



Investigation of the influence of the thermal effects on the FeCrAl alloys Kh15Yu5 and Kh23Yu5

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Abstract

FeCrAl alloys having the composition of chromium added to iron is peculiar by in the increased corrosion resistance of the new metallic alloy compared to pure iron. Such FeCrAl alloys are used in numerous different applications as a corrosion resistant, oxidation resistant and heat resistant material. Owing to their resistance and good mechanical characteristics, FeCrAl alloys are regarded as one of the main structural materials for use in nuclear power plants. They are commonly used within industrial applications where high-temperature oxidation resistance is needed. The good resistance to oxidation, sulfur resistance and corrosion resistance are attained due to a dense oxide film formed on the surface that prevents the rapid further degradation of the material. In this study, two FeCrAl alloys are investigated - Kh15Yu5 (15%Cr5%Al) and Kh23Yu5 (23%Cr5%Al). Using the method of Mössbauer spectroscopy, the study was conducted on the influence of temperature and period of heating on the cold-rolled ribbon of FeCrAl alloys Kh15Yu5 and Kh23Yu5 with the thickness of 50 µm. It is shown that these alloys, as a result of thermal effect, are prone to the layering in solid solution, forming the areas depleted and enriched with chromium and aluminum.

Keywords: FeCrAl alloys, chromium-containing alloys, Mössbauer spectroscopy, effective magnetic field, impurity atoms, solid solution layering

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INTRODUCTION

Chromium-containing alloys are widely used in various fields, in particular, in the pressure treatment of materials and in the production of medical instruments in the automotive industry. Alloying elements have the capability to block slip planes. In the case of chromium added to iron (Fe-Cr alloys), there is an advantage, which consists of a tremendous increase in the corrosion resistance of the new metallic alloy compared to pure iron. There are more than a hundred chromium-containing metallic alloys. Each one was developed for a particular need, and each has its own set of properties and characteristics. The most important characteristics common to all chromium-containing alloys, among the stainless steels, is that they contain sufficient chromium to make them corrosion resistant, oxidation resistant and/or heat resistant (Cunat 2014).

Chromium is currently used in such widely diversified products as stainless, tool and alloy steels, heat- and corrosion-resistant materials, special purpose alloys, alloy cast iron, pigments, metal plating, leather tanning, chemicals, and refractory materials for metallurgical furnaces. It is used in the metallurgical industry to enhance such properties as hardenability (response to quenching), creep (unit stress that will produce plastic

deformation at a specified rate and temperature), strength and impact strength and resistance to corrosion, oxidation, wear and galling; its major use is in the production of stainless steel. Chromium alloys are used in a large variety of applications, including jet engine parts, nuclear plants, high-temperature reaction vessels, chemical industry equipment, high temperature-resistant equipments, coinage, desalination plants, ships' propellers, acid-resistant equipment, cutting tools and implants (IARC Working Group on the Evaluation of Carcinogenic Risk to Humans 1990).

Chromium and ferrochromium have a relatively low deoxidizing ability compared to aluminum and silicon, so the Fe Cr Al complex ferroalloy is a good option for the combination of deoxidizing and alloying properties. Upon addition to the liquid steel, these alloys quickly dissolve, which reduces the duration of their contact with the air (lower oxidation and nitridation). FeCrAl alloys are produced by reducing chromium oxide raw materials with aluminum in the presence of a large excess of aluminum in the charge mixture. Some plants produce

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ferrochrome-aluminum prepared by dissolving aluminum in liquid ferrochrome, but as mentioned this route is not very economic. Additionally, production of FeCrAl by the aluminothermic method allows lower phosphorus content in the alloy in comparison with the method whereby FeCr and Al are fused. Ferro-chrome-aluminum is produced in a single step in ferroalloy furnaces by carbon reduction of fused alumina (or a similar alumina source, such as kyanite) in the presence of charge ferrochrome or ferrosilicochrome (Gasik 2013).

FeCrAl alloys are considered as one of the main structural materials for use in nuclear power plants due to their high corrosion resistance and good mechanical characteristics, in addition, vacancy swelling is uncharacteristic of them, which plays a significant role in the technology of fast neutron reactors and thermonuclear reactors (Chen et al. 2014, Pechenkin et al. 2013). According to Chen et al. (2018), FeCrAl alloys are one of the most suitable for the cladding materials because of their reasonable formability, moderate strength and excellent oxidation resistance at high temperatures. The excellent oxidation resistance is mainly attributed to the alumina (Al_2O_3) scale, which not only protects the alloy substrate from further oxidizing, but also has superior resistance to carburization compared to chromia layer. The FeCrAl alloy is the first barrier between the radioactive elements and the biosphere surrounding the nuclear power plants, as stated in his work Rebak (2017). By improving on the performance of the first barrier (cladding of the fuel), the consequence of combustible hydrogen explosion or release of radioactive elements outside the nuclear power plant is greatly minimized. The main reason FeCrAl has been selected is because it has superior oxidation resistance in the event of a severe accident. Under normal operation conditions and up to 1000 °C the protection to the alloy is given by the formation of a chromium rich oxide on the surface. However, as the temperature increases beyond 1000 °C, an aluminum oxide layer (alumina) forms between the metal and the chromium oxide layer. Eventually, in the presence of steam, the chromium oxide layer volatilizes and the alumina layer remains on the surface protecting the alloy from further oxidation up to its melting point (~1500 °C) (Rebak 2017). FeCrAl alloys, like many engineering alloys, were designed to resist attack by the environment via the development of an oxide film on the surface that slows down further degradation of the material to imperceptible values for the intended industrial application (Rebak et al. 2018).

Iron-chromium-aluminum (FeCrAl) alloys are an alloy class typically deployed within industrial applications where high-temperature oxidation resistance is needed. FeCrAl alloys mainly consist of iron (Fe), chromium (Cr), and aluminum (Al), together with minor alloying additions for various purposes, such as solid-solution

hardening, precipitate hardening, grain size control, oxidation resistance, and so on. The matrix is fully ferritic (body-centered-cubic structure, BCC) phase with typically no phase transformation to/from austenite (face-centered-cubic structure, FCC) in the range from liquidus temperature to room temperature (Yamamoto et al. 2017).

All elements may oxidise in an FeCrAl alloy depending on temperature and exposure environment. Initially (during heating) all elements present at the alloy surface will oxidise and form a mixed oxide scale called transient oxide. Different oxides will form depending on the application temperature (Israelsson 2014). The protection of FeCrAl-base alloys against oxidation at high temperatures depends on the good adhesion of the $\alpha\text{-Al}_2\text{O}_3$ scale produced. The adhesion of the oxide can be much improved if the FeCrAl alloys are doped with small amounts of Y (Mennicke et al. 1998). Prescott and Graham believe (1992), that in order to develop an understanding of the mechanisms involved in the oxidation of alumina-forming alloys, it is reasonable to begin by examining the binary Fe-Al system. In most technically relevant atmospheres and at temperatures as high as 1400 °C, these materials form very protective alumina scales that prevent rapid corrosive degradation of the metallic components. The lifetime of the FeCrAl-based alloy components can be limited by oxidation, because the scale-forming element Al is present only in a limited amount within the alloy matrix (Dimiyati et al. 2003).

The electrical properties of FeCrAl alloys have been primarily based on studies of FeCrAl wires for high-temperature strain gage applications. Studies in general have shown alloys to have favorable electrical properties including high-temperature resistivity and low-temperature coefficient of resistance. In general, FeCrAl alloys are known to exhibit excellent oxidation resistance. Overall, FeCrAl alloys with varying composition, microstructure, and processing will behave differently for a given parameter/experiment and thus data from one FeCrAl alloy may not be applicable to others (Yamamoto et al. 2017).

Iron-chromium-aluminum (FeCrAl) alloys have been in existence for nearly 90 years. They are Fe-based ferritic materials (bcc structure) containing 12% to 21% Cr and 4% to 6% Al. Some FeCrAl may also contain 2% to 3% molybdenum (Mo) and smaller amounts of other elements such as yttrium (Y), zirconium (Zr), hafnium (Hf), and titanium (Ti). FeCrAl have extraordinary resistance to degradation at high temperatures (> 1000°C) due to the formation of an external protective layer of alumina. One extraordinary attribute of the FeCrAl alloys is their resistance to attack by air and steam up to their melting point (Rebak et al. 2018).

At the same time, the alloys have some deficiencies as well:

- the tendency to irreversible grain growth during operation and, as a result, embrittlement and a sharp decrease in maintainability;
- reduced in comparison with nichromes ductility in the production of blanks and heaters;
- additional costs for preheating 600-750 °C in the production of wire heaters with a diameter of more than 5 mm.
- interaction of heaters with lining containing more than 1 % of iron oxides, as well as with slags, sodium chloride, enamels;
- the tendency to corrosion during long-term storage and a sharp life loss of heaters that came into operation with signs of corrosion attack (Mishchenko et al. 2010).

Due to the formation of the protective α -alumina, FeCrAl alloys are commonly used as heating elements for various different applications, including the electrical elements of gas burners, furnace rollers, ignitors etc (Eklund et al. 2018). FeCrAl alloys are one of the most used alloys used in electric heaters, for which characteristic are high electrical resistance, external thermal resistance, corrosion resistance, stable shape under high temperatures, etc. High electrical resistance helps to preserve the material and reduce the space occupied by the component. The alloy has a high surface load for a rapid temperature rise. It has good resistance to oxidation, a dense oxide film is formed, good performance of sulfur resistance and corrosion resistance. And it is characterized by low processing capacity, so it often becomes brittle as the crystal grain grows after long-term use at high temperature. However, because of the low cost and availability of raw materials, it is used in most electric heating materials. FeCrAl alloys are also used as a material for resistance elements such as heat resistant alloys. The high heat resistance of these alloys is due to the formation on the metal surface of protective oxide films such as spinel $\text{FeO} \cdot (\text{Al}_2\text{O}_3, \text{Cr}_2\text{O}_3)$, which have low diffusion permeability, good protective properties and the ability to prevent further oxidation of the metal. But it should be noted that the high heat resistance can be achieved only if the uniformity is preserved, i.e. when the entire surface of the alloy is covered with a protective film. The main factors affecting the formation of dense oxide films are surface quality and scale properties. The surface quality means the presence/absence of defects, non-metallic inclusions, poor removal of process lubricants, as well as the roughness of the heater surface (Mishchenko et al. 2015). FeCrAl alloys are also a suitable material for power boilers, as was stated in the work of Israelsson et al. (2015), because the reaction of KCl with Al_2O_3 which produces potassium aluminate (KAlO_2) is much less favoured thermodynamically than the formation of K_2CrO_4 at the relevant temperatures. Thus, alumina-forming alloys may provide a viable alternative for high temperature applications in which materials are exposed

to alkali chlorides under high $p(\text{O}_2)$ conditions at intermediate temperatures.

Monolithic catalyst for high-temperature conversion of hydrocarbons and, in particular, the conversion of methane and the oxidation of hydrogen include primary metal carrier - Kh15Yu5 alloy (Maltseva 2016, Postnov et al. 2007).

FeCrAl alloys composition of 14-23 % Cr, 4-5 % Al are widely used in the form of corrugated ribbon in the production of monolithic metal catalysts for the neutralization of toxic gases generated during the operation of vehicle motor and present in the smoke emissions of enterprises. They were recommended for use for this purpose as early as in 1987 in the work of Plemiannikova et al. (1987) and the technologies proposed in this work still remain relevant.

As a rule, chromium-containing alloys are operated under rather severe temperature conditions. At the same time, the use of these alloys raises questions related to their thermal stability, as for Fe-Cr Alloys (double- and more complex composition) the phenomenon of embrittlement at 475 °C takes place, associated with phase transitions inherent in such systems.

The findings of early works on this issue were discussed by Litvinov et al. (1982). In the following years, the extensive studies (Bonny et al. 2009, Danoix and Auge 2000, Kuwano et al. 1991, Taniguchi and Andoh 2002, Trindade and Vilar 1991, Xu et al. 2017) on transformations occurring in chromium-containing alloys at different temperatures and time of thermal exposure, including cases when mössbauer spectroscopy was used, have been continued. It has been shown that there is possible solid solution layering on the area enriched with and depleted in chromium (Bonny et al. 2009, Danoix and Auge 2000, Kuwano et al. 1991, Litvinov et al. 1982, Taniguchi and Andoh 2002, Trindade and Vilar 1991, Xu et al. 2017), and the mechanism of this process (spinodal or embryonic) depends on the content of chromium and other metals in the initial alloy and on heat-treatment regime. And, it is the layering (change in the coordination spheres of iron atoms) that is associated with a change in the mechanical characteristics of chromium-containing alloys.

As a rule, in the works involving the method of mössbauer spectroscopy, the concept of "mean effective magnetic field" is used, the value of which is determined by the center-of-gravity position of the spectral outer peaks (Litvinov et al. 1982).

At the same time, due to the high local sensitivity of mössbauer spectroscopy, it is possible to obtain important information about the environment of iron in a solid solution through differences in the spin and charge density of electrons in the nuclei of these atoms for a particular configuration, as this should change the parameters of the spectrum - the effective field and isomer shift.

Table 1. FeCrAl alloys elemental composition

Sample	Elements content, %, mass											
	C	Si	Mn	Ni	S	P	Cr	Ce	Ti	Al	Ca	Fe
Kh15Yu5	0.08	0.60	0.60	0.60	0.02	0.03	15.17	0.10	0.40	5.04	0.10	77.26
Kh23Yu5	0.05	0.60	0.30	0.40	0.02	0.02	23.10	0.10	0.21	5.10	0.10	70.00

Table 2. Parameters of Mössbauer spectra of FeCrAl alloys after the heat-treatment

Hours	Sextet 1				Sextet 2				Sextet 3			
	<i>I</i> s, mm·s ⁻¹	<i>Q</i> s, mm·s ⁻¹	<i>H</i> _{eff} , kOe	<i>S</i> ₁ , %	<i>I</i> s, mm·s ⁻¹	<i>Q</i> s, mm·s ⁻¹	<i>H</i> _{eff} , kOe	<i>S</i> ₁ , %	<i>I</i> s, mm·s ⁻¹	<i>Q</i> s, mm·s ⁻¹	<i>H</i> _{eff} , kOe	<i>S</i> ₁ , %
FeCrAl alloy Kh15Yu5												
0	0.08	0.01	294	25	0.05	0.01	260	46	0.01	0.02	224	29
1	0.06	-0.01	298	26	0.04	0.01	260	43	0.01	0.01	226	31
2	0.05	-0.01	296	30	0.03	0.00	260	43	0.01	-0.01	222	27
3	0.06	-0.00	297	28	0.04	0.01	261	45	0.01	0.00	220	27
4	0.05	-0.00	297	33	0.03	0.01	259	44	0.01	-0.02	216	24
5	0.05	-0.01	297	32	0.03	-0.01	259	44	-0.01	-0.01	215	24
6	0.05	-0.01	294	31	0.03	0.00	256	44	-0.00	-0.02	216	25
7	0.05	-0.01	296	34	0.03	0.00	258	42	0.01	-0.02	218	24
8	0.05	-0.00	295	37	0.03	0.01	256	41	0.00	-0.00	217	22
9	0.05	-0.00	295	38	0.03	0.01	256	42	0.01	-0.01	218	20
10	0.05	-0.00	295	41	0.03	0.01	254	41	0.01	-0.02	211	18
12	0.05	-0.00	294	40	0.03	0.01	252	43	-0.01	-0.01	201	17
14	0.05	-0.00	292	43	0.03	0.01	250	43	-0.01	-0.02	201	14
FeCrAl alloy Kh23Yu5												
069-0	0.06	-0.00	272	25	0.02	0.01	232	50	0.01	-0.01	191	24
3	0.06	0.01	274	34	0.04	0.01	233	44	0.01	0.01	189	22
6	0.07	0.00	275	41	0.03	0.00	230	41	0.00	0.02	178	18
9	0.07	0.00	275	45	0.02	0.01	229	39	-0.01	0.01	174	16
12	0.05	-0.00	275	44	0.03	0.02	229	39	-0.01	0.01	169	17

This approach was used in the present work, and the mean effective magnetic field was used as a reference point, enabling to make a more detailed analysis of the spectra, with the determination of possible options for the local environment of iron atoms before and after the heat-treatment of materials.

MATERIALS AND METHODS

Using the method of Mössbauer spectroscopy, the study was conducted on the influence of temperature effect on the cold-rolled ribbon of FeCrAl alloys Kh15Yu5 (15%Cr5%Al, mass %) and Kh23Yu5 (23%Cr5%Al, mass %) with the thickness of 50 μm, which are used as the primary carrier in the exhaust catalytic converter system (Plemiannikova et al. 1987, Taniguchi and Andoh 2002).

Co-57 in the Cr matrix with activity of 100 MCi served as a source. Spectral data was collected at room temperature. Isomer shifts (*I*s) are presented relative to α-Fe.

FeCrAl alloys were kept in air (oxidizing environment) at a temperature of 900 °C for different time intervals. The temperature of 900 °C was chosen in accordance with the requirements for heat-treatment of primary carriers of catalytic converter system specified in the work of Plemiannikova et al. (1987). Under these conditions, an aluminum oxides film is formed on the surface of FeCrAl alloys ribbons, which is most strongly surface-bound, which, in turn, serves as a carrier for the catalytically active phase.

The composition of the FeCrAl alloys is presented in **Table 1**. In the initial state, mössbauer spectra of FeCrAl

alloys Kh15Yu5 and Kh23Yu5 visually represent the sextets with large widths of outer lines ~ 1.5 mm·s⁻¹ and the mean effective magnetic fields (*H*_{eff}) ~ 259, 235 kOe, respectively.

Since the layering of solid solutions of chromium-containing alloys may involve the formation of areas depleted and enriched with chromium, it can be expected that in these areas the value of the effective magnetic fields will be more and less than the field mean value, respectively. These considerations were used in the model of the mössbauer spectra processing as a superposition of three sextets. Although Gerasimov et al. (2012) in their study of Fe-4 % Cr alloy used more amount of components, in particular, with an effective magnetic field of ~ 337 kOe, which corresponded to the absence of impurity atoms in the coordination spheres of iron atoms. For Kh15Yu5 and Kh23Yu5 there were no components with comparable *H*_{eff}.

RESULTS AND DISCUSSION

Fig. 1 shows the mössbauer spectra of FeCrAl alloys Kh15Yu5 and Kh23Yu5 after heating at 900 °C for different time intervals. **Table 2** demonstrates the results of their treatment.

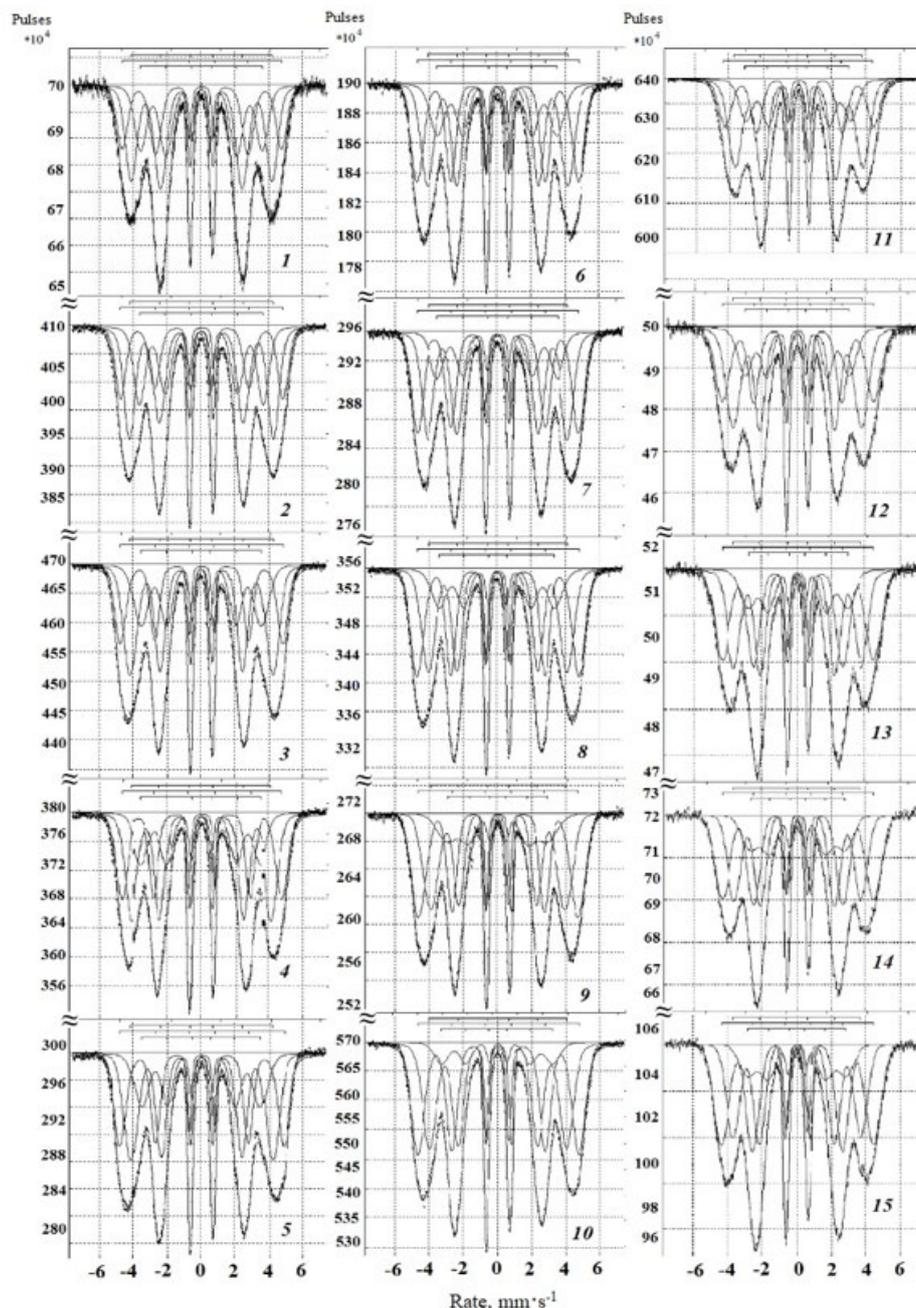


Fig. 1. Mössbauer spectra of FeCrAl alloys Kh15Yu5 (1-10) and Kh23Yu5 (11-15) after the heating at 900 °C of various periods

From **Table 2** it follows that for FeCrAl alloys Kh15Yu5, parameters of sextet 1 are insensitive to the duration of the heat-treatment. At the same time, the contribution of this sextet (*S* ratio, %) to the total spectrum rises markedly with increase in heating period (from 25-26 to 40-43 %).

For *I_s* and quadrupole splitting (*Q_s*, mm·s⁻¹) of sextet 2, the situation is similar. The effective magnetic field varies in the range of 261-250 kOe, and, apparently, has some tendency to decrease with the increase in thermal effect duration.

In the sextet 3, there are no changes in *I_s* and *Q_s*, and the effective magnetic field is obviously decreased (from 224-226 to 201 kOe) as the duration of the heat-treatment increases, the contribution of this sextet (from 29-31 to 14 %) to the total spectrum decreases.

For the Kh23Yu5 alloy, qualitatively, the situation is close to that observed in Kh15Yu5. Therefore, the *I_s* and *Q_s* for all sextets are also insensitive to the duration of heating, and the contribution of the sextet 1 (with a large value of *H_{eff}*) to the total spectrum with an increase in the duration of heating increases considerably (from 25 to 44-45 %).

Table 3. Possible configurations of iron atom environment in Kh15Yu5 and Kh23Yu5 alloys

Sextet 1			Sextet 2			Sextet 3		
Cr(<i>i; j</i>)	Al(<i>i; j</i>)	<i>H_p</i> , kOe	Cr(<i>i; j</i>)	Al(<i>i; j</i>)	<i>H_p</i> , kOe	Cr(<i>i; j</i>)	Al(<i>i; j</i>)	<i>H_p</i> , kOe
FeCrAl alloy Kh15Yu5								
(1; 1)	(0; 0)	296	(2; 0)	(1; 0)	265	(2; 1)	(1; 1)	225
(1; 0)	(1; 0)	294	(0; 2)	(1; 1)	259	(2; 0)	(2; 1)	223
			(1; 2)	(0; 1)	257	(2; 2)	(1; 0)	216
			(1; 1)	(1; 1)	254	(2; 1)	(2; 0)	214
			(2; 1)	(0; 1)	252	(1; 2)	(2; 0)	214
			(2; 0)	(1; 1)	250	(2; 1)	(1; 2)	210
						(2; 2)	(1; 1)	201
FeCrAl alloy Kh23Yu5								
(2; 0)	(1; 0)	274	(2; 1)	(1; 1)	233	(2; 2)	(2; 0)	196
			(2; 0)	(2; 1)	232	(2; 3)	(1; 1)	183
						(2; 2)	(2; 1)	181
						(3; 2)	(1; 1)	178
						(3; 1)	(2; 1)	176
						(3; 3)	(1; 0)	168
						(3; 2)	(2; 0)	167

Notes:

Cr(*i; j*), Al(*i; j*) – amount of impurity atoms (Cr and Al) in coordination spheres of iron atom [FeCr(*i; j*)Al(*i; j*)];*H_p* – calculated value of effective magnetic field depending on the population of first and second coordination spheres of iron atoms by impurities atoms

However, there are some differences. For sextet 2 there is no significant change in H_{eff} and at the same time, there is a tendency to decrease (from 50 to 39 %) in the contribution of this sextet to the total spectrum, when the decrease in the contribution of sextet 3, if it occurs, is not as significant as in the case of Kh15Yu5.

Values of Q_s for all sextets of FeCrAl alloys are close. At the same time, I_s for sextets 1-3 are in different intervals of values, and for Kh15Yu5 and Kh23Yu5 these intervals are practically identical (Table 2).

Sextet 1 Kh15Yu5 $I_s = (0.05 - 0.08) \text{ mm} \cdot \text{s}^{-1}$;
Kh23Yu5 $I_s = (0.05 - 0.07) \text{ mm} \cdot \text{s}^{-1}$

Sextet 2 Kh15Yu5 $I_s = (0.03 - 0.05) \text{ mm} \cdot \text{s}^{-1}$;
Kh23Yu5 $I_s = (0.02 - 0.04) \text{ mm} \cdot \text{s}^{-1}$

Sextet 3 Kh15Yu5 $I_s = (-0.01 - 0.01) \text{ mm} \cdot \text{s}^{-1}$;
Kh23Yu5 $I_s = (-0.01 - 0.01) \text{ mm} \cdot \text{s}^{-1}$

These data show that there is a distinct trend of I_s shift in the negative area with a decrease in H_{eff} .

Relying upon the opinions of some other scientists (Litvinov et al. 1982, Schwartz and Chandra 1971, Solomon and Levinson 1978, Wertheim et al. 1969), an assessment of possible configurations of the environment of iron atoms in FeCrAl alloys was conducted, which would be consistent with the data given in Table 2.

The effective magnetic field on the nucleus of an iron atom $H_{eff}(I, J)$ has I of impurity atoms of the nearest neighbors (the first coordination sphere) and J of impurity atoms of the next nearest neighbors (the second coordination sphere). Assuming that the effects of these atoms are additive, then, basing on the expression of Wertheim et al. (1969), we can calculate the following:

$$H_{eff}(I, J) = H_0(1 + aI + bJ) \cdot (1 + kC) \quad (1), \text{ where}$$

H_0 – effective magnetic field on the nucleus of an iron atom with no impurities;

a and b are proportional change of the field of magnetic hyperfine splitting due to one nearest and one

next nearest atom of the impurity; C is the concentration of impurity (atomic %);

k – coefficient of proportionality

Although the expression (1) was used to describe the effective magnetic field on the iron atom nucleus at low concentrations of impurities, Schwartz and Chandra (1971) showed that it is also true for chromium-containing alloys with chromium concentrations in the range 24-60 atomic %.

Table 3 provides the results of the calculation, possible variants, configurations of the environment of iron atoms in Kh15Yu5 and Kh23Yu5 alloys based on the expression (1) and correction factors (2) for chromium and aluminum (Wertheim et al., 1969), as the main (apart from iron) components of alloys (Table 1).

$$\text{Cr} - a = -0.083_s; b = -0.07_1; k = 0.4_1 \quad (2)$$

$$\text{Al} - a = -0.081_s; b = -0.046_s; k = 0.00_s$$

(In Kh15Yu5 $C_{Cr} = 15.1$; $C_{Al} = 9.7$, which in Kh23Yu5 $C_{Cr} = 23.9$; $C_{Al} = 9.8$)

From the comparison of the data given in Tables 2 and 3 we can conclude that the values of the effective magnetic fields and their change during the thermal effect on the FeCrAl alloys can be satisfactorily described in terms of the population of the first and second coordination spheres of iron atoms by impurity atoms (chromium and aluminum atoms, in this case). For Kh15Yu5, the difference between H_{eff} of sextet 1 and H_0 (H_0 was taken as equal to the effective magnetic field $\alpha\text{-Fe} - 330 \text{ kOe}$) can be attributed to the presence of two impurity atoms in the coordination spheres of the iron atom. For sextet 2 – three to four atoms, and for sextet 3 – five to six atoms.

In the case of Kh23Yu5 there is a similar situation. Sextet 1 has three impurity atoms, in sextet 2 there are five impurity atoms, and sextet 3 has six to seven atoms.

As for isomeric shifts, their division into groups matches well the population of the first and second coordination spheres of iron atoms by impurity atoms, based on H_{eff} values for sextets 1-3, since according to

different sources (Litvinov et al. 1982, Wertheim et al. 1969), the contribution of one Cr impurity atom to I_s ranges from -0.007 to $-0.02 \text{ mm}\cdot\text{s}^{-1}$, and from Al impurity atom contribution is zero.

The contribution of each sextet to the total spectrum, i.e. the area (S , %) of the corresponding component, is a quantitative indicator of the probabilities of the condition and is proportional to the number of iron atoms in this coordination.

Consequently, for Kh15Yu5, as the heating period increases (**Tables 2 and 3**), the rise of S for sextet 1, with practically unchanged H_{eff} (292-298 kOe) indicates an increase in the number of iron atoms of the configuration with 2 impurity atoms. For the sextet 2, S remains almost constant, and the tendency to some decrease in H_{eff} (261-250 kOe) may be caused by the redistribution of impurity atoms in the coordination spheres of iron atoms within the configuration with 4 impurity atoms. In the case of sextet 3, S decreases which implies the decrease in the number of iron atoms of the configuration with 5-6 impurity atoms. The decrease in H_{eff} (226-201 kOe) is probably caused by the transition from the configuration with five impurity atoms to the configuration with six impurity atoms and the change in the population of coordination spheres within these configurations.

In the case of Kh23Yu5, as the heating period increases (**Tables 2 and 3**), with nearly unchanged H_{eff} (272 - 275 kOe), the rise of S of sextet 1 occurs, which implies an increase in the number of iron atoms in the configuration with 3 impurity atoms. For sextet 2, also with almost unchanged H_{eff} (233 -238 kOe), there is a certain decrease in S , therefore, the number of iron atoms in the configuration with 5 impurity atoms slightly decreases. As for sextet 3, there is a noticeable

decrease in H_{eff} (191-169 kOe), which can be explained by the transition from the configuration with 6 impurity atoms to the configuration with 7, as well as by the redistribution of impurity atoms in the coordination spheres of iron atoms within these configurations, similar to FeCrAl alloys Kh15Yu5.

CONCLUSION

Summing up, we can conclude that the period of thermal exposure is an important factor affecting the FeCrAl alloys, in particular, the largest differences in the spectra are observed at 10-11 hours (**Fig. 1, Table 2**). The further increase in heating period does not entail significant changes. It can be assumed that after a certain period of thermal action, an equilibrium (quasi-equilibrium) condition is achieved.

Sextets 1- 3 are kind of the average conditions, that is, a superposition of conditions with close mössbauer parameters, including several close configuration options, referring to other elements (except Fe, Cr and Al) that are part of the FeCrAl alloys composition (**Table 1**) (the impact of these elements has not been directly considered due to their low content).

The lack of paramagnetic phases may specify, according to the work of Trindade and Vilar (1991), the predominantly spinodal mechanism of the processes occurring in the studied FeCrAl alloys.

It should be noted that the use of mössbauer spectroscopy method as a research method and the use of concepts related to the population of the coordination spheres of the iron atoms by impurity atoms (alloying elements) enables to obtain additional information for a description of the processes occurring in FeCrAl alloys under thermal effects.

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