

Smelting and structure of high-entropy alloys of the FeNiCrCuAl system

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Abstract: This work was aimed to smelt high-entropy alloys (HEAs) based on inexpensive and common metallic elements using iron-based alloys, ligatures, commercially pure metals and study HEAs' phase structure. High-entropy alloys of the FeNiCrCuAl system were smelted in air using induction furnace in a crucible with a rammed neutral lining made of aluminum and magnesium oxides. Elements of Fe, Ni, Cr, Cu, Al were added by way of high-alloyed cast iron or stainless-steel grade X10CrNiTi18-10 (EN 1.4541), low-carbon ferrochrome of industrial grade FeCr70C1, binary Cu-33Al ligature, tough-pitch copper and semi-finished nickel. The investigated alloys were prepared by lost foam and sand mold casting methods. A study of the microstructure showed the presence of rounded shape branches of dendrites, copper-rich interdendritic space and high-chromium carbides in the structure of samples. The phase composition of the as-cast FeNiCrCuAl alloys was represented by several phases: ordered solid solution with primitive cubic lattice of type B2, solid solutions with BCC and FCC lattices and complex carbides (FeCr)₇C₃.

Keywords: HIGH-ENTROPY ALLOYS, INDUCTION MELTING, STRUCTURE, X-RAY DIFFRACTION, CARBIDES

1. Introduction

Progress in theoretical studies on novel materials and the development of relevant technologies made it possible to prepare metallic alloys containing more than three principal elements. In the last two decades, a novel class of metallic compounds called high-entropy alloys (HEAs) was developed [1, 2]. These systems contain at least five principal metals with a content of 5 at. % to 35 at. % each. The main feature of high-entropy alloys is the possibility to form thermodynamically stable, high-strength, single-phase substitutional solid solutions with mainly FCC or BCC lattices [3]. Stabilization of the solid solutions and prevention of the formation of intermetallic phases during crystallization are ensured by high entropy of mixing of the components ($S_{\text{mix}} > 1.61R$, where $R=8.314 \text{ J mol}^{-1}\text{K}^{-1}$ is the universal gas constant) in the initial (charge mixture) and molten states. The maximum entropy is attained at equimolar ratio of the constituent elements. Based on the Boltzmann hypothesis, the larger the number of elements used to prepare a solid solution the higher the configurational entropy (ΔS_{conf}). An increase in ΔS_{conf} of the molten and solidified alloy favours the formation of a simple structure in the form of a single-phase disordered substitutional solid solution (one crystal lattice), which is thermodynamically favorable compared to the formation of a multiphase solid solutions. Therefore, a tendency to formation of ordered structures becomes much less pronounced owing to minimization of the Gibbs free energy; segregation of elements in the course of solidification also becomes less probable [4]. In reality, multicomponent systems are usually multiphase structures in which ordered phases coexist with disordered phases of a solid solution. The authors of [5] analyzed the structure of high-entropy alloys and formulated three principles of formation of solid solutions:

- high entropy of mixing requires that the number of principal elements be at least five;
- the atomic radii of the elements should differ by at most 12%;
- the enthalpy of mixing should vary between – 40 and 10 kJ mol^{-1} .

The distinctive features of high-entropy alloys include [6]:

- high entropy of mixing,
- lattice distortion,
- sluggish diffusion,
- so-called cocktail effect.

Due to their structural features, high-entropy alloys are characterized by low diffusion coefficients, corrosion resistance, increased plasticity at low temperatures and other special properties that can be very useful for many promising materials and

technologies [7, 8, 9]. Almost all types of such alloys (structural, cryogenic and heat-resistant, corrosion-resistant, with special magnetic and electrical properties), as well as compounds (carbides, nitrides, oxides, borides, silicides) are being developed. The vast majorities of HEAs are made from components with a purity of at least 99.5% and contain a significant amount of such expensive elements as Co, W, V, Nb, Mo, Ta, Ti [10, 11] and others, which significantly reduces the economic feasibility of their practical application. Therefore, this work aimed to smelt the HEAs in air based on inexpensive and common metallic elements (FeNiCrCuAl), use ligatures, ferrous compounds, and study HEAs' phase structure.

2. Preparation of HEAs, materials and methods

High-entropy alloys of the FeNiCrCuAl system were melted in air by induction furnace in a crucible with a rammed neutral lining made of aluminum and magnesium oxides with their mass ratio of 9:1, and borax with a mass fraction of 2% was used as a binder. FeNiCrCuAl alloy do not contain such an expensive element as cobalt (Co), which is usually present in similar metallic systems. Aluminum was introduced into the melt in the form of a copper-aluminum master alloy (Cu-33Al) due to its high chemical reactivity towards oxygen. Chromium, due to its relatively high melting point (1857 °C), was also introduced in the form of a low-carbon ferrochrome of the industrial grade FeCr70C1, which made it possible not to overheat the melt. In the manufacture of Cu-Al ligature, copper grade Cu-ETP (99.9 wt. %), aluminum ingot grade ENAW-1085 (99.85 wt. %) were used. The Cu-Al ligature with a mass fraction of aluminum of 33% was obtained by induction melting in a graphite crucible. First, copper was melted, and then aluminum was introduced into the liquid metal. Other charge materials were high-alloyed cast iron (elements content, wt. %: C=2.60, Si=1.80, Mn=1.30, Ni=17.00, Cr=2.30, Cu=3.60, S=0.05, P=0.07), stainless steel grade X10CrNiTi18-10 (EN 1.4541) and semi-finished nickel with a purity of 99.5 wt. %. The preparation of ligatures and the use of ferroalloys allowed improving the dissolution of elements in the melt, which in turn contributed to its homogenization. Iron-based alloys were loaded onto the bottom of the crucible and a portion of ferrochrome was placed on top. After the appearance of the liquid melt, ferrochrome continued to be introduced, as well as nickel and Cu-Al ligature. After melting and dissolving all components, the high-entropy FeNiCrCuAl alloy was superheated above the liquidus temperature by 250–300 °C, and then the liquid metal was poured into casting molds using a lost foam method or conventional casting into a sand mold. In details about the features of casting methods and casting properties of HEAs are described in the work [12].

The chemical composition of the studied high-entropy alloys samples was determined on an X-ray fluorescence express analyzer "EXPERT 3L" and is presented in Table 1. The alloys No1, No2

were smelted using high-alloyed cast iron and stainless steel, respectively. The chemical composition of individual phases was determined using the X-ray microprobe MS-46 manufactured by CAMECA. The temperatures and heats of melting/crystallization of the HEAs were investigated using a thermal analyzer STA 449 Jupiter F1 manufactured by NETZSCH. The mass fraction of carbon in the experimental alloys was determined on an old type AN-7529 express analyzer using the method of automatic coulometric titration by pH.

Table 1: Chemical composition of HEA samples melted in air and obtained by casting methods, at. %

No alloy	Fe	Ni	Cr	Cu	Al	C	Si	P+S
1	24.73	19.83	18.49	20.83	11.95	3.22	0.81	0.028
2	21.77	20.58	14.02	23.22	19.50	0.30	0.23	0.020

High entropy alloy samples were examined by X-ray diffraction on a DRON-3 diffractometer and Bruker D8 Advance powder diffractometer with a horizontal θ - 2θ goniometer in Bragg-Brentano focusing geometry using $\text{CoK}\alpha$ radiation ($\lambda = 0.17902$ nm) and $\text{Mo-K}\alpha$ ($\lambda = 0.07093187$ nm), respectively, with a diffracted-beam graphite monochromator. The 2θ range of 20° - 100° was measured with a step width of 0.02° and a pulse acquisition time of 2 s with a DRON-3 diffractometer. Using a Bruker D8 diffractometer the X-ray diffraction pattern was taken in the 2θ range from 15° to 135° with a step of 0.05° and a pulse acquisition time of 2 s. The phase composition of the high-entropy alloys was studied by X-ray diffraction analysis on a diffractometer Ultima-IV (Rigaku, Japan) using $\text{CuK}\alpha$ radiation ($\lambda = 0.15418$ nm). XRD recording was performed in the 2θ range of 25° - 105° with a scanning step of 0.05° and a count time of 1 sec per step.

To accurately determine the lattice parameters the XRD peaks were scanned at far angles with a pulse acquisition time of 12-16 s and a scan step of 0.01° .

To investigate the microstructure and chemical phase composition of the HEA samples, scanning electron microscope with energy dispersive microanalyzer (REM 106I manufactured with JSC "SELMI") and optical microscope structural analyzer EPIQUANT (by Carl Zeiss Jena) were used.

3. Results and discussion

3.1. Phase formation conditions for high-entropy alloys

The authors of [5] analyzed the structure of high-entropy alloys and formulated three principles of formation of solid solutions:

- high entropy of mixing (ΔS_{mix}) requires that the number of principal elements be at least five;
- the atomic radii (δ) of the elements should differ by at most 12%;
- the enthalpy of mixing (ΔH_{mix}) should vary between -40 kJmol^{-1} and 10 kJmol^{-1} ($-40 \text{ kJmol}^{-1} < \Delta H_{\text{mix}} < 10 \text{ kJmol}^{-1}$);

Further studies of stabilization factors of the formation of solid solutions made it possible to determine more accurate parameters [13, 14, 15] namely, the coefficients Ω and δ . Based on analysis of the structures of high-entropy systems, one state that the formation of a solid solution is probable at $\Omega > 1.1$ and $\delta \leq 6.6\%$. The parameter Ω takes into account the influence of the entropy and enthalpy of mixing as well as the melting point on the formation of a solid solution. To better characterize the collective behaviour of the constituent elements in high-entropy systems, it was proposed to use two parameters, the electronegativity difference ($\Delta\chi$) and the valence electron concentration (VEC) [16, 17]. According to Liu and co-workers [16], VEC is a physical parameter that governs the probability of formation of solid solution phases with the BCC and FCC lattices. The parameter $\Delta\chi$ has almost no effect on the formation of solid solutions or amorphous phase [17]; however, studies [18] showed that large $\Delta\chi$ values favour the formation of more complex compounds (e.g., intermetallics). The valence electron concentration can also be used to predict the formation of

intermetallics [19, 20]. As mentioned above, high-entropy alloys mainly form single-phase substitutional solid solutions with the FCC or BCC lattices. At high VEC values (≥ 8), the FCC phase is formed; at $6.87 < \text{VEC} < 8$, a FCC + BCC mixed structure is formed; at lower VEC values (< 6.87), the BCC phase is formed.

To assess phase formation in the studied alloys of the FeNiCrCuAl system, various parameters were calculated (ΔS_{mix} , ΔH_{mix} , Ω , δ , $\Delta\chi$, VEC) and presented in Table 2. It can be seen that the valence electron concentration in alloys No 1, No 2 of the FeNiCrCuAl system is found to have values of 7.8914 and 7.8276. That is, in alloys of the FeNiCrCuAl system, a mixture of solid solutions based on phases with BCC and FCC lattices should be formed, which was also confirmed by X-ray diffraction phase analysis.

The value of the parameter Ω larger than 1.1, relatively small negative values of ΔH_{mix} (-7.31 and $-3.86 \text{ kJ/mol}\cdot\text{K}$) within the range of $-40 \text{ kJ/mol} \leq \Delta H_{\text{mix}} \leq 10 \text{ kJ/mol}$ (see Table 2), and the ratio $S_{\text{mix}}/R \geq 1.61$ also indicate the possibility of the formation of solid solutions. For preparation of HEAs where high-alloyed cast iron was used as the charge material (see Table 1, alloy No 1) has a more negative value of the $\Delta H_{\text{mix}} = -7.31 \text{ kJ/mol}\cdot\text{K}$, a greater difference in the atomic radii ($\delta = 8.52\%$) and the electronegativity ($\Delta\chi = 17.41$) of the elements, as well as a smaller value of the thermodynamic parameter ($\Omega = 3.14$) than in the alloy that was made of steel (see Table 1, alloy No 2). This difference is explained by the formation of a significant amount of complex high-chromium carbides in alloy No 1, and there is no carbon in alloy No 2.

Table 2: Calculated thermodynamic parameters (ΔS_{mix} , ΔH_{mix} , Ω , δ , $\Delta\chi$, VEC) of HEAs FeNiCrCuAl system

No alloy	S_{mix}/R^*	ΔS_{mix} , J/mol·K	ΔH_{mix} , kJ/mol·K	Ω	δ , %	$\Delta\chi$, %	VEC
1	1.7193	14.2951	-7.3079	3.1366	8.5204	17.406	7.8914
2	1.6440	13.6687	-3.8635	5.5271	6.0115	12.961	7.8276

*R – universal gas constant ($8.314463 \text{ J/mol}\cdot\text{K}$)

In FeNiCrCuAl alloys with carbon impurities, the atomic radii of the elements Al (143 pm) and C (70 pm) differ significantly from the atomic radii of the elements Fe (126 pm), Ni (124 pm), Cr (130 pm), Cu (128 pm). This difference in atomic radii distorts the atomic lattice of the disordered solid solution near the C and Al atoms, which leads to the formation of an ordered bcc phase B2 (by type AlNi) and complex carbides ($\text{Fe, Cr}_7\text{C}_3$).

3.2. Study of thermal characteristics of the HEAs with differential scanning calorimetry

The temperatures and heats of melting and crystallization of the alloys were investigated using differential scanning calorimetry (DSC). Samples of the experimental HEAs were heated to a temperature of 1450°C at a rate of 20 K/min , and then cooled to room temperature. The onset melting temperature (t_{sol} , solidus) and the onset solidification temperature (t_{liq} , liquidus) were determined in the process of heating and cooling of the high entropy alloys. The crystallization interval of the alloys were determined as the difference between the liquidus and solidus temperatures ($\Delta t = t_{\text{liq}} - t_{\text{sol}}$) (Table 3).

Table 3: Solidus and liquidus temperatures, heats of melting/crystallization of the studied high-entropy alloys of FeNiCrCuAl system

No. alloy	t_{sol} , $^\circ\text{C}$	t_{liq} , $^\circ\text{C}$	Δt , $^\circ\text{C}$	ΔH_{sol} , J/g				
				1	2	3	4	5
1	1105	1275	170	4.62	120	68.3	0.45	15.6
2	1090	1321	231	226	-	181	-	-

ΔH_{m} – the heat of melting, ΔH_{sol} – the heat of crystallization.

Solidus and liquidus temperatures were determined at the intersection of two tangent lines on the DSC curves. The studied HEAs have a wide crystallization interval (see Table 3). Melting

and then crystallization of alloys of the FeNiCrCuAl system occurs in several stages. As shown in Figs. 1a and 1b, the DSC curve has a complex profile – the first phase had not managed to melt or crystallize, the other phase had already begun to melt or crystallize, etc. The DSC peaks from individual phases merge with each other into a broad heating-cooling triple peak and this fact indicates that the studied alloys No 1 and No 2 have a multiphase composition. The melting and crystallization DSC profiles differed significantly from each other, so this fact indicates a redistribution of the chemical composition of individual phases (Figs. 1a and b) after the first melting.

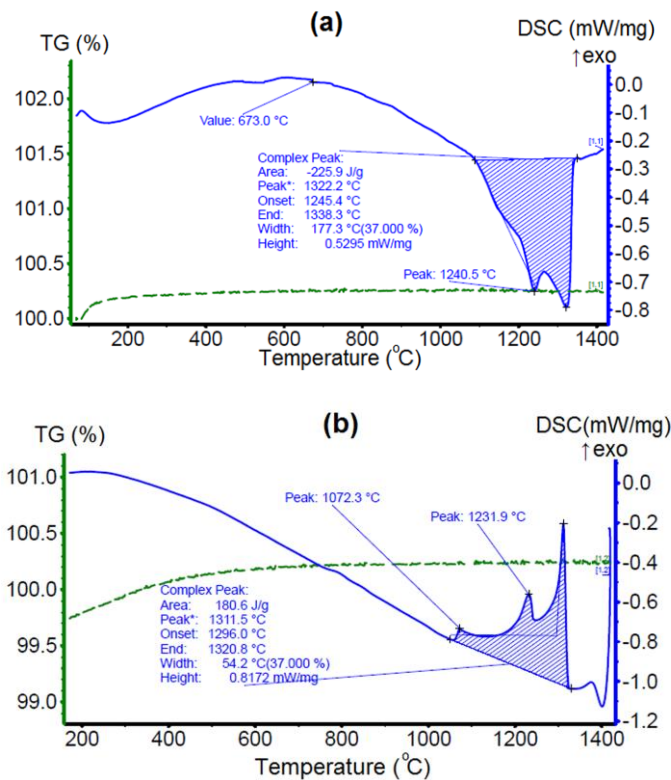


Fig. 1 DSC curves of alloy No 2 of the FeNiCrCuAl system: (a) heating, (b) cooling.

3.3. X-ray phase analysis of the HEAS FeNiCrCuAl system

High entropy alloys of the FeNiCrCuAl system have several phases with different structures: BCC (Im3m) and FCC (Fm3m) lattices and cubic primitive lattice (Pm3m). In alloys prepared using high-alloyed cast iron (as charge material), a large number of high-chromium carbides were found. The results of the phase analysis and the lattice periods of the formed phases are presented in Table 4. The lattice parameters were calculated from each reflection (*hkl*) in the X-ray diffraction patterns, and then the average values of the lattice parameters were determined. For some X-ray diffraction patterns, Miller indices at large angles were selected and the lattice parameters were determined from them. The lattice parameters depend on chemical composition.

Table 4: Results of phase analysis and lattice parameters of alloys of the FeNiCrCuAl system

No alloy	Space group	Radiation	Lattice parameter, Å
1	BCC (Im3m) or Primitive (Pm3m) FCC (Fm3m)	MoK α	2.8872±0.00545 -
2	Primitive (Pm3m) FCC (Fm3m)	CuK α	2.8887±0.0120 3.6433±0.0034

Calculations of the average electron concentration (VEC) for high-entropy alloys do not contradict the data of X-ray phase analysis. In alloys No 1 and No 2, the VEC has a value of 7.8914 e/at. and 7.8276 e/at. (Table 2), which indicates the probability of the formation of solid solutions based on phase mixture with BCC and FCC structures. A more detailed analysis of the X-ray diffraction patterns presented in Figures 2a, b shows that for alloys of the FeNiCrCuAl system, the diffraction pattern from one phase is similar to the diffraction pattern of austenite or copper (as γ -Fe, Cu) with an FCC lattice, and from the another phase does to the diffraction pattern with a BCC structure as chromium. It should be noted that the diffraction patterns of alloys No 1, 2 (Figs. 2a, b) contain a diffraction maximum at the scattering angles $2\theta = 14^\circ, 30.93^\circ$ which can be uniquely identified as the diffraction maximum (100) from an ordered solid solution of type B2, which exists in equiatomic NiAl alloys with a primitive cubic lattice (Pm3m). The B2 structure was fixed in a large number of HEAs, both as the main structure and in the form of inclusions [21]. A small peak at $2\theta = 17.7^\circ$ in the diffractogram (Fig. 2a) using MoK α radiation can be attributed to the complex carbide (FeCr) $_7$ C $_3$.

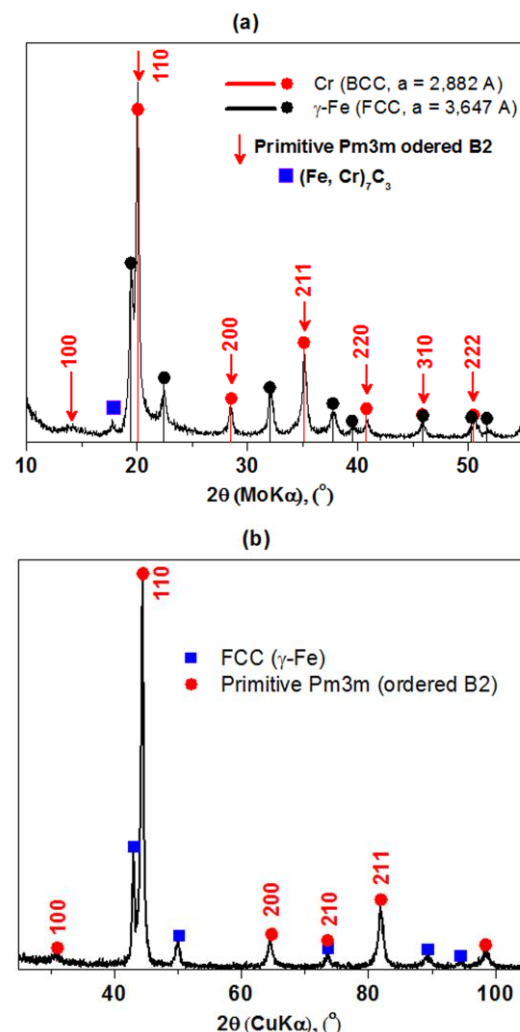


Fig. 2 Diffraction patterns of high-entropy alloys (a) No1 (b) No2 of the FeNiCrCuAl system and reference spectra of alloys from the PDF-2 database.

3.4. Microstructure of high-entropy alloys of the FeNiCrCuAl system

According to the technological phase diagrams, the molten alloys consist of various solid solutions with an FCC structure (L12 phase, as γ -Fe, Cu), a solid solution BCC with an ordered structure of type B2 (as NiAl), or a disordered BCC structure of type A2 (as Cr) [22].

Table 5: Chemical composition of different phases of high-entropy alloys of the FeNiCrCuAl system

No alloy	Place	Chemical composition, at. %									VEC, el./at.	Lattice
		Ni	Fe	Cr	Al	Cu	Si	C	P	S		
1	1	0.685	8.508	64.941	-	0.2186	0.074	25.570	-	-	-	-
	2	13.608	29.807	21.619	10.400	20.599	1.644	2.172	0.032	0.034	7.783	BCC+FCC+B2
	3	30.820	13.207	4.241	25.709	22.338	2.890	0.543	0.041	0.048	7.775	BCC+FCC+B2
2	4	14.86	34.43	25.74	13.23	10.68	1.07	-	-	-	7.399	BCC+B2
	5	9.64	3.99	1.27	12.71	71.76	-	0.62Mn	-	-	9.684	FCC
	6	10.61	4.52	0.99	13.30	69.95	-	0.63Mn	-	-	9.620	FCC
	7	5.92	48.67	33.20	5.50	5.38	1.34	-	-	-	7.288	BCC+B2

The typical microstructure of samples of the FeNiCrCuAl system after their crystallization is presented in Fig. 3. As-cast samples have a heterogeneous structure consisting of several phases – dendrites and interdendritic space. The branches of dendrites are round in shape. The chemical composition of individual phases was determined using X-ray microanalysis (EDX analysis). In Figure 3, the structural components are indicated by numbers (1-7), and their chemical composition is given in Table 5. The more refractory elements such as iron and chromium are concentrated in the branches and trunks of the dendrites, but the interdendritic space is enriched with elements with lower melting points such as copper, aluminum and nickel. White veins in the interdendritic space of alloy No 2 are enriched with copper (Fig. 3b, points 5, 6). The calculated concentrations of valence electrons of separate phases (Table 5) indicate the probability of the formation of three solid solutions in alloys of the FeNiCrCuAl system: white areas (Fig. 3b) enriched with copper have an FCC structure, the dendrites themselves most likely have a mixture of two solutions – a disordered solid solution with a BCC structure, and an ordered solid solution with a primitive cubic lattice of type B2.

The presence of a larger amount of chromium and iron in the branches and trunks of dendrites of alloy No 1 led to the fact that the microhardness of the dendrite branches is 1.1 times larger than the microhardness of the interdendritic space (see Table 6). The microhardness of carbides is 3-5 times larger than the microhardness of dendrites and interdendritic space. The formation of carbides is due to the high content of carbon, chromium and iron (Fig. 3a). Carbon appeared in alloy No1 (with the mass fraction of carbon no more than 0.74 wt. %) because cast iron was used as a charge material.

Table 6: Microhardness of structural components of high-entropy alloy samples of the FeNiCrCuAl system

No alloy	Microhardness, H _μ , kgf/mm ²		
	Interdendritic space	Dendrites	Carbide
1	281±29	311±42	1207±175
2	328±51	290±52	-

4. Conclusions

A literature review was conducted and the conditions for the formation of disordered solid solutions in the structure of high-entropy alloys were determined. The following parameters correspond to the formation of a solid solutions in the HEAs: entropy of mixing $13.4 < \Delta S_{\text{mix}} \leq 22$ J/mol·K; enthalpy of mixing $-40 < \Delta H_{\text{mix}} < 10$ kJ/mol; difference in atomic radii $0 \leq \delta \leq 12.0\%$ and difference in electronegativities of elements $\Delta \chi \leq 12\%$; concentration of valence electrons $\text{VEC} > 8$ (FCC), $\text{VEC} < 6.87$ (BCC), $6.87 < \text{VEC} < 8$ (BCC+FCC); thermodynamic parameter $\Omega \geq 1.1$. A technology for preparation high-entropy alloys of the FeNiCrCuAl system in air by casting methods has been developed. High-alloyed cast iron, stainless steel and ligatures were used as charge materials for the preparation of HEAs. It has been determined that to obtain high-quality castings from high-entropy alloys, it is necessary to overheat the liquid metal above the liquidus temperature by 250-300 °C. The microstructure of high-entropy alloys of the FeNiCrCuAl system has a dendritic phase morphology consisting of several solid solutions based on the disordered BCC and FCC lattices and ordered primitive cubic (B2) lattice and high-chromium carbides.

5. References

1. J. -W. Yeh, Y. -L. Chen, S. -J. Lin, S. -K. Chen, Mater. Sci. Forum, **560**, 1 (2007)
2. Y. Zhang, Y. J. Zhou, Mater. Sci. Forum, **561 – 565**, 1337 (2007)
3. J. -W. Yeh, S. -K. Chen, S. -J. Lin, J. -Y. Gan, T. -S. Chin, T. -T. Shun, C. -H. Tsai, S. -Y. Chang, Adv. Eng. Mater., **6(5)**, 299 (2004)
4. Y. Zhang, *High-Entropy Materials: A Brief Introduction*. (Springer Nature Singapore Pte Ltd. 2019, pp. 35–61).
5. Y. Zhang, S. Guo, C.T. Liu, X. Yang, *Phase formation rules. In: High-Entropy Alloys: Fundamentals and Applications*. (Springer International Publishing, 2016, pp. 21–49)
6. J. Y. Yang, Y. J. Zhou, Y. Zhang, Chin. Mater. Sci. Techn. Equip., **5**, 61 (2007)

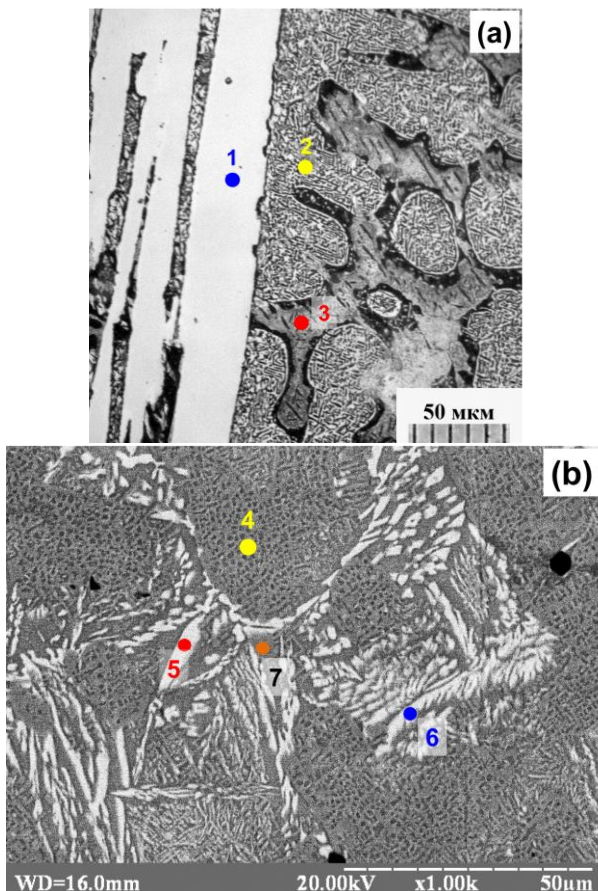


Fig. 3 Microstructure of as-cast high-entropy alloys (a) No1 (b) No2 of the FeNiCrCuAl system. Structural components are indicated by numbers. The chemical composition of individual phases is given in Table 5.

6. J. W. Yeh, Ann. Chim. Sci. Mater., **31**, 633 (2006)
7. M. Slobodyan, E. Pesterev, A. Markov, Materials Today Communications, **36**, 1-82 (2023)106422
8. X. Wang, W. Guo, Y. Fu, J. Mater. Chem. A, **9(2)**, 663 (2021)
9. V. O. Shcheretskyi, O. A. Shcheretskyi, R. A. Sergiienko, A. M. Verkovliuk, D. S. Kanibolotsky, L. D. Taranuhina, I. G. Byba, O. S. Roik, Casting processes, **No3(157)**, 46 (2024) [in Ukrainian]
10. O. Myslyvchenko, JOM **76**, 3960 (2024).
11. O. A. Shcheretskyi, R. A. Sergiienko, A. M. Verkovliuk, Casting processes, **No2(148)**, 50 (2022) [in Ukrainian]
12. A. M. Verkhovliuk, R. A. Sergiienko, O. A. Shcheretskyi, R. S. Serhiiko, O. G. Potrukh, D. S. Kanibolotsky, I. G. Byba, O. V. Zhelezniak, Casting processes, **No4(158)**, 56 (2024) [in Ukrainian]
13. Y. Zhang, Y. J. Zhou, J. P. Lin, G. L. Chen, P. K. Liaw, Adv. Eng. Mater., **10(6)**, 534 (2008)
14. X. Yang, Y. Zhang, Mater. Chem. Phys., **132(2-3)**, 233 (2012)
15. Y. Zhang, Mater. Sci. Forum, **654 - 656**, 1058 (2010)
16. S. Guo, C. Ng, J. Lu, C. T. Liu, J. Appl. Phys., **109(10)**, 103505 (2011)
17. G. Sheng, C. T. Liu, Prog. Nat. Sci.: Mater. Int., **21(6)**, 433 (2011)
18. A. K. Singh, A. Subramaniam, J. Alloys Compd., **587**, 113 (2014)
19. C. T. Liu, Int. Met. Rev., **29(1)**, 168 (1984)
20. J. H. Zhu, P. K. Liaw, C. T. Liu, Mater. Sci. Eng. A, **239 - 240**, 260 (1997)
21. O. M. Myslyvchenko *Features of structure formation and properties of high-entropy alloys of the Cr-Al-Fe-Co-Ni-Cu-Mn-V system: dis. ...cand. tech. sciences: 05.16.01. Kyiv, (2016) pp. 21-28* [in Ukrainian]
22. H. Mao, H. L. Chen, Q. J. Chen, Phase Equilibria Diffus., **38**, 353 (2017)