fcc $CuCoNiCrAl_{0.5}Fe$ alloy with boron addition, *Metall. Mater. Trans., A*, 2004, vol. 35, pp. 1465–1469. https://doi.org/10.1007/s11661-004-0254-x
10. Tsai, M.H., Yeh, J.W., and Gan, J.Y., Diffusion barrier properties of AlMoNbSiTaTiVZr high-entropy alloy layer between copper and silicon, *Thin Solid Films*, 2008, vol. 516, no. 16, pp. 5527–5530. https://doi.org/10.1016/j.tsf.2007.07.109
11. Zhu, G., Liu, Y., and Ye, J., Early high-temperature oxidation behavior of Ti(C,N)-based cermets with multi-component AlCoCrFeNi high-entropy alloy

binder, *Int. J. Refract. Met. Hard Mater.*, 2014, vol. 44, pp. 35–41.
https://doi.org/10.1016/j.ijrmhm.2014.01.005

12. Gludovatz, B., Hohenwarter, A., Catoor, D., Chang, E.H., George, E.P., and Ritchie, R.O., A fracture-resistant high-entropy alloy for cryogenic applications, *Science*, 2014, vol. 345, no. 6201, pp. 1153–1158.
https://doi.org/10.1126/science.1254581
13. Xia, S.Q., Yang, X., Yang, T.F., Liu, S., and Zhang, Y., Irradiation resistance in Al_xCoCrFeNi high entropy alloys, *JOM*, 2015, vol. 67, pp. 2340–2344.
https://doi.org/10.1007/s11837-015-1568-4
14. Chuang, M.-H., Tsai, M.-H., Wang, W.-R., Lin, S.-J., and Yeh, J.-W., Microstructure and wear behavior of $Al_xCo_{1.5}CrFeNi_{1.5}Ti_y$ high-entropy alloys, *Acta Mater.*, 2011, vol. 59, no. 16, pp. 6308–6317.
https://doi.org/10.1016/j.actamat.2011.06.041
15. Senkov, O.N., Wilks, G.B., Miracle, D.B., Chuang, C.P., and Liaw, P.K., Refractory high-entropy alloys, *Intermetallics*, 2010, vol. 18, no. 9, pp. 1758–1765.
https://doi.org/10.1016/j.intermet.2010.05.014
16. Zou, Y., Maiti, S., Steurer, W., and Spolenak, R., Size-dependent plasticity in an $Nb_{25}Mo_{25}Ta_{25}W_{25}$ refractory high-entropy alloy, *Acta Mater.*, 2014, vol. 65, pp. 85–97.
https://doi.org/10.1016/j.actamat.2013.11.049
17. Maiti, S. and Steurer, W., Structural-disorder and its effect on mechanical properties in single-phase TaNbHfZr high-entropy alloy, *Acta Mater.*, 2016, vol. 106, pp. 87–97.
https://doi.org/10.1016/j.actamat.2016.01.018
18. Braic, V., Balaceanu, M., Braic, M., Vladescu, A., Panseri, S., and Russo, A., Characterization of multi-principal-element (TiZrNbHfTa)N and (TiZrNbHfTa)C coatings for biomedical applications, *J. Mech. Behav. Biomed. Mater.*, 2012, vol. 10, pp. 197–205.
https://doi.org/10.1016/j.jmbbm.2012.02.020
19. Wong, K.-K., Hsu, H.-C., Wu, S.-C., and Ho, W.-F., Structure and properties of Ti-rich Ti–Zr–Nb–Mo medium-entropy alloys, *J. Alloys Compd.*, 2021, vol. 868, art. ID 159137.
https://doi.org/10.1016/j.jallcom.2021.159137
20. Akmal, M., Hussain, A., Afzal, M., Lee, Y.I., and Ryu, H.J., Systematic study of $(MoTa)_x$NbTiZr medium-and high-entropy alloys for biomedical implants—In vivo biocompatibility examination, *J. Mater. Sci. Technol.*, 2021, vol. 78, pp. 183–191.
https://doi.org/10.1016/j.jmst.2020.10.049
21. Zuo, T., Gao, M.C., Ouyang, L., Yang, X., Cheng, Y., Feng, R., Chen, S., Liaw, P.K., Hawk, J.A., and Zhang, Y., Tailoring magnetic behavior of CoFeMnNiX (X = Al, Cr, Ga, and Sn) high entropy alloys by metal doping, *Acta Mater.*, 2017, vol. 130, pp. 10–18.
https://doi.org/10.1016/j.actamat.2017.03.013
22. Mishra, R.K. and Shahi, R. A systematic approach for enhancing magnetic properties of CoCrFeNiTi-based high entropy alloys via stoichiometric variation and annealing, *J. Alloys Compd.*, 2020, vol. 851, art. ID 153534.
https://doi.org/10.1016/j.jallcom.2019.153534
23. Zhang, Y., *High-Entropy Materials: A Brief Introduction*, Singapore: Springer-Verlag, 2019,
24. Dong, Z., Huang, S., Strom, V., Chai, G., Varga, L.K., Eriksson, O., and Vitos, L., $Mn_xCr_{0.3}Fe_{0.5}Co_{0.2}Ni_{0.5}Al_{0.3}$ high entropy alloys for magnetocaloric refrigeration near room temperature, *J. Mater. Sci. Technol.*, 2021, vol. 79, pp. 15–20.
https://doi.org/10.1016/j.jmst.2020.10.071
25. Fu, M., Ma, X., Zhao, K., Li, X., and Su, D., High-entropy materials for energy-related applications, *Science*, 2021, vol. 24, no. 3, art. ID 102177.
https://doi.org/10.1016/j.isci.2021.102177
26. Tang, J., Xu, J.L., Ye, Z.G., Li, X.B., and Luo, J.M., Microwave sintered porous CoCrFeNiMo high entropy alloy as an efficient electrocatalyst for alkaline oxygen evolution reaction, *J. Mater. Sci. Technol.*, 2021, vol. 79, pp. 171–177.
https://doi.org/10.1016/j.jmst.2020.10.079
27. Zhao, S., Wu, H., Yin, R., Wang, X., Zhong, H., Fu, Q., Wan, W., Cheng, T., Shi, Y., Cai, G., Jiang, C., and Ren, F., Preparation and electrocatalytic properties of $(FeCrCoNiAl_{0.1})O_x$ high-entropy oxide and NiCo-$(FeCrCoNiAl_{0.1})O_x$ heterojunction films, *J. Alloys Compd.*, 2021, vol. 868, art. ID 159108.
https://doi.org/10.1016/j.jallcom.2021.159108
28. Liang, H., Qiao, D., Miao, J., Cao, Z., Jiang, H., and Wang, T., Anomalous microstructure and tribological evaluation of $AlCrFeNiW_{0.2}Ti_{0.5}$ high-entropy alloy coating manufactured by laser cladding in seawater, *J. Mater. Sci. Technol.*, 2021, vol. 85, pp. 224–234.
https://doi.org/10.1016/j.jmst.2020.12.050
29. Dada, M., Popoola, P., Mathe, N., Pityana, S., Adeosun, S., and Aramide, O., The comparative study of the microstructural and corrosion behavior of laser-deposited high entropy alloys, *J. Alloys Compd.*, 2021, vol. 866, art. ID 158777.
https://doi.org/10.1016/j.jallcom.2021.158777
30. Adomako, N.K., Shin, G., Park, N., Park, K., and Kim, J.H., Laser dissimilar welding of CoCrFeMnNi-high entropy alloy and duplex stainless steel, *J. Mater. Sci. Technol.*, 2021, vol. 85, pp. 95–105.
https://doi.org/10.1016/j.jmst.2021.02.003
31. Marik, S., Varghese, M., Sajilesh, K.P., Singh, D., and Singh, R.P., Superconductivity in equimolar Nb–Re–Hf–Zr–Ti high entropy alloy, *J. Alloys Compd.*, 2018, vol. 769, pp. 1059–1063.
https://doi.org/10.1016/j.jallcom.2018.08.039
32. Marik, S., Motla, K., Varghese, M., Sajilesh, K.P., Singh, D., Breard, Y., Boullay, P., and Singh, R.P., Superconductivity in a new hexagonal high-entropy alloy, *Phys. Rev. Mater.*, 2019, vol. 3, no. 6, art. ID 060602.
https://doi.org/10.1103/PhysRevMaterials.3.060602
33. Sogabe, R., Goto, Y., and Mizuguchi, Y., Superconductivity in $EO_{0.5}F_{0.5}BiS_2$ with high-entropy-alloy-type blocking layers, *Appl. Phys. Express*, 2018, vol. 11, art. ID 053102.
https://doi.org/10.7567/APEX.11.053102
34. Rogachev, A.S., Structure, stability and properties of high-entropy alloys, *Phys. Met. Metallogr.*, 2020, vol. 121, no. 8, pp. 733–764.
https://doi.org/10.31857/S0015323020080094
35. Murty, B.S., Yeh, J.W., Ranganathan, S., and Bhattacharjee, P.P., *High-Entropy Alloys*, Amsterdam: Elsevier, 2019, 2nd ed.
36. Gromov, V.E., Rubannikova, Yu.A., Konovalov, S.V., Osintsev, K.A., and Vorob'ev, S.V., Generation of increased mechanical properties of Cantor high-entropy alloy, *Izv. Vyssh. Uchebn. Zaved., Chern. Metall.*, 2021, vol. 64, no. 8, pp. 599–605.
https://doi.org/10.17073/0368-0797-2021-8-599-605

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