

**HIGH-ENTROPY ALLOYS AS A PROSPECTIVE CLASS OF NEW  
RADIATION-TOLERANT MATERIALS RESEARCH DEVELOPMENT  
ANALYSIS BASED ON THE INFORMATION DATABASES**

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A new class of metallic materials, so-called “high-entropy alloys” (HEAs), was under review. Various definitions of these alloys are given, their main differences from the conventional alloys are indicated and the dynamics of publications in the period from the first publications in 2004 to the end of 2020 are presented. It is noted the almost exponential growth of the article numbers concerning these alloys, and the main reasons of such high interest are discussed. Experimental results of development the radiation-tolerant materials based on the concept of high-entropy alloys and study of the radiation damage mechanisms are summarised.

**HIGH-ENTROPY (MULTICOMPONENT)  
ALLOYS**

A set of ideas and approaches was put forward and developed in the area of structural metallic materials in the last century. This has enriched science with new knowledge and led to creation of the materials with radically new properties. Without pretending to a complete list of these materials, we will list some of them – precipitation hardening (ageing) alloys, amorphous metal alloys (include, bulk), composite materials, oxide dispersion-strengthened alloys (ODS) etc. Apparently, an idea of creating so-called “high-entropy alloys” (HEAs) (Yeh [1]) or “equiatomic multicomponent alloys” (Cantor [2]) is chronologically the last. This idea differs significantly from the conventional alloys producing method, based on alloying a principal metal (i.e., Fe or Ni) with relatively small addition of other elements. Most of the known alloys named by their main component are made according to this principle. These alloys were divided into such classes as copper alloys, iron alloys, nickel alloys, aluminium alloys etc. According to the new approach, an alloy is obtained by mixing (fusion, mechanical alloying, spraying etc.) a number of elements (4–5 and more) in equal or near-equal ratio. It is clear that there is no base element in such alloys so that multicomponent alloys cannot be assigned into the classes listed above. The novel approach can be illustrated by triple phase diagram: in this way, researchers use the composition laid in the “central” part of the phase diagram instead of “corners” and “sides” in a classic case (Fig. 1,a).

Richard Feynman’s expression “There is plenty room at the bottom”<sup>\*</sup> characterized the call for transition

<sup>\*</sup>The future Nobel’s prizewinner in physics (1965) Richard P. Feynman in 1959 delivered in California University the lecture “There is plenty room at the bottom”. In this lecture he

of science and technology, namely the area of material design, from micro- to nanoscale. Paraphrasing it, the idea of high-entropy alloys can be formulated as “There is still plenty room in the centre”. By this, we want to mention the centre of multidimensional space “element – phase composition”, and alloys laid near the centre could be extremely interesting in the point of science and practical prospects. Continuing the analogy, there had been no thorough study of this space among the world’s materials scientists before 2004; nevertheless, some works had started much earlier [3].

One circumstance should be noted, that has prevented the emergence of research in the mentioned direction for a long time. As known, alloys, which concentration located in the corners of phase diagram, are either solid solutions or the mixture of solid solution with intermetallic compounds (usually, one or two). In other words, the main number of well-known alloys used in technique are single-, two- or, relatively rare, three-phased. Structure and properties of these alloys are easy to control by varying the phase amount, volume fraction, dispersion and shape. It seems intuitively that a large number of phases, especially complex intermetallic phases, must coexist in a multicomponent system, supposing its element concentration laid in the central part of the phase diagram. Obviously, it will be extremely difficult to control the structure of such alloys. Namely, the development of these alloys seemed to be of little prospect, at least when it comes to structural materials, since intermetallic phases are mostly brittle and their volume fraction may be large.

noted, “It is a staggeringly small world that is below. In the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction”. That lecture is considered to have served as the starting point to begin an active works in the field of nanotechnologies and nanomaterials.

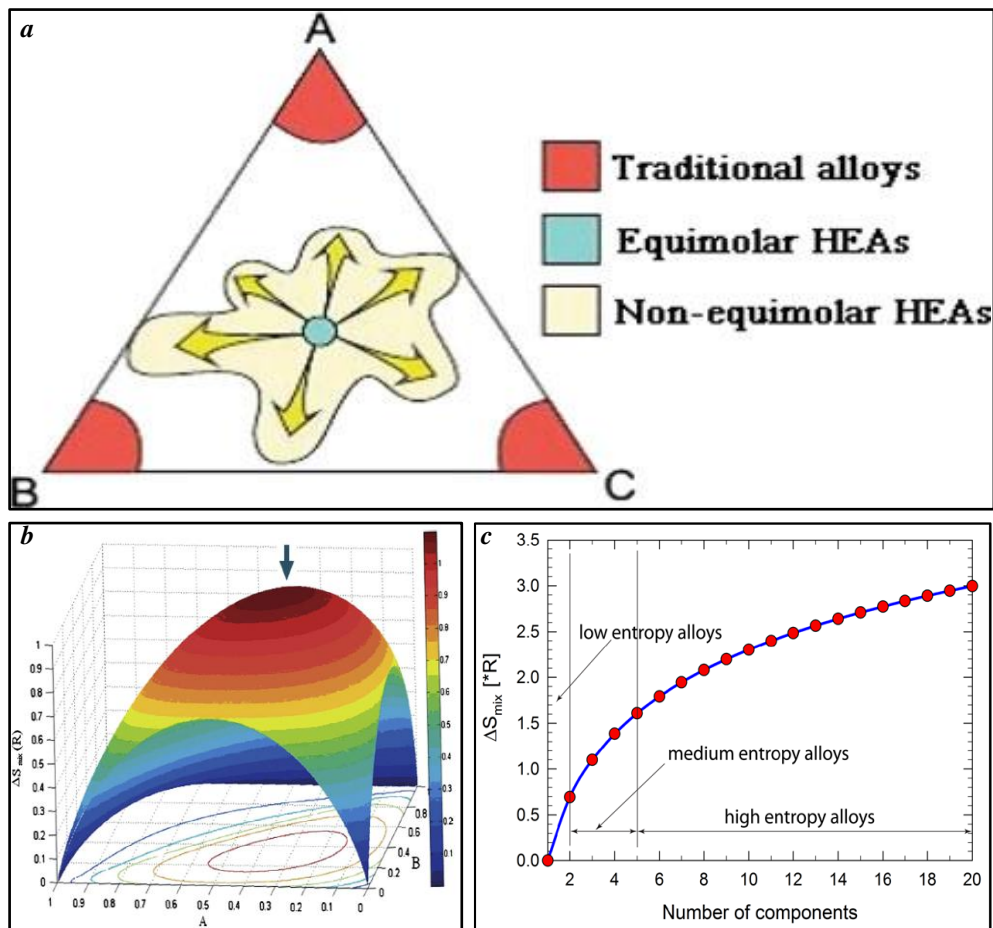


Fig. 1. Concentration areas in 3-component system used for development the conventional alloys and “HEAs” [4] (a); mixing entropy changes depending on the element concentrations in a 3-component system [5] (b); dependence of mixing entropy on the number of components (c)

The intuitive idea of a large phase number in a multicomponent alloy may be well supported by the known Gibbs phase rule. Whereby, the possible number of phases  $P$  in a multicomponent system (alloy) in an equilibrium state is determined by the expression:

$$P = C + 1 - F, \quad (1)$$

where  $C$  is the number of components (elements) in the alloy, and  $F$  is the number of thermodynamic degrees of freedom or independent variables (temperature, pressure, etc.) in the system.

For example, according to (1), the maximum possible number of phases in a five-component system is 6 (in the nonvariant system, i.e.,  $F = 0$ ).

However, “opportunity” does not mean “obligation” and in fact, it turned out that the situation is not so hopeless. Thus, Cantor and co-authors established [2] that five-component equiatomic CoCrFeMnNi alloy forms a single-phase structure during crystallization – a disordered solid solution with a simple fcc lattice. Yeh and co-authors [1] suggested that a stable single-phase structure, or rather, a disordered solid solution, can be stabilized in the multicomponent equiatomic (or near-equiatomic) alloys due to the high mixing entropy. The prerequisites for this are the following considerations.

It is known, that state with the minimal Gibbs free energy  $G$ , is realized in the equilibrium system:

$$G = H - TS, \quad (2)$$

where  $H$  – enthalpy of the system;  $S$  – entropy of the system;  $T$  – absolute temperature.

The ability of a system to transit from one state to another is determined by the change in free energy  $\Delta G$ :

$$\Delta G = G_2 - G_1, \quad (3)$$

where  $G_1$  and  $G_2$  – free energies of the system at initial and final states, respectively.

If  $\Delta G < 0$ , then the transition is thermodynamically possible, when  $\Delta G > 0$ , the transition is thermodynamically impossible, and when  $\Delta G = 0$ , the transition can arbitrarily occur in both directions, i.e., it is reversible.

Let’s imagine a system consisted of several separate components, i.e., metals, and mix the atoms of these components at a certain temperature  $T$ . Then the change in the free energy during mixing  $\Delta G_{mix}$  can be written as:

$$\Delta G_{mix} = \Delta H_{mix} - T\Delta S_{mix}, \quad (4)$$

where  $\Delta H_{mix}$  – change in enthalpy;  $\Delta S_{mix}$  – change in the entropy of the system, when components are mixed (so-called mixing enthalpy and entropy).

A natural question arises: what state of the alloy will realize after the mixing. The choice took place between solid solution (ordered or disordered), intermetallic compound (one or several), amorphous phase or their combination (i.e., solid solution + intermetallic compound). In terms of thermodynamics, that state will be realized, which has a negative maximum absolute value  $\Delta G_{mix}$ . Generally,  $\Delta H_{mix}$  and  $\Delta S_{mix}$  accurate calculations for multicomponent alloys are extremely complex, if not impossible. However, if several simplifying assumptions are made [1], then it will be possible to trace the trends of state realizing with the component mixing.

Firstly, it is assumed, that the dominant contribution to the mixing entropy among all (configurational, vibrational, magnetic, electronic) is the configurational entropy [1]. Secondly, it is considered, that solid solution is completely disordered and could be described as an ideal, i.e., atoms of the components do not interact with each other. Then, the entropy of mixing can be calculated as:

$$\Delta S_{mix} = -R \sum_{i=1}^N (c_i \ln c_i), \quad (5)$$

where  $R$  – gas constant ( $R = 8.314$  kJ/(kmol·K));  $c_i$  – atomic concentration of  $i$ -component. Obviously, the maximum mixing entropy is reached at equal atomic concentration of the alloy components

$$\Delta S_{mix} = -\ln(1/n) = R \ln n, \quad (6)$$

where  $n$  – number of components in equiatomic alloy.

Fig. 1,b illustrates the change in configurational entropy of mixing in three-component alloy with changing the component concentration, and Fig. 1,c represents the change in entropy depending on the number of components in equiatomic alloy. It can be seen, that high entropy values realize in centre of a concentration triangle (see Fig. 1,b) and mixing entropy increases with growing number of components (see Fig. 1,c). Mixing enthalpy  $\Delta H_{mix}$  can be represented as

$$\Delta H_{mix} = \sum_{i=1, j \neq i}^N 4\Delta H_{mix}^{(i,j)} c_i c_j, \quad (7)$$

where  $\Delta H_{mix}^{(i,j)}$  – mixing enthalpy of equiatomic binary  $i,j$  – alloy [6], calculated on the base of Miedema's model [7]. Thus, it is possible to determine  $\Delta H_{mix}$  and  $\Delta S_{mix}$  values and estimate the gain in free energy with one or other implemented structural state as a result of mixing in the system.

It was established [8–11] after the comparing the calculated values of mentioned parameters and experimental results on the structure formed during the crystallization, that a simple disordered solid solution preferentially forms at the high mixing entropy and low mixing enthalpy. Compounds formed in system at high negative values of mixing enthalpy (strong interaction between atoms of different types) and low values of mixing entropy.

Nowadays, there are proposed an impressive number of empirical or semi-empirical criteria, which make it

possible to “predict” structure state of a certain alloy with sufficient probability [8–14]. Analysis of these criteria is presented in number of reviews [15–19], but their discussion is beyond the scope of this article. It should merely be mentioned that atomic radii, concentration of valence electrons, electronegativity, melting temperature of elements etc. are analysed as parameters, which determined alloy's structure, besides the entropy and enthalpy of mixing. When analysing, most authors try to adapt the known Hume-Rothery rules for multicomponent system. Should also be noted the quite successful attempts of thermodynamic calculations of high-entropy alloys phase diagram [20, 21] as well as structure predictions using machine learning method [22].

The calculations show that there are a large number of single-phase alloys with disordered solid solution structure among the multicomponent systems [23]. Experimental studies of as-cast and annealed at high (pre-melting) temperatures alloys confirm this conclusion. However, these alloys show the appearance of second phases upon the prolonged annealing at medium and low temperatures. A prime example of this is the above-mentioned 5-component equiatomic CoCrFeMnNi alloy (Cantor alloy) being considered as disordered solid solution, thermodynamically stable for all temperatures. However, long-time annealing (up to 1000 h) of this as-cast alloy [24] or short-time annealing (1 h) of deformed alloy at 600...800 °C [25] led to second-phase ( $\sigma$ -phase) formation.

Another example is equiatomic high-temperature HfNbTaTiZr alloy [26], in which the hcp-phase precipitates form in bcc lattice during annealing at 600...800 °C. Probably, these processes are due to reduction the contribution of the second (entropic) part in the expression (4) with decreasing  $T$ . Thereby, phase state of high-entropy alloys substantially depends on the temperature. More detailed discussion of this issue can be found in reviews [16, 18].

## VARIOUS DEFINITION OF THE NOVEL CLASS OF MATERIALS AND A SEARCH QUERY FORMULATION FOR PUBLICATIONS

As it was mentioned above, the main characteristics of this new alloy class are the large number and high concentration of each component (chemical element), i.e., alloy is in the central part of multidimensional state diagram. However, such qualitative definition needs to be included of some quantitative characteristics for more certainty. Various attempts to clarify qualitative formulations, their semantics, quantitative parameters and contradictions of existing definitions are described in detail in reviews and monographs [16–18]. For the purpose of this article, we will limit ourselves to the minimal information.

To begin with, we note that in one of the first papers [2], the main motivation was the study of multicomponent alloys in the unexplored central part of the multidimensional compositional space without reference to the magnitude of entropy and the search for a single-phase solid solution (see [16]).

In other papers published in the same year [1], the main focus was on finding a single-phase solid solution and the role of mixing entropy in stabilizing this state. Several definitions were proposed for “high-entropy alloy”. First one is a “compositional” definition: high-entropy alloys must include at least 5 basic elements with the concentration of each is between 35 and 5 at.%. Second one is “entropy” definition, which refers to the alloys with mixing entropy (5)  $\Delta S_{mix} > 1.61 R$  to a high-entropy alloy. Wherein, alloys with  $0.69 R < \Delta S_{mix} < 1.61 R$  are assigned to medium-entropy alloys and alloys with  $\Delta S_{mix} < 0.69 R$  – to low-entropy alloys. Based on the contradiction between “compositional” and “entropy” definitions some authors [16] proposed to refer the alloys with  $\Delta S_{mix} > 1.5 R$  or even  $\Delta S_{mix} > 1.39 R$  to high-entropy alloys (the last definition allows to attribute equimolar four-component alloys to HEA).

Analysing database and materials' behaviour under irradiation, we will further include in a consideration all the articles, used “high-entropy”, “medium-entropy”, “multicomponent”, “complex concentrated” terms, i.e., alloys, except the binary ones, whose composition is in the middle part of the corresponding state diagram.

The specific search query formulation for publications on these alloys was as follows: (“high entropy alloy” or “high entropy alloys”), (“multiprincipal alloy” or “multiprincipal alloys”), (“complex concentrated alloy” or “complex concentrated alloys”), (“medium entropy alloy” or “medium entropy alloys”). All found publications are combined in the framework of «high-entropy alloys» formulation, which is conditional, but widely used.

## PUBLICATION DYNAMICS

Due to the fact that none of the currently existing databases (DB) in the field of natural sciences does not exhaust the entire list of primary sources, we have chosen 3 specialized databases to analyse publications on high-entropy materials (INSPEC, Institution of Engineering and Technology, UK, 1969–2020; Materials Science Citation Index (MSCI), Institute for Scientific Information, USA, 1992 – April 2011; International Nuclear Information System (INIS), IAEA, 1970–2020) and the universal database SCOPUS, Elsevier, Netherlands, 2004–2020. The growth rate of the number of publications reflected in the listed above databases is shown in Figs. 2, 3.

These figures show a rapid increase in publications on the problem under consideration, with the most

representative databases SCOPUS and INSPEC (the MSCI database, unfortunately, has not been updated since 2012).

Fig. 4 displays the countries whose scientists have published the largest number of papers in the field of high-entropy alloys. The total number of countries in which studies are conducted is 58, according to the SCOPUS database, 48, according to INSPEC, 33, according to INIS and 9 countries are reflected in the MSCI database. It has to be noted, that the greatest number of papers were published by scientists from Taiwan organizations (see MSCI DB on Fig. 4) in the first years (2004–2011) of work in this area. Probably because one of two first articles [1] was published by Taiwanese researchers. Moreover, they introduced the concept “high-entropy alloys”. It is noteworthy that the number of references on this work exceeds 5000, according to Google Scholar. In the subsequent period the number of publications was sharply increased by researchers from China, USA, Germany, India, South Korea, Ukraine and other countries. The overwhelming majority of publications are in the form of articles in journals, and the main language of publications is English. It should be noted the close cooperation of scientists from different countries in conducting these studies: many articles are written by representatives of four, five or more countries. In total, there are more than 300 organizations participated in the study of high-entropy alloys, according to the SCOPUS database. Table 1 provides a list of 30 organizations whose employees published the largest number of papers in this area.

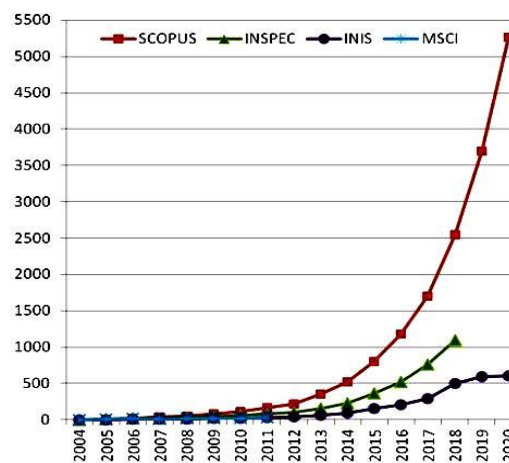


Fig. 2. Cumulative increase in number of publications reflected in various databases

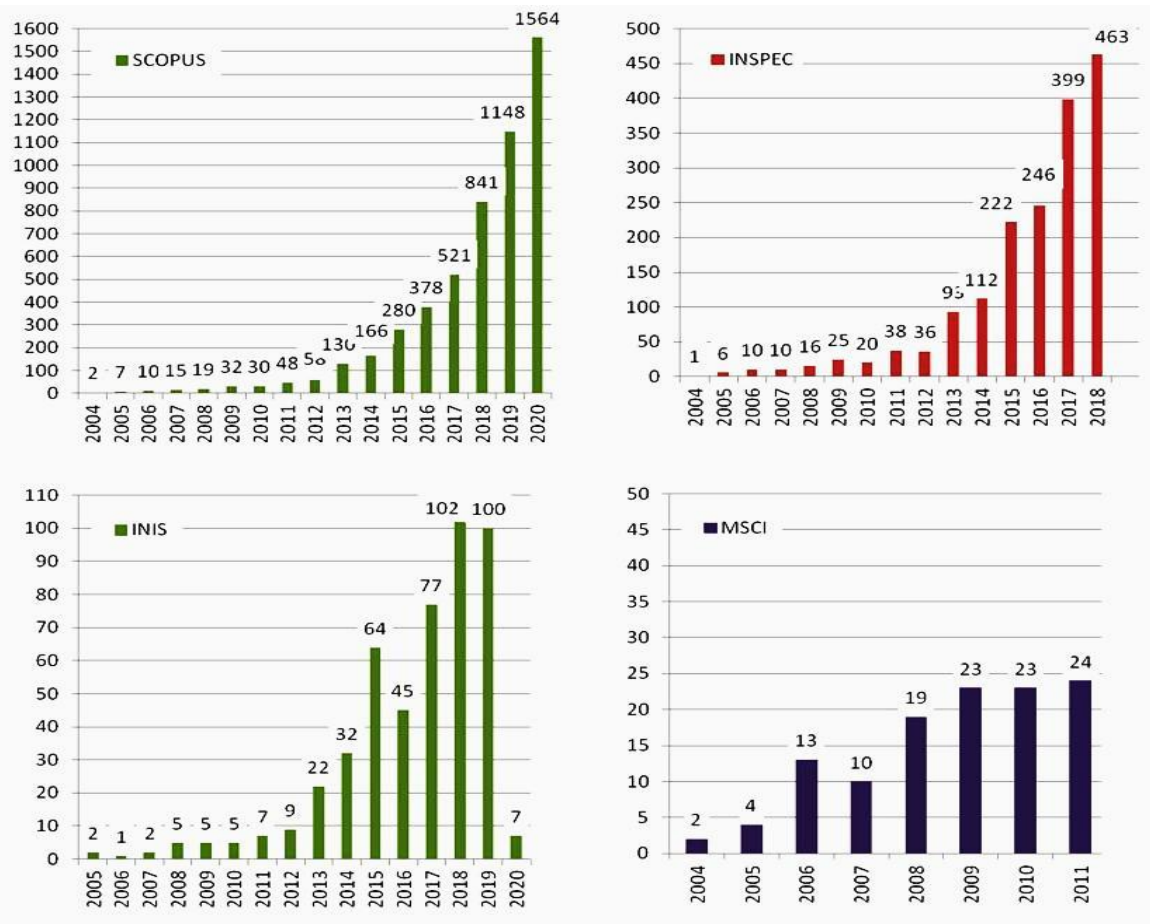


Fig. 3. The number of publications reflected in various databases in a particular year

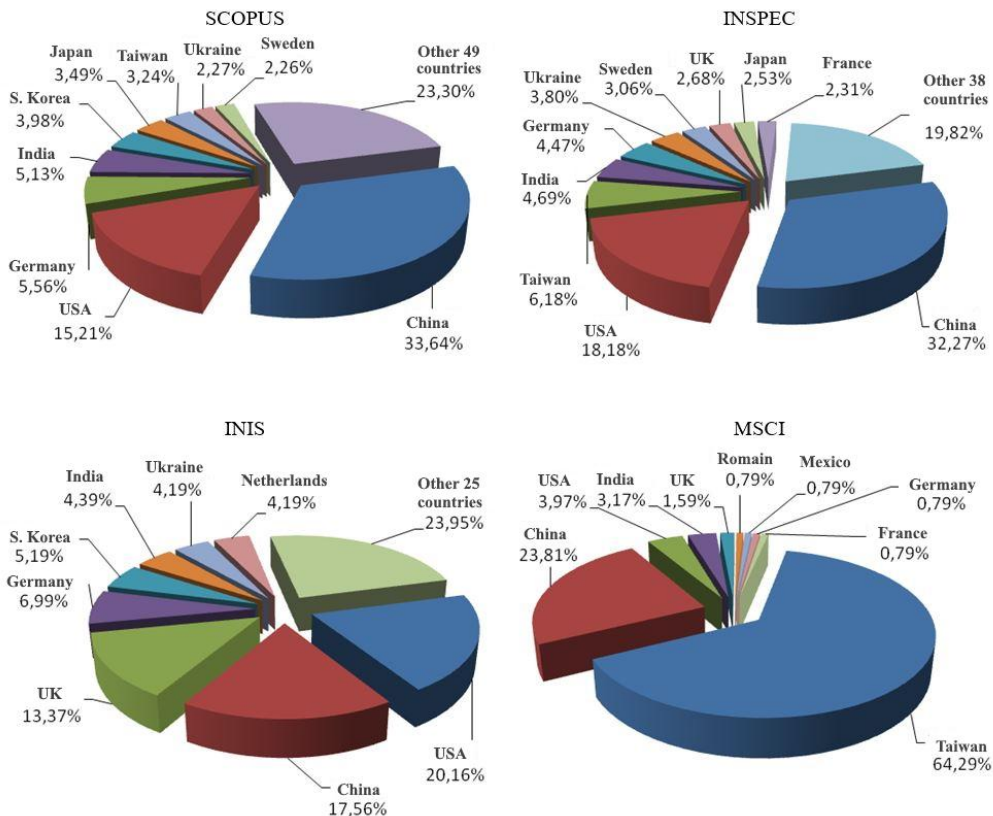


Fig. 4. Distribution of publications by countries (MSCI database has not been updated since 2012)



Table 1

The list of organizations whose employees published the largest number of papers on high-entropy alloys (according to SCOPUS DB)

	Organizations	Number of publications
1	University of Tennessee, Knoxville, <b>USA</b>	353
2	University of Science and Technology Beijing, <b>China</b>	320
3	Central South University, <b>China</b>	232
4	Oak Ridge National Laboratory, <b>USA</b>	208
5	City University of Hong Kong, <b>China</b>	200
6	National Tsing Hua University, <b>Taiwan</b>	189
7	Northwestern Polytechnical University, <b>China</b>	155
8	Dalian University of Technology, <b>China</b>	154
9	University of North Texas, <b>USA</b>	153
10	Max-Planck-Institut für Eisenforschung, <b>Germany</b>	143
11	Harbin Institute of Technology, <b>China</b>	141
12	Chinese Academy of Science, <b>China</b>	117
13	Northwestern Polytechnical Univ. State Key Lab. of Solidification Processing, <b>China</b>	107
14	Indian Institute of Technology, Madras, <b>India</b>	101
15	Ministry of Education, <b>China</b>	98
16	Pohang University of Science and Technology, <b>Korea</b>	93
17	The Royal Institute of Technology KTH, <b>Sweden</b>	82
18	Institute of Metal Research Chinese Academy of Sciences, <b>China</b>	79
19	Yanshan University, <b>China</b>	71
20	Uppsala Universitet, <b>Sweden</b>	70
21	Zhengzhou University, <b>China</b>	65
22	National Science Center “Kharkov Institute of Physics and Technology” Nat. Acad. of Sciences, <b>Ukraine</b>	64
23	Belgorod State University, <b>Russian Federation</b>	63
24	Institute for Materials Research, Tohoku University, <b>Japan</b>	56
25	Wright-Patterson AFB, <b>USA</b>	53
26	Chalmers University of Technology, <b>Sweden</b>	50
27	South China University of Technology, <b>China</b>	49
28	Taiyuan University of Technology, <b>China</b>	48
29	Inst. for Problems of Materials Science Nat. Acad. of Sciences, <b>Ukraine</b>	46
30	CNRS Centre National de la Recherche Scientifique, <b>France</b>	46

### WHY SUCH INTEREST IN HEAS?

The development of the civilization is inextricably linked with the emergence and improvement of new materials. Moreover, it is the new materials that mostly determine the progress of society evidenced by the names of various periods of its development – the Stone Age, the Iron Age, the Bronze Age, the age of semiconductors etc. Regarding to metallic materials, the traditional approach to improving their properties is being almost exhausted. Therefore, the concept of multicomponent concentrated (high-entropy) alloys proposed in [1, 2] was met with enthusiasm by the scientific community. Firstly, it was due to a great number of possible alloy combinations [3, 16, 23], and secondly – the possibility of obtaining the materials with unique mechanical properties at both very high [27, 28] and ultra-low (down to 0.5 K) [28, 29] temperatures. It was established, that number of HEAs have a high corrosion resistance, so they can be used in the chemical industry. Moreover, the coatings based on HEAs have a high hardness and thermal stability, which makes them a promising one for tools hardening. High lattice distortions in HEAs, caused by the difference in atomic radii of elements, as well as the features of their electronic structures improve the activity of these

materials in the chemical reactions, where they can act as catalysts. Certain success was achieved in obtaining and studying the properties of superconducting HEAs, HEA-hydrogen storage and biocompatible materials for the medical implants manufacture. Data on these properties have been published in a number of original papers, monographs and reviews.

### HIGH-ENTROPY ALLOYS AS A PROSPECTIVE CLASS OF RADIATION-TOLERANT MATERIALS

The prospects for using HEAs in nuclear and thermonuclear power industry are of a great interest. The development of these areas requires the creation of materials with a complex of properties that satisfy harsh operating conditions. In particular, nuclear reactors of the fourth generation (Gen IV) require the materials capable to withstand high temperature and radiation doses (up to 200 dpa and more), to be high corrosion and crack resistant, high creep resistant, etc. [30]. At the same time, radiation resistance is a key characteristic determined the interest in a particular material class and the prospects for its use. While preparing this article, we have collected and considered the results, obtained in the study of different aspects of HEAs behavior under irradiation with particles of different type.

Table 2

Alloy composition, processing methods and short results after irradiation

Alloy	Processing*	Irradiation method	Results	source
<b>FCC</b>				
NiCoFeCrMn	NA	Ni ions, 3MeV, $5 \times 10^{16} \text{ cm}^{-2}$ , 60 dpa, 500° C	swelling 0,1%	32
NiCoFeCrMn	NA Gs: ~ mm	Ni ions, 3MeV, $5 \times 10^{16} \text{ cm}^{-2}$ , 53 dpa, 500° C	average diameter of the dislocation loops: 24 nm; loop density: $10^{22} \cdot \text{m}^{-3}$ ; suppressed RIS	33,34
CrFeCoNi	Ø3mm disk	ē, 1.3 MeV, 400° C, 1dpa	stable microstructure	35
CrFeCoNiMn	1200° C/1week		L <sub>10</sub> (NiMn)-type ordering decomposition	
CrFeCoNiPd	Gs: >500µm Ø3mm disk		<100> -oriented Spinodal decomposition Co/Ni и Pd	
NiCoFeCrMn	1 µm thick films Gs: 30 nm	Ag <sup>+</sup> ions, 2.6MeV, 0-500° C	Grain sizes increases up to 66 nm at 480° C; No defect loops or SFTs	36
CoCrFeMnNi	CR, 1200° C/48h Gs: 400µm	Kr ions, 1MeV, $6.3 \times 10^{12} \text{ cm}^{-2}$ RT, 500° C	RT: higher defect density, smaller defect size; mobile interstitials 500° C: smaller defect density, higher defect size; mobile interstitials and vacancies	37
NiCoFeCr	NA	Ni ions, 3MeV 1) $5 \times 10^{16}$ ions/cm <sup>2</sup> (123 dpa), 500° C 2) $8 \times 10^{16}$ ions/cm <sup>2</sup> (196 dpa), 500° C 3) $5 \times 10^{16}$ ions/cm <sup>2</sup> , 580° C	1,3: Up to 900 nm: no void formation (Ni/Co depletion) 900nm-1600nm: void region (Ni/Co enrichment) Beyond 1600nm: no damage (no segregation) 2: up to 900 nm: significant swelling (Ni/Co depletion) 900-1600nm: minor swelling (Ni/Co enrichment) Beyond 1600nm: no damage (no segregation)	38
NiFeCoCrCu	Ø50x0.7 µm Ø50x1 µm Gs: 15.6mm	Ni <sup>+</sup> ions, 3 MeV, RT 1m - 9h 30m 1.2 - 600 dpa	Annealing: 300° C - stable FCC, moderate grain growth (~5nm); 500° C - secondary phases formation; Irradiation: grain growth from 1.5,6 to 2.5,2 nm at 0,73 dpa and 368,5 dpa; stable FCC up to 600 dpa	39
CrFeCoNiCu	2.5x6x50mm	Cu <sup>+</sup> ions, 9.5 MeV, RT Cu <sup>+</sup> ions, 13.3 MeV, RT	Appearance of subgrains	40
Cr <sub>20</sub> Fe <sub>40</sub> Mn <sub>20</sub> Ni <sub>20</sub>	10x5x0.5mm 850° C/24h CR, 850° C/1h	Ar ions, 1.4 MeV, RT 0.1-10dpa	Occurrence of recrystallization and polygonization	41
Cr <sub>10</sub> Fe <sub>40</sub> Mn <sub>20</sub> Ni <sub>20</sub> -ODS	10x5x0.5mm HR (850° C) 1100° C/1h		Similar dislocation loop evolution Hardening effect is less than that for SS316 CrFeMnNi-ODS: Nanohardness is 20% higher	
Fe <sub>30</sub> Ni <sub>30</sub> Mn <sub>30</sub> Cr <sub>10</sub>	1200° C/10h	Fe <sup>2+</sup> ions, 3.7MeV, $1 \times 10^{17}$ ions/cm <sup>2</sup> , 120 dpa 300°, 500° C	stable FCC; increase in loop size at higher T <sub>irrad</sub> ; more radiation-induced hardening due higher number of dislocation loops stable FCC + L <sub>10</sub> (Ni-Ti-Al); larger loops, smaller density than that for Fe <sub>30</sub> Ni <sub>30</sub> Mn <sub>30</sub> Cr <sub>10</sub>	42
(Fe <sub>30</sub> Ni <sub>30</sub> Mn <sub>30</sub> Cr <sub>10</sub> ) <sub>94</sub> Ti <sub>2</sub> Al <sub>4</sub>	1200° C/10h, 30% CR, 1000° C/2h, aged 800° C/18h			

(CoCrFeNi) <sub>94</sub> Ti <sub>2</sub> Al <sub>4</sub>	1200° C/4h (A) + CR, 800° C/18h(B)	Au ions, 4MeV, RT 2×10 <sup>15</sup> ions/cm <sup>2</sup> ·1×10 <sup>16</sup> ions/cm <sup>2</sup> Peak dose: 49dpa	Good phase stability B: smaller growth of dislocation loops, disordering and partial dissolution of precipitates, no hardening effect A: 30% hardening	43
FeCrMnNi	NA	He <sup>+</sup> ions, 6 keV, RT Xe <sup>+</sup> 134 keV, RT 4 dpa	He bubbles growth is slower in HEA compared with in AISI-316; He <sup>+</sup> : generate Frenkel pairs; Xe <sup>+</sup> : small defect cluster that induces tie-up of defects	44
Cr <sub>18</sub> Fe <sub>40</sub> Mn <sub>28</sub> Ni <sub>14</sub>	1050° C/24h, CR, 1100° C/3h, 850° C / 1050° C	Ar ions, 1.4 MeV, RT 0.3-5dpa	850° C: hardness increases with dose increasing, presence of second phases 1050° C: smaller hardening effect, no phase formation Less plasticity losses compared to Cr18Ni10Ti and SS316	45
Cr <sub>20</sub> Fe <sub>40</sub> Mn <sub>20</sub> Ni <sub>20</sub>	1200° C/48h, CR, 900° C/4h Gs:~35µm	Ni ions, 3 MeV RT: 0.1dpa, 1dpa 500° C: 1dpa, 10dpa	Stable structure with no detectable phases >3wt%; 500° C: Cr and Mn enrichment along the grain boundary with the dose increase	46
Fe <sub>27</sub> Ni <sub>28</sub> Mn <sub>27</sub> Cr <sub>18</sub>	thin foils (60-80nm) 1200° C/ 48h, CR, 900° C/4h Gs:~35µm	Ni ions RT: 0.03 dpa, 0.3 dpa 500° C: 0.3 dpa, 3 dpa 1 dpa, 500° C 10 dpa: 400° -700° C	Stable FCC with a low density of Cr and Mn rich oxide precipitates; 500-700° C: Ni enrichment at Gb (with maximum at 600° C); No void formation	47
Fe <sub>27</sub> Ni <sub>28</sub> Mn <sub>27</sub> Cr <sub>18</sub>	0.76x1.5x2.5mm Ø3x0.4 mm 1200° C/ 24h, CR, 900° C/4h Gs:~35µm	n, E>0.1 MeV, 60° C 0.1dpa: 32.4h at 8.57x10 <sup>14</sup> n/cm <sup>2</sup> s 1dpa: 311.4h at 8.9x10 <sup>14</sup> n/cm <sup>2</sup> s	No phase change Increase in nanohardness, yield stress in >110% and >145%, accordingly Electrical resistivity increase is stable up to 700° C Annealing at 500° C: radiation-induced vacancy defect clusters are dissolved	48
(Fe <sub>28</sub> Mn <sub>40</sub> Ni <sub>11</sub> Al <sub>4</sub> Cr <sub>7</sub> )C <sub>x</sub> (x = 0, 0.5, 1)	as-cast	Xe <sup>3+</sup> : 5 MeV, 1.4x10 <sup>15</sup> cm <sup>-2</sup> 300° C, 500° C	No void formation 300° C: dislocation loops density increases with carbon content, loop size – decreases; no swelling 500° C: with x=0.5,1 – more dispersed defect distribution; swelling decreased with carbon content increasing	49
Al <sub>4</sub> CoCrFeNi (x=0.1,0.75,1.5)	Ø80x0.1 mm	Au ions, 3MeV, RT (105 dpa, 91 dpa, 81 dpa)	No significant ordering, amorphization or phase separation; x=0.1: FCC, great stability; x=0.75: FCC+B2, great stability; x=1.5: B2 + spherical A2 (BCC) (~80nm), great stability, highest volume swelling	50
Al <sub>0.1</sub> CoCrFeNi		Au ions, 3 MeV, ~31dpa 250-650° C	Great phase stability; Ni, Co enrichment and Cr, Fe depletion at dislocation loops and dislocations; T <sub>hard</sub> increase: defect density decreases, defect size increases; 650° C: small SFTs – thermally unstable, SFTs density greatly decrease	51
Al <sub>0.1</sub> CoCrFeNi	18x8x1.5 mm HIP (1200° C, 100 MPa/ 4h)	Au ions, 10 MeV 80° C	Peak swelling is 1.2% at 70 dpa; No evidence of voids or dislocations	52
Al <sub>0.5</sub> CoCrFeNi		Ni ions, 5 MeV RT, 400° C	Good radiation resistance up to 60 dpa; No voids/dislocations; structures remain FCC	
Al <sub>0.5</sub> CuCrFeNi <sub>5</sub>		Au ions, 3 MeV, 31dpa 250° C - 650° C	Cu and Al enriched matrix No voids formation T<650° C: suppression the L12 precipitation	53



				T=650° C: formation/growth of B2 precipitation defects –dislocation segments and network dislocations	
$Al_xCoCrFeNi$ ( $x=0.1, 0.75, 1.5$ )	$\emptyset 5 \times 0.1$ mm	Au ions, 3MeV, RT $5 \times 10^{15}$ , $1 \times 10^{16} \text{ cm}^{-2}$ (~43 dpa)		$x=0.1$ : FCC, high structure stability up to 43 dpa  $x=0.75$ : FCC+B2 $x=1.5$ : B2+ A2 (B2 – Al, Ni-enriched, slow growth; A2 – Cr, Fe- enriched, distinct growth with increasing fluence)	54
<b>BCC</b>					
$Mo_{0.5}NbTiV$	$\emptyset 3 \times 0.1$ mm	$Au^{1+}$ ions, 4MeV, 10 dpa		BCC single structure, stable; $NbTiVZr_{0.5}$ – Zr interstitials; $NbTiVZr$ , $NbTiVZr_2$ – amorphous regions	55
$MoNbTiV$					
$NbTiVZr_{0.5}$					
$NbTiVZr$					
$NbTiVZr_2$	$\emptyset 3 \times 0.1$ mm 2x2x2 mm	$Au^{1+}$ ions, 4MeV, 10 dpa $Au^{3+}$ ions, 12MeV, 20 dpa $He^{2+}$ ions, 5 dpa		BCC matrix + Nb phases – slight decrease in lattice parameter; defect concentration increases; $He^{+}$ irradiation lowered volume fraction of non-crystalline regions	56
$Si_3Fe_{3.5}V_{1.6}Cr_{3.3}Mo_9$ $Si_6Fe_{3.8}V_{1.8}Cr_{3.8}$	NA	$Au^{2+}$ ions, 5MeV, $5 \times 10^{15}$ ions/cm <sup>2</sup> , RT		HT: $SiFeVCr$ , $SiFeVCrMo$ high temperature (>1000° C) $\sigma$ BCC phase transformation; Irradiated: $SiFeVCrMo$ : $\sigma$ to BCC phase transformation; RC after HT/ Irradiation results in stable BCC at RT for $SiFeVCr$ and $SiFeVCrMo$	
$Ti_2ZrHFV_{0.3}Mo_{0.2}$	10x6.5x1 mm Gs: 300-500 $\mu$ m	$He^{+}$ ions, 3 MeV, 600° C $5 \times 10^{15}$ , $1 \times 10^{16}$ , $3 \times 10^{16}$ ions/cm <sup>2</sup>		No hardening; Lower number density of He bubble $\sim (3.4-11.9) \times 10^{21} \text{ m}^{-3}$ than for traditional alloys; Higher vacancy concentration than in traditional alloys	57
$TiZrNbHfTa$	$\emptyset 8$ mm disk 1) CR, 1100° C/ 5h, AC in He Gs: ~80 $\mu$ m + 2) HPT Gs: ~40 $\mu$ m CR, 1200° C/ 15min	$He^{2+}$ ions, 5 MeV, T < 50° C $1.6 \times 10^{12}$ – $4.4 \times 10^{17}$ ions/cm <sup>2</sup>		Unchanged Gs and morphology Appearance of He bubbles Nano-hardness increase in 10% with no loss of ductility: 1) lattice defects 2) He at grain boundaries + lattice defects	58
$HfNbTaTiZr$	1x1x0.3 cm CR, 1200° C/ 15min	$Ni^{+}$ ions, 300 keV, 100° C $1.5 \times 10^{16}$ cm <sup>-2</sup> (30dpa)		Swelling 1.23% Almost no hardening effect No phase transformation	59
$HfTaTiVZr$	Gs: 150 $\mu$ m	$Ni^{2+}$ ions, 4.4 MeV, 40 dpa, RT		13% hardening; 20-25 dpa: unchanged microstructure; 35-40 dpa: amorphous+crystalline phases	60
$W_{3.5}Ta_{3.5}V_{1.5}Cr_{1.5}$	thin foil (100nm)	$He^{+}$ ions, 2 keV, 950° C $1.65 \times 10^{17}$ cm <sup>-2</sup>		Uniform distribution of He bubbles Higher resistance to irradiation than in nc W and W-TiC	61
$W_{3.8}Ta_{3.6}V_{1.1}Cr_{1.5}$	thin film	$Kr^{2+}$ ions, 1 MeV, 800° C		No dislocation loops	62

Zr-Hf-Nb	Gs: ~2 nm	$\bar{e}$ : 2.0 MeV -170°C: 180 s (10.6 dpa), 600 s (35.4 dpa), 900 s (53.1 dpa), $1.8 \cdot 10^3$ s (106 dpa) RT: 60 s (3.5 dpa), 180 s (10.5 dpa), 300 s (17.7 dpa), 600 s (35.4 dpa)	Formation of Cr- and V-rich precipitates irradiation-induced crystalline phases formed at -170° C and RT; total dose for the irradiation-induced structural change increased with a decrease in the $T_{\text{irrad}}$ ; no void formation	63
$V_{2.5}Cr_{1.2}WMoCo_{0.04}$	as-cast	$Au^+$ ions, 5MeV, $5 \times 10^{15}$ ions/cm <sup>2</sup> , RT peak dose: 42dpa	Excellent phase stability Elemental separation – appearance of 2 <sup>nd</sup> BCC structure (4wt %) – self-healing	64

\* AM = arc melting, HT = heat treatment, AC – air cooled, CR = cold rolled, HR = hot rolled, RT = room temperature, NA = not available, SFTs = stacking-fault tetrahedral, HIP = hot isostatic pressing, RC = rapid cooling, Gs = grain size

However, quite recently a detailed review [31] has been published, authors of which gave a detailed critical analysis of these works. Therefore, we will provide only a table that displays a list of studied HEAs, irradiation conditions and the main results (see Table 2). It is worth noting, that promising features of HEA behavior under irradiation, such as higher resistance to a radiation-induced defect formation, lower void swelling, higher microstructural stability and limited radiation-induced hardening in alloys, have been found in a number of studies [31]. Various reasons for such behavior associated with HEAs' complex composition are discussed, i.e., effect of reduced thermal conductivity on cascades dynamics, effect of sluggish diffusion on damage accumulation and effect of defect formation energy on damage accumulation. However, Pickering et al. have mentioned in the final part of the review [31], "Our understanding of the irradiation responses of HEAs remains in its infancy, and much work is needed in order for our knowledge of any single HEA system to match our understanding of conventional alloys like austenitic steels".

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#### REFERENCES

1. J.-W. Yeh, S.-K. Chen, S.-J. Lin, J.-Y. Gan, T.-S. Chin, T.-T. Shun, C.-H. Tsau, S.-Y. Chang. Nanostructured high-entropy alloys with multiple principal elements: Novel alloy design concepts and outcomes // *Adv. Eng. Mater.* 2004, N 6(5), p. 299-303.
2. B. Cantor, I.T.H. Chang, P. Knight, A.J.B. Vincent. Microstructural development in equiatomic multicomponent alloys // *Mat. Sci. Eng.: A*. 2004, N 375-377, p. 213-218.
3. B. Cantor. Multicomponent and high entropy alloys // *Entropy*. 2014, N 16(9), p. 4749-4768.
4. Y. Zhang. *High-Entropy Materials: A Brief Introduction*. Springer Nature Singapore Pte Ltd, 2019, 152 p.
5. Y. Zhang, Y. Zhou, J. Lin, G. Chen, P. Liaw. Solid-Solution Phase Formation Rules for Multi-component Alloys // *Adv. Eng. Mater.* 2008, N 10(6), p. 34-538.
6. A.I. Takeuchi. Mixing enthalpy of liquid phase calculated by Miedema's scheme and approximated with sub-regular solution model for assessing forming ability of amorphous and glassy alloys // *Intermetallics*. 2010, N 18, p. 1779-1789.
7. A.R. Miedema, P.F. de Châtel, F.R. de Boer. Cohesion in alloys—fundamentals of a semi-empirical model. // *Phys.B+C*. 1980, N 100(1), p. 1-28.
8. S. Guo, C.T. Liu. Phase stability in high entropy alloys: Formation of solid-solution phase or amorphous phase // *Progress in Natural Science: Materials International*. 2011, N 21(6), p. 433-446.
9. Y. Zhang, Y.J. Zhou, J.P. Lin, G.L. Chen, P.K. Liaw. Solid-solution phase formation rules for multi-component alloys // *Adv. Eng. Mater.* 2008, N 10, p. 4-538.
10. T.S. Srivatsan, M. Gupta. *High-entropy alloys : Innovations, Advances, and Applications*. Boca Raton: CRC Press, 2020, 758 p.
11. X. Yang, Y. Zhang. Prediction of high-entropy stabilized solid-solution in multi-component alloys // *Mater. Chem. And Phys.* 2012, N 132(2-3), p. 233-238.
12. S. Tripathy, G. Gupta, S.G. Chowdhury. High Entropy Alloys: Criteria for Stable Structure // *Metallurgical and Materials Transactions: Part A*. 2017, N 49(1965), p. 1-11.
13. M.C. Tropicovsky, J.R. Morris, P.R.C. Kent, A.R. Lupini, G.M. Stocks. Criteria for predicting the formation of single-phase high-entropy alloys // *Phys. Rev. X*. 2015, N 5(1), p. 011041.1-6.
14. M.G. Poletti, L. Battezzati. Electronic and thermodynamic criteria for the occurrence of high entropy alloys in metallic systems // *Acta Mater.* 2014, N 75, p. 297-306.
15. B.S. Murty, J.W. Yeh, S. Ranganathan. *High-entropy alloys*. Elsevier Science & Technology (Elsevier inc), 2014, 218.
16. D.B. Miracle, O.N. Senkov. A critical review of high entropy alloys and related concepts // *Acta Mater.* 2017, N 122, p. 448-511.
17. M.C. Gao, J.-W. Yeh, P.K. Liaw, Y. Zhang. *High-entropy Alloys: Fundamentals and Applications*, New York, Springer Publishing Co., 2016, p. 516.
18. E.J. Pickering, N.G. Jones. High-entropy alloys: a critical assessment of their founding principles and future prospects // *Int. Mater. Rev.* 2016, N 61, p. 183-202.
19. Y. Zhang, T.T. Zuo, Z. Tang, M.C. Gao, K.A. Dahmen, P.K. Liaw, Z.P. Lu. Microstructures and properties of high-entropy alloys // *Prog. Mat. Sci.* 2014, N 61, p. 1-93.
20. F. Zhang, C. Zhang, S.L. Chen, J. Zhu, W.S. Cao, U.R. Kattner. An understanding of high entropy alloys from phase diagram calculations // *Calphad*. 2014, N 45, p. 1-10.
21. S. Gorsse, O.N. Senkov. About the reliability of CALPHAD predictions in multicomponent systems // *Entropy*. 2018, N 20(12), p. 899.
22. Soo Young Lee, Seokyeong Byeon, Hyung Seop Kim, Hyungyu Jin, Seungchul Lee. Deep learning-based phase prediction of high-entropy alloys: Optimization, generation, and explanation // *Materials & Design*. 2021, N 197, p. 109260.
23. B. Cantor. Multicomponent high-entropy Cantor alloys // *Progress in Materials Science*. 2020.
24. E.J. Pickering, R. Muñoz-Moreno, H.J. Stone, N.G. Jones. Precipitation in the equiatomic high-entropy alloy CrMnFeCoNi // *Scr. Mater.* 2016, N 113, p. 106-109.
25. N.D. Stepanov, D.G. Shaysultanov, M.S. Ozerov, S.V. Zharebtsov, G.A. Salishchev. Second phase formation in the CoCrFeNiMn high entropy alloy after recrystallization annealing // *Materials Letters*. 2016, N 185, p. 1-4.

26. N.D. Stepanov, N.Yu. Yurchenko, S.V. Zhe-rebtsov, M.A. Tikhonovsky, G.A. Salishchev Aging behavior of the HfNbTaTiZr high entropy alloy // *Materials Letters*. 2011, p. 87-90.
27. O.N. Senkov, D.B. Miracle, K.J. Chaput, J.-P. Couzinie. Development and exploration of refractory high entropy alloys – A Review // *Journal of materials research*. 2018, N 33(19), p. 3092-3128.
28. Y. Shang, J. Brechtel, C. Psitidda, P.K. Liaw. Mechanical behavior of high-entropy alloys: A review. arXiv:2102.09055. 85.
29. E.D. Tabachnikova, M.A. Laktionova, Yu.A. Semerenko, S.E. Shumilin, A.V. Podolskiy, M.A. Tikhonovsky, J. Miskuf, K. Csach. Mechanical properties of the high-entropy alloy Al<sub>0.5</sub>CoCrCuFeNi in various structural states at temperatures of 0.5–300 K // *Low Temperature Physics*. 2017, N 43(9), p. 1108-1118.
30. T. Yang, W. Guo, J. D. Poplawsky, D. Li, L. Wang, Y. Li, W. Hu, M. L. Crespillo, Z. Yan, Y. Zhang, Y. Wang, S.J. Zinkle. Structural damage and phase stability of Al<sub>0.3</sub>CoCrFeNi high entropy alloy under high temperature ion irradiation // *Acta Materialia*. 2020, N 188, p. 1-15.
31. E. Pickering, A. Carruther, P. Barron, S. Middleburgh, D. Armstrong, A. Gandy. High-Entropy Alloys for Advanced Nuclear Applications // *Entropy*. 2021, N 23(98).
32. C. Lu, L. Niu, N. Chen, et al. Enhancing radiation tolerance by controlling defect mobility and migration pathways in multicomponent single-phase alloys // *Nature Communications*. 2016, N7, p. 13564.
33. K. Jin, C. Lu, L.M. Wang, J. Qu, W.J. Weber, Y. Zhang, H. Bei. Effects of compositional complexity on the ion-irradiation induced swelling and hardening in Ni-containing equiatomic alloys // *Scripta Materialia*. 2016, N 119, p. 65-70.
34. C. Lu, T. Yang, K. Jin, N. Gao, P. Xiu, Y. Zhang, F. Gao, H. Bei, W. J. Weber, K. Sun, Y. Dong, L. Wang. Radiation-induced segregation on defect clusters in single-phase concentrated solid-solution alloys // *Acta Materialia*. 2017, N 127, p. 98-107.
35. M.-R. He, S. Wang, S. Shi, K. Jin, H. Bei, K. Yasuda, S. Matsumura, K. Higashida, I.M. Robertson. Mechanisms of radiation-induced segregation in CrFeCoNi-based single-phase concentrated solid solution alloys // *Acta Materialia*. 2017, N 126, p. 182-193.
36. G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, K. Hattar, R.S. Averback, S.J. Dillon. Irradiation induced creep in nanocrystalline high entropy alloys // *Acta Materialia*. 2019, N 182, p. 68-76.
37. W.-Y. Chen, J.D. Poplawsky, Y. Chen, et al. Irradiation-induced segregation at dislocation loops in CoCrFeMnNi high entropy alloy // *Materialia*. 2020, N 14, p. 100951.
38. Z. Fan, W. Zhong, K. Jin, H. Bei, Y. Osetsky, Y. Zhang. Diffusion-mediated chemical concentration variation and void evolution in ion-irradiated NiCoFeCr high-entropy alloy // *Journal of Materials Research*, 2020, p. 1-13.
39. Y. Zhang, M.A. Tunes, M.L. Crespillo, F. Zhang, W.L. Boldman, P.D. Rack, L. Jiang, C. Xu, G. Greaves, S.E. Donnelly, L. Wang, W.J. Weber. Thermal stability and irradiation response of nanocrystalline CoCrCuFeNi high-entropy alloy // *Nanotechnology*. 2019, N 30, p. 294004.
40. J. Kim, J.W. Lim and J.K. Kim, et al. Suppressed radiation-induced dynamic recrystallization in CrFeCoNiCu high-entropy alloy // *Scripta Materialia*. 2021, N 190, p. 158-162.
41. V.N. Voyevodin, S.A. Karpov, G.D. Tolstolutskaia, M.A. Tikhonovsky, A.N. Velikodnyi, I.E. Kopanets, G.N. Tolmachova, A.S. Kalchenko, R.L. Vasilenko, I.V. Kolodiy. Effect of irradiation on microstructure and hardening of Cr–Fe–Ni–Mn high-entropy alloy and its strengthened version // *Philosophical Magazine*. 2019, N 100(7), p. 822-836.
42. A. Hoffman, L. He, M. Luebbe, H. Pommerenke, J. Duan, P. Cao, K. Sridharan, Z. Lu, H. Wen. Effects of Al and Ti Additions on Irradiation Behavior of FeMnNiCr Multi-Principal-Element Alloy // *JOM*. 2020, N 72(1), p. 150-159.
43. P.P. Cao, H. Wang, J.Y. He, C. Xu, S.H. Jiang, J.L. Du, X.Z. Cao, E.G. Fu, and Z.P. Lu, Effects of nanosized precipitates on irradiation behavior of CoCrFeNi high entropy alloys // *Journal of Alloys and Compounds*. 2020, N859, 158291.
44. M. A. Tunes, H. Le, G. Greaves, C. G. Schön, H. Bei, Y. Zhang, P. D. Edmondson, S. E. Donnelly. Investigating sluggish diffusion in a concentrated solid solution alloy using ion irradiation with in situ TEM // *Intermetallics*. 2019, N 110, p. 106461.
45. G.D. Tolstolutskaia, G.Y. Rostova, V.N. Voyevodin, A.N. Velikodnyi, M.A. Tikhonovsky, G.N. Tolmachova, A.S. Kalchenko, R.L. Vasilenko, I.E. Kopanets. Hardening of Cr-Fe-Ni-Mn high-entropy alloys caused by the irradiation with argon ions // *PAST*. 2017, N 5, p. 40-47.
46. N.A.P. Kiran Kumar, K.J. Leonard, H. Bei, T.S. Byun, Y. Zhang, S.J. Zinkle. Ion irradiation effects on high entropy alloy // *Fusion Reactor Materials Program*. 2013, DOE/ER-0313/54.
47. N.A.P. Kiran Kumar, C. Li, K.J. Leonard, H. Bei, S.J. Zinkle. Microstructural Stability and Mechanical Behavior of FeNiMnCr High Entropy Alloy under Ion Irradiation // *Acta Materialia*. 2016, N 113, p. 230-244.
48. C. Li, X. Hu, T. Yang, N.A.P. Kiran Kumar, B.D. Wirth, S.J. Zinkle. Neutron irradiation response of a Co-free high entropy alloy // *Journal of Nuclear Materials*. 2019, N 527, p. 151838.
49. S. Shen, F. Chen, X. Tang, et al. Irradiation damage and swelling of carbon-doped Fe<sub>38</sub>Mn<sub>40</sub>Ni<sub>11</sub>Al<sub>4</sub>Cr<sub>7</sub> high-entropy alloys under heavy ion irradiation at elevated temperature // *J Mater Sci*. 2020, N 55, p. 17218-17231.
50. S. Xia, M.C. Gao, T. Yang, P.K. Liaw, Y. Zhang. Phase stability and microstructures of high entropy alloys ion irradiated to high doses // *Journal of Nuclear Materials*. 2016, N 480, p. 100-108.
51. T. Yang, S. Xia, W. Guo, R. Hu, J.D. Poplawsky, G. Sha, Y. Fang, Z. Yan, C. Wang, C. Li, Y. Zhang, S.J. Zinkle, Y. Wang. Effects of temperature on the irradiation responses of

- Al<sub>0.1</sub>CoCrFeNi high entropy alloy // *Scripta Materialia*. 2018, N 144 (C), p. 31-35.
52. P.K. Liaw, T. Egami, C. Zhang, F. Zhang, Y. Zhang. Radiation Behavior of High-Entropy Alloys for Advanced Reactors. Report, DOE/NEUP-11-3196, Project N 11-3196 (2015).
53. T. Yang, W. Guo, J.D. Poplawsky, D. Li, L. Wang, Y. Li, W. Hu, M.L. Crespillo, Z. Yan, Y. Zhang, Y. Wang, S.J. Zinkle. Structural damage and phase stability of Al<sub>0.3</sub>CoCrFeNi high entropy alloy under high temperature ion irradiation // *Acta Materialia*. 2020, N 188, p. 1-15.
54. T. Yang, S. Xia, S. Liu, C. Wang, S. Liu, Y. Fang, Y. Zhang, J. Xue, S. Yan, Y. Wang. Precipitation behavior of Al<sub>x</sub>CoCrFeNi high entropy alloys under ion irradiation // *Scientific Reports*. 2016, N 6, p. 32146.
55. D.J.M. King. *Investigation of high-entropy alloys for use in advanced nuclear applications*: PhD diss. University of Technology Sydney, 2016.
56. A.S. Gandy, B. Jim, G. Coe, D. Patel, L. Hardwick, S. Akhmadaliev, N. Reeves-McLaren, R. Goodall. High temperature and ion implantation-induced phase transformations in novel reduced activation Si-Fe-V-Cr (-Mo) high entropy alloys // *Frontiers in Materials*. 2019, N 6, p. 146.
57. Y. Lu, H. Huang, X. Gao, C. Ren, J. Gao, H. Zhang, S. Zheng, Q. Jin, Y. Zhao, C. Lu, T. Wang, T. Li. A promising new class of irradiation tolerant materials: Ti<sub>2</sub>ZrHfV<sub>0.5</sub>Mo<sub>0.2</sub> high-entropy alloy // *Journal of Materials Science & Technolog.* 2019, N 35(3), p. 369-373.
58. M. Moschetti, A. Xu, B. Schuh, A. Hohenwarter, J.-P. Couzinié, J.J. Kruzic, D. Bhattacharyya, B. Gludovatz. On the Room-Temperature Mechanical Properties of an Ion-Irradiated TiZrNbHfTa Refractory High Entropy Alloy // *JOM*. 2020, N 72, p. 130-138.
59. S. Chang, K.-K. Tseng, T.-Y. Yang, D.-S. Chao, J.-W. Yeh, J.-H. Liang. Irradiation-induced swelling and hardening in HfNbTaTiZr refractory high-entropy alloy // *Materials Letters*. 2020, N 272, p. 127832.
60. M. Sadeghilaridjani, A. Ayyagari, S. Muskeri, V. Hasannaemi, R. Salloom, W.-Y. Chen, S. Mukherjee. Ion irradiation response and mechanical behavior of reduced activity high entropy alloy // *Journal of Nuclear Materials*. 2020, N 529, p. 151955.
61. O. El-Atwani, A. Alvarado, K. Unal, et al. Helium implantation damage resistance in nanocrystalline W-Ta-V-Cr high entropy alloys // *Materials Today Energy*. 2021, N 19, p. 100599.
62. D. Sobieraj, J.S. Wróbel, T. Rygiel, K.J. Kurzydowski, O. El Atwani, A. Devaraj, Saez E. Martinez, D. Nguyen-Manh. Chemical short-range order in derivative Cr-Ta-Ti-V-W high entropy alloys from the first-principles thermodynamic study // *Phys Chem Chem Phys*. 2020, N 22(41), p. 23929-23951.
63. T. Nagase, S. Anada, P.D. Rack, J.H. Noh, H. Yasuda, H. Mori, T. Egami. Electron-irradiation-induced structural change in Zr-Hf-Nb alloy // *Intermetallics*. 2012, N 26, p. 122-130.
64. D. Patel, M.D. Richardson, B. Jim, S. Akhmadaliev, R. Goodall, A.S. Gandy. Radiation damage tolerance of a novel metastable refractory high entropy alloy V<sub>2.5</sub>Cr<sub>1.2</sub>W<sub>Mo</sub>Co<sub>0.04</sub> // *Journal of Nuclear Materials*. 2020, N 531, p. 152005.

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## ВИСОКОЭНТРОПІЙНІ СПЛАВИ – ПЕРСПЕКТИВНИЙ КЛАС РАДІАЦІОННО СТОЙКИХ МАТЕРІАЛІВ. АНАЛІЗ РОЗВИТКУ ДОСЛІДЖЕНЬ НА ОСНОВІ ІНФОРМАЦІЙНИХ БАЗ ДАНИХ

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Рассмотрен новый класс металлических материалов – так называемые «высокоэнтропийные сплавы». Даны их различные определения, указаны основные отличия этих материалов от традиционных сплавов и приведена динамика публикаций за период от первых работ в 2004 году до конца 2020 года. Обнаружен практически экспоненциальный рост числа работ, посвященных этим сплавам, обсуждены причины такой высокой активности исследований в данной области. Приведены результаты разработок радиационно стойких материалов на базе концепции высокоэнтропийных сплавов, и просуммированы исследования механизмов радиационных повреждений в таких материалах.

## ВИСОКОЭНТРОПІЙНІ СПЛАВИ – ПЕРСПЕКТИВНИЙ КЛАС РАДІАЦІОННО СТОЙКИХ МАТЕРІАЛІВ. АНАЛІЗ РОЗВИТКУ ДОСЛІДЖЕНЬ НА ОСНОВІ ІНФОРМАЦІЙНИХ БАЗ ДАНИХ

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Розглянуто новий клас металічних матеріалів – так звані «високоентропійні сплави». Надано різні їх визначення, вказано основні відмінності цих матеріалів від традиційних сплавів, наведено динаміку публікацій за період від перших робіт у 2004 році до кінця 2020 року. Виявлено практично експоненціальне збільшення числа статей, присвячених цим сплавам, обговорено причини такої високої активності досліджень у даній області. Наведено результати розробки радіаційно стійких матеріалів на основі концепції високоентропійних сплавів, та підсумовано дослідження механізмів радіаційних пошкоджень у таких матеріалах.

