

УДК 669.018: 539.216.2

ВЫСОКОЭНТРОПИЙНЫЕ СПЛАВЫ Al-Co-Cr-Fe-Mn-Ni-Si-V У ЛИТОМУ ТА РІДКОЗАГАРТОВАНОМУ СТАНІ

БАШЕВ В. Ф.¹, д.ф.-м.н., проф.,
КУШНЕРЬОВ О. І.^{2*}, к.ф.-м.н., доц.

¹ Кафедра експериментальної фізики та фізики металів, Дніпропетровський національний університет ім. О. Гончара, пр. Гагаріна, 72, 49010, Дніпропетровськ, Україна

^{2*} Кафедра експериментальної фізики та фізики металів, Дніпропетровський національний університет ім. О. Гончара, пр. Гагаріна, 72, 49010, Дніпропетровськ, Україна, тел. +38 (056) 776-58-86, e-mail: kushnrv@gmail.com, ORCID ID: 0000-0002-9683-2041

Анотація. Мета. Дану роботу присвячено встановленню впливу складу та швидкості охолодження розплаву на мікротвердість, фазовий склад та параметри тонкої структури високоентропійних сплавів (ВЕС) системи Mn-Ni-Si-V в литому та рідкозагартваному стані. **Методика.** Литі зразки сплавів були отримані із застосуванням мідної виливниці (швидкість охолодження $\sim 10^2$ К/с). Гартування з рідкого стану (ЗРС) проводилося за відомою методикою splat-охолодження. Оцінена за товщиною фольги швидкість охолодження розплаву становила $\sim 10^6$ К/с. Рентгеноструктурний аналіз проводився із використанням дифрактометра ДРОН-2.0. Мікротвердість вимірювалася за допомогою мікротвердоміра ПМТ-3. Підбір компонентів досліджених ВЕС здійснювався, виходячи з прийнятих у літературі критеріїв компоновки та оцінки фазового складу ВЕС, основаних на обчисленні ентропії та ентальпії змішування, концентрацій валентних електронів а також різниці атомних радіусів компонентів. **Результати.** Встановлено, що у структурі литих сплавів присутні неупорядковані тверді розчини типу ОЦК та впорядкований твердий розчин типу В2, в той час, як в ЗРС сплавах – лише неупорядковані тверді розчини типу ОЦК. Визначені параметри решітки дозволяють припустити, що формування твердих розчинів відбувається на основі Cr як елемента із найвищою температурою плавлення. Усі литі зразки сплавів системи Al-Co-Cr-Fe-Mn-Ni-Si-V демонструють наявність чітко вираженої дендритної структури із різними конфігураціями та об'ємами міждендритного простору. Показано позитивний вплив мікронапружень та густини дислокацій на рівень механічних характеристик досліджених сплавів. Встановлено, що ЗРС сплави системи Al-Co-Cr-Fe-Mn-Ni-Si-V характеризуються більш високими значеннями мікротвердості, ніж литі сплави. **Наукова новизна.** У даній роботі були вперше отримані і досліджені ВЕС системи Al-Co-Cr-Fe-Mn-Ni-Si-V у литому і рідкозагартваному стані. **Практична значимість.** ВЕС характеризуються унікальною структурою та цілим комплексом виняткових експлуатаційних характеристик, таких як твердість, зносостійкість, стійкість до окислення, корозії та іонізуючих випромінювань, висока термічна стабільність. Дослідження тонких плівок ВЕС, отриманих шляхом гартування з рідкого стану, також становить великий практичний інтерес, оскільки одним з перспективних застосувань ВЕС є саме тонкоплівкові покриття.

Ключові слова: високоентропійний сплав, гартування з рідкого стану, фазовий склад, структура, мікротвердість

ВЫСОКОЭНТРОПИЙНЫЕ СПЛАВЫ Al-Co-Cr-Fe-Mn-Ni-Si-V В ЛИТОМ И ЖИДКОЗАКАЛЕННОМ СОСТОЯНИИ

БАШЕВ В. Ф.¹, д.ф.-м.н., проф.,
КУШНЕРЕВ А. И.^{2*}, к.ф.-м.н., доц.

¹ Кафедра экспериментальной физики и физики металлов, Днепропетровский национальный университет им. О. Гончара, пр. Гагарина, 72, 49010, Днепропетровск, Украина

^{2*} Кафедра экспериментальной физики и физики металлов, Днепропетровский национальный университет им. О. Гончара, пр. Гагарина, 72, 49010, Днепропетровск, Украина, тел. +38 (056) 776-58-86, e-mail: kushnrv@gmail.com, ORCID ID: 0000-0002-9683-2041

Аннотация. Цель. Настоящая работа посвящена установлению влияния состава и скорости охлаждения расплава на микротвердость, фазовый состав и параметры тонкой структуры высокоэнтропийных сплавов (ВЭС) системы Al-Co-Cr-Fe-Mn-Ni-Si-V в литом и жидкозакаленном состоянии. **Методика.** Литые образцы сплавов были получены с использованием медной изложницы (скорость охлаждения $\sim 10^2$ К/с). Закалка из жидкого состояния (ЗЖС) проводилась по известной методике splat-охлаждения. Оцененная по толщине фольги скорость охлаждения расплава составляла $\sim 10^6$ К/с. Рентгеноструктурный анализ проводился с использованием дифрактометра ДРОН-2.0. Микротвердость измерялась на микротвердомере ПМТ-3. Подбор компонентов исследованных ВЭС осуществлялся, исходя из принятых в литературе критериев компоновки и оценки фазового состава ВЭС, основанных на вычислении энтропии и энтальпии смешивания, концентраций валентных электронов а так же разницы атомных радиусов компонентов. **Результаты.** Установлено, что в структуре литых сплавов присутствуют неупорядоченные твердые растворы типа ОЦК и упорядоченный твердый раствор типа В2, в то время, как в ЗЖС сплавах – только неупорядоченные твердые растворы типа ОЦК. Оцененные параметры решетки позволяют предположить, что формирование твердых растворов происходит на базе Cr как элемента с наивысшей

температурой плавления. Все литые образцы сплавов системы Al-Co-Cr-Fe-Mn-Ni-Si-V демонстрируют наличие ярко выраженной дендритной структуры с различными конфигурациями и объемами междендритного пространства. Показано положительное влияние микронапряжений и плотности дислокаций на уровень механических характеристик исследованных сплавов. Установлено, что ЭЖС сплавы системы Al-Cu-Fe-Ni-Si характеризуются более высокими значениями микротвердости, чем литые сплавы. **Научная новизна.** В данной работе были впервые получены и исследованы ВЭС системы Al-Co-Cr-Fe-Mn-Ni-Si-V в литом и жидкозакаленном состоянии. **Практическая значимость.** ВЭС характеризуются уникальной структурой и целым комплексом замечательных эксплуатационных характеристик, таких как твердость, износостойкость, устойчивость к окислению, коррозии и ионизирующим излучениям, высокая термическая стабильность. Исследование тонких пленок ВЭС, полученных при помощи ЭЖС, также представляет большой практический интерес, поскольку одним из перспективных применений ВЭС являются именно тонкопленочные покрытия.

Ключевые слова: высокоэнтропийный сплав, закалка из жидкого состояния, фазовый состав, структура, микротвердость

HIGH-ENTROPY ALLOYS Al-Co-Cr-Fe-Mn-Ni-Si-V IN AS-CAST AND SPLAT-QUENCHED STATES

BASHEV V. F.¹, *Dr. Sc. (Phys. & Math.), Prof.*,
KUSHNEROV O. I.^{2*}, *Ph.D. (Phys. & Math.), Assoc. Prof.*

¹ Department of Experimental Physics and Physics of Metals, Oles Honchar Dnipropetrovsk National University, 72, Gagarin ave., Dnipropetrovsk 49010, Ukraine

^{2*} Department of Experimental Physics and Physics of Metals, Oles Honchar Dnipropetrovsk National University, 72, Gagarin ave., Dnipropetrovsk 49010, Ukraine, tel. +38 (056) 776-58-86, e-mail: kushnriv@gmail.com, ORCID ID: 0000-0002-9683-2041

Abstract. Purpose. This work is dedicated to establish the effects of the composition and the melt cooling rate on microhardness, phase composition and parameters of the fine structure of high-entropy alloys (HEA) of Al-Co-Cr-Fe-Mn-Ni-Si-V system in the as-cast and rapid quenched state. **Methodology.** As-cast alloy samples were obtained using a copper mold (cooling rate $\sim 10^2$ K/s). Quenching from a liquid state was carried out by a known technique of splat-quenching (SQ). Cooling rate estimated by foil thickness was $\sim 10^6$ K/s. The X-ray diffraction analysis was carried out with use of the DRON-2.0 diffractometer. Microhardness was measured on the PMT-3 microhardnessmeter. Selection of components of the studied HEAs was carried out on the basis of the criteria adopted in the literature for the HEA composition based on calculation of the entropy and enthalpy of mixing, valence electron concentrations as well as the difference between the atomic radii of the components. **Findings.** It was found that the as-cast alloys show a multiphase BCC+B2 structure, while the SQ alloys - fully disordered BCC crystal structure only. The value of lattice parameters of the investigated alloys suggests that the solid solutions are form on the base of Cr lattice, in view of its higher melting temperature. All of the as-cast alloys display a typical cast dendritic structure with various configurations and volumes of the interdendritic space. The positive influence of microstrains level and dislocation density on the microhardness values of splat-quenched Al-Co-Cr-Fe-Mn-Ni-Si-V alloys has been established. Improved mechanical characteristics are ensured by the strong distortion of the crystal lattice due to the differences in atomic radii of the elements. It was found that the splat-quenching HEAs of Al-Co-Cr-Fe-Mn-Ni-Si-V system are characterized by higher values of microhardness than as-cast alloys. **Originality.** At present work were first obtained and studied HEAs of Al-Co-Cr-Fe-Mn-Ni-Si-V system in the as-cast and splat-quenched state. **Practical value.** The HEAs possess many attractive properties, such as high hardness, outstanding wear resistance, irradiation resistance, excellent high-temperature strength, good thermal stability and corrosion resistance. The study of thin films obtained by splat-quenching from the liquid state is also of great practical interest, since one of the promising applications of HEAs are thin film coatings.

Keywords: high-entropy alloy, splat-quenching, phase composition, structure, microhardness

Introduction

Traditionally, the development of new metallic alloys has been carried out by selecting one or two basic elements with subsequent alloying using optimum concentrations of useful impurities. However in the last time, increasing industrial demands for various structural and functional metallic materials have stimulated the advent of new technologies and the development of multicomponent alloys. Recently a new class of materials known in the literature as multicomponent high-entropy alloys (HEA) was obtained [10]. High-entropy alloys are defined as solid solution alloys that contain more than five principal elements (usually from five to thirteen) in equal or near equal atomic percent. The basic principle of HEAs is the stabilization of solution phase by the

significantly higher configurational entropy of mixing ΔS_{mix} compared to conventional alloys. The configurational entropy of mixing during the formation of regular solution alloy can be determined as

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

c_i - atomic fraction of the i -th component, R - universal gas constant. Increasing of mixing entropy reduces the Gibbs free energy of the alloy and improves the stability of the solid solution. For the alloy where n is the number of components maximum mixing entropy is when they are mixed in equal atomic fractions.

Usually in HEAs value of ΔS_{mix} is in the range of 12 - 19 J/(mol·K). Due to the high mixing entropy HEAs are solid solutions typically having simple crystal structures (FCC or BCC), but to avoid the appearance of brittle intermetallic compounds, complex microstructures and amorphous phases in the structure of alloys, some phase formation criteria are required to be completed. According to [20, 21], the Ω parameter can be used to estimate the phase composition of HEA.

$$\Omega = \frac{T_m \Delta S_{mix}}{|\Delta H_{mix}|}, \quad (2)$$

where T_m is the average melting temperature of alloy, ΔH_{mix} - the mixing enthalpy

$$T_m = \sum_{i=1}^n c_i (T_m)_i, \quad (3)$$

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

where the regular melt-interaction parameter between i -th and j -th elements $\Omega_{ij} = 4\Delta H_{mix}^{AB}$, and ΔH_{mix}^{AB} - mixing enthalpy of binary liquid AB alloy. Alloy components should not have large atomic-size difference, which is described by the parameter

$$\delta = 100 \sqrt{\sum_{i=1}^n c_i \left(1 - \frac{r_i}{\bar{r}}\right)^2}, \quad (5)$$

where $\bar{r} = \sum_{i=1}^n c_i r_i$, r_i - the atomic radius of the i -th element.

According to [21] the high-entropy alloys for which $\Omega \geq 1.1$ and $\delta \leq 6.6$ can form the solid solutions without intermetallic compounds and amorphous phases. However, simple (not ordered) solid solutions form if $-15 \text{ kJ/mol} < \Delta H_{mix} < 5 \text{ kJ/mol}$ and $\delta \leq 4.6$.

The other useful parameter is the valence electron concentration, VEC , which has been proven useful in determining the phase stability of high- entropy alloys [4,5]. VEC is defined by:

$$VEC = \sum_{i=1}^n c_i (VEC)_i, \quad (6)$$

where $(VEC)_i$ - valence electron concentration (including the d -electrons) of the i -th element. As pointed in [5] at $VEC \geq 8.0$, sole FCC phase exists in alloy; at $6.87 \leq VEC < 8.0$, mixed FCC and BCC phases will co-exist and sole BCC phase exists at $VEC < 6.87$.

In some studies also proposed structure prediction method, based on an evaluation of the difference of electronegativity values and concentrations of valence electrons for the alloy components. This method is based on the Hume-Rothery rules, according to which for the formation of a binary substitutional solid solution the solvent and solute elements must be characterized by similar values of electronegativity and valence, as well as the minimum difference in the atomic sizes. However, based on the results of [2,9,11], one may say that, in

general, for HEAs this method cannot reliably predict the phase composition of the alloys.

It has been reported that HEAs possess many attractive properties, such as high hardness, outstanding wear resistance, irradiation resistance, excellent high-temperature strength, good thermal stability and corrosion resistance, magnetic and thermoelectric properties [1, 6-8,12-14,16-19,22]. Improved mechanical characteristics are ensured by strong distortion of the crystal lattice due to the differences in atomic radii of the elements.

In this work effect of the value of mixing entropy and composition on the microhardness, phase composition and parameters of the fine structure of HEAs of Al-Co-Cr-Fe-Mn-Ni-Si-V alloy system is discussed (Mn and Si are added as minor elements to improve mechanical properties and corrosion resistance).

Experimental Details

The samples of Al-Co-Cr-Fe-Mn-Ni-Si-V high-entropy alloys were taken from the as-cast (cooling rate of $\sim 10^2 \text{ K/s}$) ingots, polished and etched for examining the microstructure under an optical microscope Neophot-21 and scanning electron microscope (SEM, JSM-6490LV) with energy dispersive spectrometry (EDS). The quenching from the molten state (splat-quenching, SQ) was performed using the well-known technique of melt spinning, i.e., spreading of melt droplets on the internal surface of a rapidly rotating copper cylinder. The rate of cooling as estimated from the thickness of the obtained foils was $\sim 10^6 \text{ K/s}$. The XRD studies were carried out using a DRON-2.0 X-ray diffractometer operating with Cu $K\alpha$ radiation. The microhardness was measured on a PMT-3 microhardness-meter at a load of 200g.

Results and Discussion

Using the data from [4,15], the following quantities are calculated for the investigated HEAs (Tab.1): ΔS_{mix} , ΔH_{mix} , δ , Ω and VEC .

The phase composition of investigated alloys, crystal lattice parameters and fine structure parameters (size of coherently scattering domains and microstrains) (Tab.2) were determined from the XRD patterns (Fig.1, 2). The microhardness values of HEAs are also given in Tab. 2.

The analysis of the XRD patterns allowed us to establish that the investigated HEAs in the as-cast state have two-phase body-centered cubic (BCC) + B2 (caesium chloride) structure. Indeed, from the analyses of Tab. 1 it is seen that ΔH_{mix} has a large negative value favoring the formation of a compound. The low value of VEC favours the formation of a BCC phase. These factors put together leads to the formation of a mixture of BCC and B2 phases (the ordered version of BCC). Exception is the AlCoCrFe_{1.87}Mn_{0.03}NiSi_{0.1}V alloy, for which the value of VEC lies in the range, where a face-centered cubic (FCC) + BCC mixture is favoured. But, as pointed in [11], if the value of VEC is close to the boundary values, predictions of the phase compositions sometimes not work.

Meanwhile the XRD patterns of SQ alloys do not have a (100) B2 superlattice reflection and consequently SQ HEAs contains only disordered BCC phase. In our opinion the high cooling rate during the formation of thin SQ film should prevent it from possible separation and hinder the appearance of structures and phases typical for equilibrium as-cast states.

Table 1

Values of ΔH_{mix} , ΔS_{mix} , δ , VEC и Ω for HEAs of Al-Co-Cr-Fe-Mn-Ni-Si-V alloy system

Alloy	ΔH_{mix} , kJ/mol	ΔS_{mix} , J/(mol·K)	δ	VEC	Ω
AlCoCrFe _{0.87} Mn _{0.03} NiSi _{0.1} V	-17.04	15.52	5.18	6.76	1.6
AlCoCrFe _{1.87} Mn _{0.03} NiSi _{0.1} V	-14.6	15.18	4.96	6.94	1.84
Al ₂ CoCrFe _{0.87} Mn _{0.03} NiSi _{0.1} V	-18.98	15.07	5.78	6.22	1.3
Al ₂ CoCrFe _{1.87} Mn _{0.03} NiSi _{0.1} V	-16.81	14.97	5.66	6.45	1.48

Table 2

Phase composition, size of coherently scattering domains (L), degree of distortion of the crystal lattice ($\Delta a/a$) and microhardness (H_{μ}) of investigated alloys

Alloy	Phase composition	L, nm	$\Delta a/a$	H_{μ} , MPa
As-cast AlCoCrFe _{0.87} Mn _{0.03} NiSi _{0.1} V	BCC + B2 (a=0.2888 nm)	20±2	3.2·10 ⁻³	6800 ±300
SQ film AlCoCrFe _{0.87} Mn _{0.03} NiSi _{0.1} V	BCC (a=0.2882 nm)	34±2	3.8·10 ⁻³	6900 ±300
As-cast AlCoCrFe _{1.87} Mn _{0.03} NiSi _{0.1} V	BCC + B2 (a=0.2882 nm)	30±2	2.5·10 ⁻³	4800 ±200
SQ film AlCoCrFe _{1.87} Mn _{0.03} NiSi _{0.1} V	BCC (a=0.2879 nm)	25±2	2.8·10 ⁻³	6200 ±300
As-cast Al ₂ CoCrFe _{0.87} Mn _{0.03} NiSi _{0.1} V	BCC + B2 (a=0.2888 nm)	35±2	1.6·10 ⁻³	6500 ±300
SQ film Al ₂ CoCrFe _{0.87} Mn _{0.03} NiSi _{0.1} V	BCC (a=0.2887 nm)	33±2	1.8·10 ⁻³	7500 ±300
As-cast Al ₂ CoCrFe _{1.87} Mn _{0.03} NiSi _{0.1} V	BCC + B2 (a=0.2886 nm)	37±2	1.5·10 ⁻³	4600 ±200
SQ film Al ₂ CoCrFe _{1.87} Mn _{0.03} NiSi _{0.1} V	BCC (a=0.2881 nm)	33±2	1.7·10 ⁻³	5600 ±200

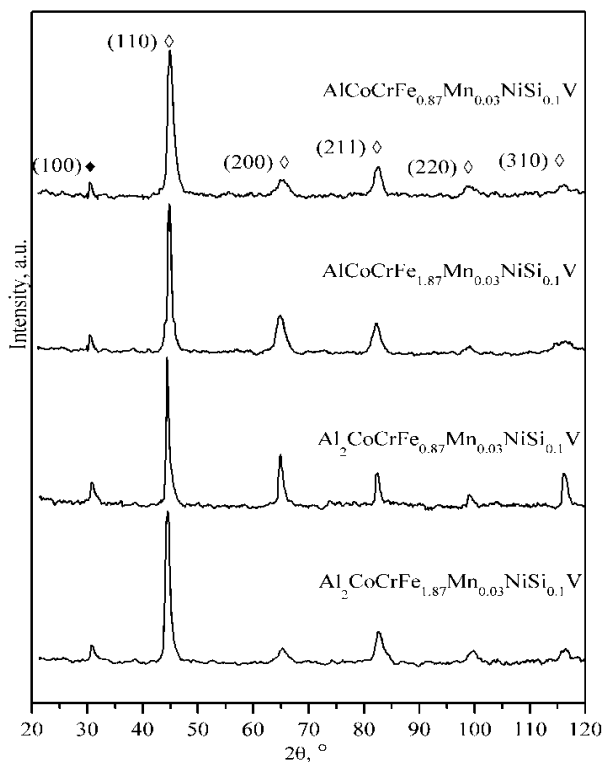


Fig.1. XRD patterns of as-cast HEAs of Al-Co-Cr-Fe-Mn-Ni-Si-V alloy system: \diamond -BCC, \blacklozenge -B2.

The values of lattice parameters of the investigated alloys suggests that the solid solutions are form on the base of Cr lattice ($a = 0.2884$ nm), in view of its higher melting temperature.

High microhardness values of Al-Co-Cr-Fe-Mn-Ni-Si-V HEAs (Tab.2) can be explained by the presence of the dissimilar atoms of elements with different size, electronic structure and thermodynamic properties in the crystal lattice. This leads to significant distortion ($\Delta a/a$) of the crystal lattice. Consequently the hardness of the alloys increases. As seen from Tab. 2, microhardness of the SQ alloys is higher than that of the as-cast alloys. This result is not unexpected, since the microstructure and the phase composition of the as-cast alloy after decomposition is in a more equilibrium multiphase state, while SQ alloys yields higher level of microstrains and dislocation density.

Fig. 3,4 are SEM micrographs of the as-cast HEAs of Al-Co-Cr-Fe-Mn-Ni-Si-V system. All of the alloys display a typical cast dendritic structure with various configurations and volumes of the interdendritic space. The EDS analysis made it possible to reveal the dendritic segregation in alloys. Tab. 3 shows the chemical composition of different areas analyzed by EDS. According to Tab. 3 The bright dendritic area has a higher amount of Al and Ni than dark interdendritic area, but the dark section of interconnected microstructure enriched with Fe, V and Cr elements. In contrast of the previous research [3] the addition of V not reduce segregation of Al, Ni, Fe, Cr elements. Obviously this is influenced by Mn and Si.

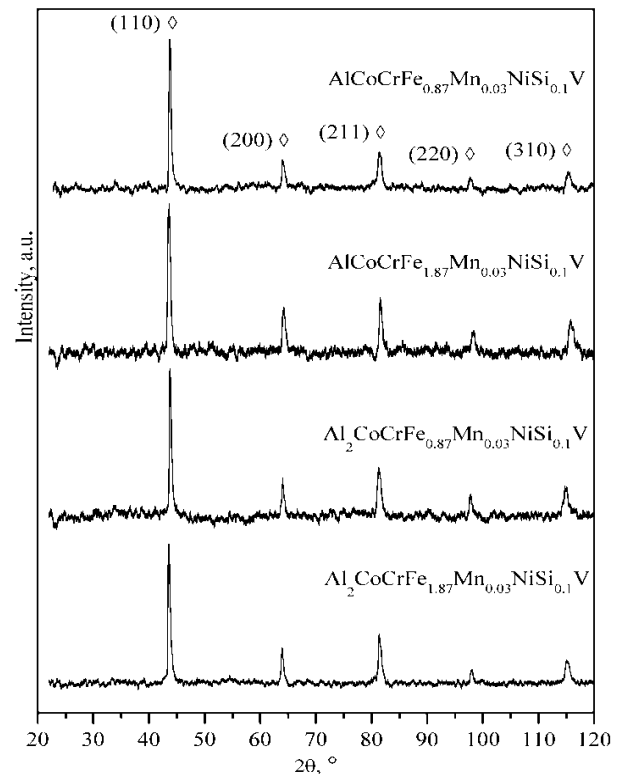


Fig.2. XRD patterns of splat-quenched HEAs of Al-Co-Cr-Fe-Mn-Ni-Si-V alloy system: \diamond -BCC.

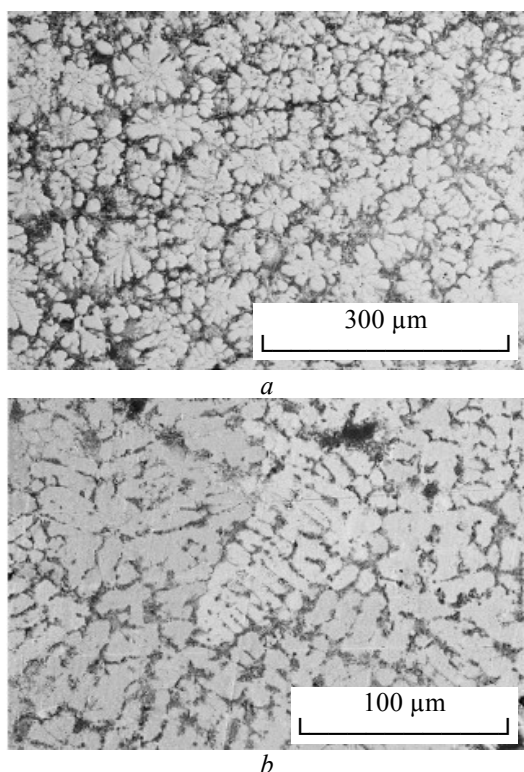


Fig.3. SEM images of as-casted HEAs specimens:
 a - $AlCoCrFe_{0.87}Mn_{0.03}NiSi_{0.1}$;
 b - $AlCoCrFe_{1.87}Mn_{0.03}NiSi_{0.1}V$

Conclusions

Based on the study of the Al-Co-Cr-Fe-Mn-Ni-Si-V HEAs, produced in the as-cast and splat quenched state, the following conclusions can be drawn:

1. As-cast alloys have multiphase BCC + B2 structure while SQ alloys exhibit only disordered BCC solid solution structure.
2. With the increase of cooling rate the level of microstrains, dislocation density and microhardness of Al-Co-Cr-Fe-Mn-Ni-Si-V HEAs increases.

3. The obtained results confirm the leading role of the element with higher melting temperature as the basis for the formation of solid solutions in the studied alloys.
4. The splat-quenched HEAs of Al-Co-Cr-Fe-Mn-Ni-Si-V system characterized by higher values of microhardness than as-cast alloys, which is obviously caused by higher level of microstrains and dislocation density.

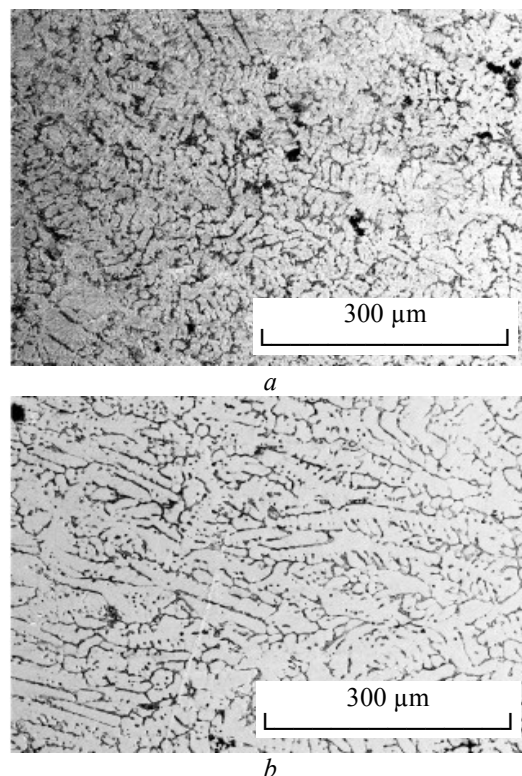


Fig.4. SEM images of as-casted HEAs specimens:
 a - $Al_2CoCrFe_{0.87}Mn_{0.03}NiSi_{0.1}$;
 b - $Al_2CoCrFe_{1.87}Mn_{0.03}NiSi_{0.1}V$

Table 3

Chemical composition of as-cast HEAs of Al-Co-Cr-Fe-Mn-Ni-Si-V alloy system

Alloy		Elements, at. %							
		Al	Co	Cr	Fe	Mn	Ni	Si	V
$AlCoCrFe_{0.87}Mn_{0.03}NiSi_{0.1}V$	Dendrite	20.13	17.25	14.77	14.03	0.29	19.64	1.07	12.82
	Interdendrite	10.30	16.14	20.95	17.34	0.71	14.05	2.47	18.04
	Nominal	16.67	16.67	16.67	14.49	0.5	16.67	1.66	16.67
$AlCoCrFe_{1.87}Mn_{0.03}NiSi_{0.1}V$	Dendrite	15.71	14.08	13.91	26.23	0.42	15.48	1.19	15.38
	Interdendrite	11.46	14.37	16.71	27.85	0.47	13.81	1.61	13.72
	Nominal	14.28	14.28	14.28	26.74	0.43	14.28	1.43	14.28
$Al_2CoCrFe_{0.87}Mn_{0.03}NiSi_{0.1}V$	Dendrite	30.35	16.25	11.10	11.31	0.28	18.21	1.10	11.40
	Interdendrite	9.28	10.10	21.90	18.85	0.70	8.10	1.57	29.50
	Nominal	28.58	14.28	14.28	12.44	0.43	14.28	1.43	14.28
$Al_2CoCrFe_{1.87}Mn_{0.03}NiSi_{0.1}V$	Dendrite	30.03	11.8	11.25	21.04	0.27	13.47	0.96	11.08
	Interdendrite	9.97	15.8	15.32	25.02	0.57	10.63	1.49	21.11
	Nominal	25	12.5	12.5	23.37	0.38	12.5	1.25	12.5

REFERENCES

1. Bashev V.F. and Kushnerov O.I. *Structure and properties of high-entropy CoCrCuFeNiSn_x alloys* // The Physics of Metals and Metallography. 2014, vol. 115, no. 7, pp. 692–696.
2. Dong Y., Lu Y., Jiang L., Wang T. and Li T. *Effects of electro-negativity on the stability of topologically close-packed phase in high entropy alloys* // Intermetallics. 2014, vol. 52, pp. 105–109.
3. Dong Y., Zhou K., Lu Y., Gao X., Wang T. and Li T. *Effect of vanadium addition on the microstructure and properties of AlCoCrFeNi high entropy alloy* // Materials and Design. 2014, vol. 57, pp. 67–72.
4. Guo S., Liu C.T. *Phase stability in high entropy alloys: Formation of solid-solution phase or amorphous phase* // Progress in Natural Science: Materials International. 2011, vol. 21, no. 6, pp. 433–446.
5. Guo S., Ng C., Lu J. and Liu C.T. *Effect of valence electron concentration on stability of fcc or bcc phase in high entropy alloys* // Journal of Applied Physics. 2011, vol. 109, no. 10, pp. 1–5.
6. He J.Y., Wang H., Huang H.L., Xu X.D., Chen M.W., Wu Y., Liu X.J., Nieh T.G., An K. and Lu Z.P. *A precipitation-hardened high-entropy alloy with outstanding tensile properties* // Acta Materialia. 2016, vol. 102, pp. 187–196.
7. Körmann F., Ma D., Belyea D.D., Lucas M.S., Miller C.W., Grabowski B. and Sluiter M.H.F. *“Treasure maps” for magnetic high-entropy-alloys from theory and experiment* // Applied Physics Letters. 2015, vol. 107, no. 14, p. 142404.
8. Lu Z.P., Wang H., Chen M.W., Baker I., Yeh J.W., Liu C.T. and Nieh T.G. *An assessment on the future development of high-entropy alloys: Summary from a recent workshop* // Intermetallics. 2015, vol. 66, pp. 67–76.
9. Miracle D., Miller J., Senkov O., Woodward C., Uchic M. and Tiley J. *Exploration and Development of High Entropy Alloys for Structural Applications* // Entropy. 2014, vol. 16, no.1, pp. 494–525.
10. Murty B.S., Yeh J.-W. and Ranganathan S. *High-Entropy Alloys*. Oxford: Butterworth-Heinemann, 2014, 219 p.
11. Singh A.K., Kumar N., Dwivedi A. and Subramaniam A. *A geometrical parameter for the formation of disordered solid solutions in multi-component alloys* // Intermetallics. 2014, vol. 53, pp. 112–119.
12. Shafeie S., Guo S., Hu Q., Fahlquist H., Erhart P. and Palmqvist A. *High-entropy alloys as high-temperature thermoelectric materials* // Journal of Applied Physics. 2015, vol. 118, no. 18, p. 184905.
13. Stepanov N.D., Shaysultanov D.G., Salishchev G. A. and Senkov O.N. *Mechanical Behavior and Microstructure Evolution during Superplastic Deformation of the Fine-Grained AlCoCrCuFeNi High Entropy Alloy* // Materials Science Forum. 2016, vol. 838-839, pp. 302–307.
14. Stepanov N.D., Shaysultanov D.G., Salishchev G.A. and Tikhonovsky M.A. *Structure and mechanical properties of a light-weight AlNbTiV high entropy alloy* // Materials Letters. 2015, vol. 142, pp. 153–155.
15. Takeuchi A. and Inoue A. *Classification of bulk metallic glasses by atomic size difference, heat of mixing and period of constituent elements and its application to characterization of the main alloying element* // Materials Transactions. 2005, vol. 46, no. 12, pp. 2817–2829.
16. Tsai M.-H. and Yeh J.-W. *High-Entropy Alloys: A Critical Review* // Materials Research Letters. 2014, vol. 2, no. 3, pp. 107–123.
17. Yeh J.-W. *Physical Metallurgy of High-Entropy Alloys* // JOM. 2015, vol. 67, no. 10, pp. 2254–2261.
18. Yu P.F., Zhang L.J., Cheng H., Zhang H., Ma M.Z., Li Y.C., Li G., Liaw P.K. and Liu R.P. *The high-entropy alloys with high hardness and soft magnetic property prepared by mechanical alloying and high-pressure sintering* // Intermetallics. 2016, vol. 70, pp. 82–87.
19. Zaddach A.J., Niu C., Oni A.A., Fan M., LeBeau J.M., Irving D.L. and Koch C.C. *Structure and magnetic properties of a multi-principal element Ni–Fe–Cr–Co–Zn–Mn alloy* // Intermetallics. 2016, vol. 68, P 107–112.
20. Zhang Y., Yang X. and Liaw P.K. *Alloy Design and Properties Optimization of High-Entropy Alloys* // JOM. 2012, vol. 64, no. 7, pp. 830–838.
21. Zhang Y., Zhou Y.J., Lin J.P., Chen G.L. and Liaw P.K. *Solid-Solution Phase Formation Rules for Multi-component Alloys* // Advanced Engineering Materials. 2008, vol. 10, no. 6, pp. 534–538.
22. Zhang Y., Zuo T.T., Tang Z., Gao M.C., Dahmen K.A., Liaw P.K. and Lu Z.P. *Microstructures and properties of high-entropy alloys* // Progress in Materials Science. 2014, vol. 61, pp. 1–93.

Статья рекомендована к публикации д-ром техн. наук, В.И. Большаковым и д-ром техн. наук, Д.В. Лаухиным (Украина)