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INVESTIGATION OF THE PROPERTIES OF THE CoCrFeMnNi ALLOY DEVELOPED ON THE BASIS OF THE ENTROPY APPROACH

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The paper presents the results of studying some properties and structure of a quasi high-entropy alloy (QHEA) of the CoCrFeMnNi system melted with the use of ferroalloys. The paper presents the results of a study of some properties and structure of a quasi-high-entropy alloy of the CoCrFeMnNi system, smelted using low-carbon ferromanganese and ferrochrome. Chemical composition, strength and microhardness have been studied. The structure contains a small number of inclusions of silicate nature. The experimental alloy demonstrated properties close to the level of properties of a similar alloy melted with the use of pure metals by 5-fold remelting. The results obtained showed the possibility of partial replacement of pure metals with ferroalloys when smelting of QHEAs, which will positively affect their cost.

Keywords: ferroalloy system, smelting, quasi high-entropy alloy, mechanical properties, structure.

INTRODUCTION

High-entropy alloys (HEAs) are an updated trend in the development of structural metal materials.

When developing a HEA, there is used a completely different principle. The alloy composition contains the minimum of 5 components, preferably in equiatomic concentration or with the content of each element from 35 to 5 %.

The idea of making a HEA is based on the thermodynamic principle of increasing entropy when mixing various components. This process is accompanied by the decreasing of free energy, which increases the likelihood of the formation of simple structures, such as substitutional solid solutions of increased stability. In most HEAs, a single-phase structure of a substitutional solid solution with a simple FCC or BCC lattice is formed [1].

Currently, there is a fairly large number of works that deal with the development of HEAs based on various systems [2-10]. The work [11] describes the classical alloy of the CoCrFeMnNi system (Cantor's alloy) that showed the promise of using alloys of this system for further research. This study shows that with the base CoCrFeMnNi system, a single-phase substitutional solid solution with an FCC lattice is formed. In [5] it was shown that alloying with such substitutive elements as Ti,Nb,V and B causes high strength properties, determines the practical application of this HEAs.

It should be noted that a common disadvantage of all of the listed HEAs is their high cost compared to traditional materials. This is related both to the charge, because HEAs are smelted with the use of pure metals and due to the peculiarities of smelting that includes mandatory remelting, accelerated crystallization and the other methods of increasing the structure homogeneity.

The creation of so-called quasi-high-entropy alloys (QHEAs), which are subject to less stringent structural requirements, is becoming an increasingly popular trend. [6].

The general principle of developing QHEAs is the same as that of HEAs: a multicomponent system is used that consists at least 5 components, however, the equiatomic concentration is not strictly observed and in the production of QHEAs the requirements for the charge and smelting method are much lower. This makes it possible to increase the commercial attractiveness of QHEAs with the level of properties comparable to those of HEAs.

The purpose of this work is to study the possibility of smelting a QHEA based on the CoCrFeMnNi system with partial use of ferroalloys, which will significantly reduce the cost of the alloy.

Experimental studies

Equipment and tools

The following charge materials were used for smelting: ferromanganese grade FeMn80C05 (GOST 4755-91), ferrochrome grade FH001A GOST 4757-91, grade N-1u (SS 849-97) metallic nickel and grade K1Au (SS 123-2008) metallic cobalt. The chemical composition of the charge materials is given in Table 1. The content of the main elements was determined using a Niton spectrometer, the values of the remaining elements are indicated in accordance with SS.

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Table 1 **Composition of charge materials**

Element / %	FeMn80C05	FH001A	Ni H-1y	Co K1Ay
Mn	75,1	-	-	0,03
Fe	25,2	32,04	-	0,2
Cr	-	68,2	-	-
Ni	-	-	99,95	-
Co	-	-	-	99,3
C	to 0,1	to 0,01	to 0,01	0,02
Si	1,85	0,82	0,002	-
P	to 0,3	to 0,02	0,001	0,001
S	to 0,03	to 0,02	0,003	0,004

The composition of the charge was selected in such a way that the share of each component in the final alloy would be about 20 %.

The dispersion of all the components was 90 % represented by the fraction of 3-5 mm. Next, the charge mixture was thoroughly mixed and smelted in a UIP-16-10-0,005(Fe)-UHL4 laboratory furnace with an enhanced cooling system. To achieve a uniform composition and to eliminate external contamination, the resulting ingot (weight 0,9 kg) was poured into a chemically inert crucible, remelted and then poured back into the crucible. After complete cooling, samples were prepared from the ingot for analysis. The chemical composition, microhardness, strength and structure were studied.

The chemical composition of the test ingot was determined using a Poly Spec-F spectrometer. To study the fine structure of the prototypes, a TESCAN VEGA scanning electron microscope equipped with an X-ray energy-dispersive spectrometer was used.

X-ray studies were carried out on an X'PertPRO diffractometer using CuK_{α}- radiation. The experimental spectra were processed using the diffractometer software: X'Pert High Score Plusversion 2.2b and X'Pert High Score version 2.2b.

Microhardness was determined using a Willson 1150 instrument; measurements were taken at no less than 5 points. Tensile strength was determined on an INSTRON testing machine with 3 takes.

Table 2 presents the results of the chemical analysis of the experimental ingot. The characteristics of the alloy indicated in [18] were used as a comparison (reference) sample.The alloy specified in [5] belongs to the HEAs class and was obtained by electric arc melting of pure metals followed by casting into a water-cooled copper mold. To ensure chemical homogeneity, the ingot was melted at least 5 times.

It is seen from the data in Table 2 that the composition of the experimental alloy does not correspond to the equiatomic composition, although it can be classified as a quasi high-entropy alloy, because the content of each element does not exceed 35 % but is larger than 5 %.

For this purpose, an analysis of the microhardness and strength of the experimental alloy was carried out. Table 3 shows similar characteristics of the comparison alloy for comparison.

Table 2 **Chemical composition of the ingot obtained**

No	1	2
Element / %	Experimental	Comparison (reference) alloy
Fe	15,3	20,06
Cr	23,3	19,87
Mn	22,4	19,46
Co	19,1	19,87
Ni	19,2	19,97
Si+ rem	0,70	0,77

Table 3 **Microhardness and strength of the the samples**

Sample	Microhardness / HV	Ultimate strength / MPA
Experimental	130	430
Reference (comparison) alloy	136	443

The data in Table 3 show that the experimental alloy is not inferior to the comparison sample in terms of the specified characteristics.

Figure 1 shows the structure of the experimental alloy and the results of MRSA at 4 points. It can be seen from the data in Table 4 and the given characteristic spectrum that the structure contains Fe, Cr, Mn, Co and

Table 4 **Chemical elements concentrations expressed in weight percent**

Spectra	Element content in the selected spectrum / %					
	Ni	Cr	Fe	Mn	Co	Si
1	18,9	23,1	15,3	21,43	18,9	-
2	19,32	23,2	14,87	22,13	19,21	-
3	19,21	22,98	15,02	22,31	19,5	-
4	19,28	22,30	15,2	22,48	19,6	-
5	-	-	-	-	-	0,9

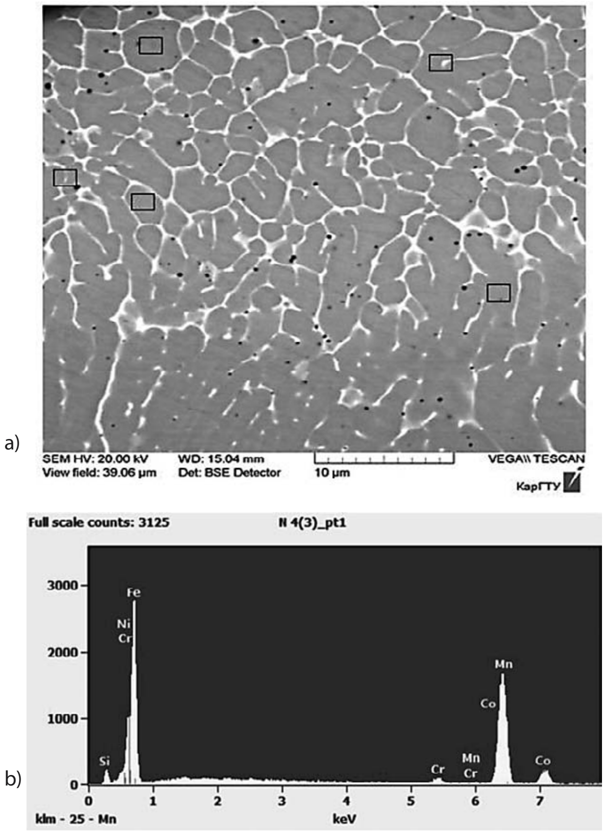

Figure 1 a) structure of the experimental alloy; b) characteristic spectrum of the experimental alloy

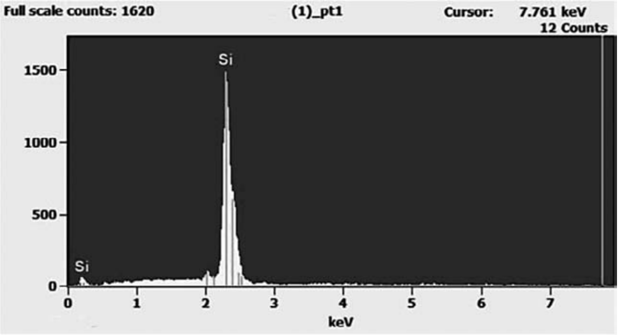

Figure 2 Inclusion characteristic spectrum

Ni, and their concentration practically coincides with the concentration of elements obtained on Poly Spec-F.

The structure of the experimental alloy is represented by a solid solution, presumably of the substitution type with an FCC lattice [4]. The matrix also contains minor inclusions, presumably of silicate nature. Table 3 shows concentrations of chemical elements in the selected spectra.

Spectrum 5 (inclusion) differs in composition from the other spectra; the only one of the spectra contains silicon in the complete absence of other elements. Analysis of the inclusion (Figure 2) showed that the inclusion appears to be of silicate nature; its genesis is associated with the presence of silicon in the charge materials.

Inclusions of silicate type are undesirable in the matrix, because they disrupt its homogeneity and can play the role of a glassy phase, which reduces the plasticity of the matrix.

Having analyzed such parameters as the microhardness and strength of the experimental alloy in comparison with similar characteristics of a high-entropy alloy based on a similar CoCrFeMnNi system, it can be argued that the experimental alloy can be classified as a HEAs. However, given that the equiatomic concentration has not been reached in the experimental alloy, and there are also some impurities in the form of silicate inclusions, this alloy can be characterized as quasi-high-entropy.

The conducted studies on the smelting of QHEAs with partial use of ferroalloys instead of pure metals have shown the fundamental possibility of such a replacement. In this work, the replacement rate was 40 % (2 out of 5 components). The expansion of the basic system, for example, to 6 components, will increase the proportion of replacement ferroalloys to 50 %, which, accordingly, will increase the concentration of iron in the alloy and will allow to obtain a composition even closer to the equiatomic concentration. In addition, the use of ferroalloys in the smelting of QHEAs provides broad prospects for creating certain properties, such as corrosion resistance, provided that ferroalloys containing an element of the desired nature are used.

CONCLUSIONS

As a result of the studies, the possibility of smelting QHEAs based on the FeCrMnNiCo system with partial replacement of pure metals with ferroalloys was established. The properties of the experimental alloy are similar to those of QHEAs based on a similar system but smelted with the use of pure metals with a 5-fold remelting. The results obtained show the possibility of partial replacing pure metals with ferroalloys when smelting QHEAs, which will have a positive effect on their cost. This suggests that the experimental alloy will be attractive for further research in order to improve its properties for industrial use.

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Note: Responsible for the English language is Natalya Drak,
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