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The High-Energy Radiation Effect on the Modified Iron-Containing Composite Material

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Abstract: In the work there are presented photos and main physical, mechanical and performance characteristics of the modified iron-containing composite material. There are considered the peculiarities of the composite material's iron atoms structural condition under the action of fast electrons flow: the research by means of infrared spectroscopy and nuclear gamma resonance indicate the generation and development of structural transformations in the iron atomic groupings, which results in forming of magnetite. The surface structure of the modified iron-containing composite material has been studied by method of scanning atomic force probe microscopy before and after bombarding it with gamma-quanta: at comparing the basic properties of the composite material surface around all the scanned area before and after gamma-quanta bombarding it was proved, that after treating the composite material with gamma-quanta, the structure of its surface undergoes no evident alterations. It was found out, that the modified iron-containing composite material on the base of hematite and metallic aluminum remains stable in the basic physical and mechanical properties under the action of fast electrons flow with energy 6,2 MeV, fluence 10^{18} el/cm^2 and absorbed dose to 2 MGy and at bombarding it with gamma-quanta with energy to 1,2 MeV and absorbed dose to 1 MGy.

Key words: Composite material · Iron-containing · Modified · High-energy radiation · Fast electrons · Gamma-quanta · Optical photos · Properties · Surface · Structure · Irradiation · Hematite · Aluminum

INTRODUCTION

The end of XX and beginning of XXI century are marked with an increasing pace in using nuclear energy almost in all sectors of national economy, which makes more urgent the necessity of developing new types of metallic composite materials, having the high-performance mechanical and radioprotection properties.

For nuclear industry (nuclear power stations, radiochemical plants, radioactive waste storages), as well as for a wide range of various industries and enterprises, possessing the nuclear engineering objects, developing the new building materials having high strength characteristics, serviceable under the conditions of dynamic, alternating temperature and combined radiation loads, resistant to constant heat difference (fire safety), having small overall dimensions, consisting of environmentally safe components and having the long working lifespan without replacing (dismantling) the main screening frame (structure) is of great current importance.

The main drawback of most of the currently known radioprotective materials is the very low strength characteristics, due to which materials can't carry the structural load (usually such materials refer to facing ones and the latter in their turn have large overall dimensions, which increases mass and volume of the screened object). Besides, many radioprotective materials have complex composition and include rare and expensive raw materials which increase their cost price. Often the raw materials base includes toxic (lead-containing) materials, which limits the sphere of their application considerably.

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The above mentioned drawbacks of most of the currently known radioprotective materials were the reason for monitoring new environmentally safe composite materials of different assignment.

Such materials may include different building composite materials and constructions on their base [1], metal-ceramic composites [2], composites on the base of non-ferrous metals and alloys [3], construction composite materials on the base of polystyrene matrix [4], metal-glass composites on the base of metallic matrix and dense flints [5], composite materials, combining the plastic metallic matrix (aluminic, plumbic, cupric, stannic etc.) and strong metallic and non-metallic reinforcing components of natural and artificial origin (granites, basalts, limestones, dolomites, quartzites, marble, smelter slags, ashes, haydite, iron-oxide systems etc.) [6-10].

One of such materials is the construction composite material on the base of high-dispersity modified iron oxide (hematite) and metallic aluminum.

Methodology: The optical studies were carried out with optical microscope Polam Đ-312. The infrared spectra within the frequency range 4000-400 cm $^{-1}$ were studied with a double-beam spectrophotometer "Specord-751R". The Moessbauer effect (nuclear gamma resonance) was used for researching the structure of modified hematite, treated with fast electrons flow. The action of high-energy radiations on the composite material was carried out according to National State Standard 25146-82. The electron microscopy research was performed with a scanning probe microscope (class of atomic-force microscopes) Stand Alone "Smena", which is a universal atomic-force microscope, which can be used for the integrated research of any objects' surface. Its basic elements are a probe, a piezoscanner, probe declination monitoring system and scanner control system. The operating principle of an atomic-force microscope is based on probing the sample's surface with a sharp needle, which scans along the plane of the sample. The material's microstructure was researched by means of lateral forces microscopy.

The Main Part: In Figure 1 there are given optical photos of general appearance, surface, spall and shear of the modified iron-containing composite material.

This composite material has the following physical, mechanical and performance characteristics (Table 1).

Let us consider the peculiarities of structural condition of the composite material's iron atoms under the action of fast electrons flow with energy 6,2 MeV, fluence 10^{18} el/cm^2 and absorbed dose to 2 MGy. Under the influence of electron irradiation in the modified hematite samples there takes place the alteration of phase composition and the appearance of infrared spectrum (Fig. 2).

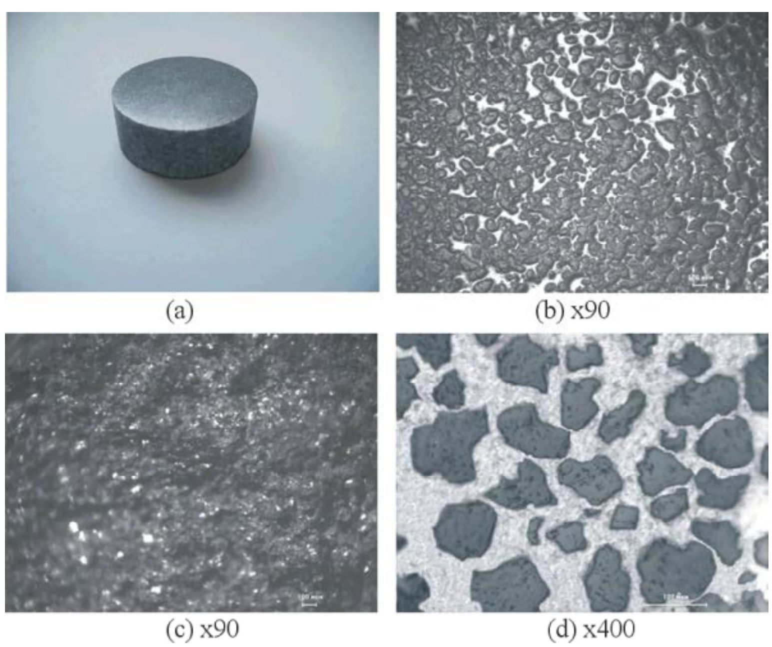


Fig. 1: Modified iron-containing composite material:
a) general appearance of a cylinder-shaped composite material sample; b) surface; *c*) spall; *d)* shear.

Table 1: Main physical, mechanical and performance characteristics of the modified iron-containing composite material

# П/П	Factor	Value
1	Density, kg/m^3	3870
2	Extension strength, MPa	195
3	Flexing strength, MPa	250
4	Compression strength, MPa	750
5	Vickers microhardness number, MPa	3320
6	Brinell hardness number, HB (10,300,10)	215
7	Rockwell hardness number, HRB	87
8	Melting temperature, °C	1165
9	Thermal resistance, °C	660
10	Heat conductivity, W/m·K	23,5
11	Water absorption (30 days), %	0
12	Chemical resistance (without loss of mass), pH	4-9

Table 2: Parameters of nuclear gamma resonance spectra of the modified hematite, treated with fast electrons flow

			Spectrum parameters	
Material	The absorbed dose, MGy	The electronic state and coordination of iron ions	Isomer shift± 0,06	Quadrupolar splitting ± 0,06
Modified hematite	-	$[Fe^{3+}O_6]$	0,64	0,94
	-	$[Fe^{3+}O_4]$	0,16	0,71
	0,2	$[Fe^{3+}O_6]$	0,81	1,20
	0,2	$[Fe^{3+}O_4]$	0,26	1,41
	0,66	$[Fe^{3+}O_6]$	0,96	1,58
	0,66	$[Fe^{3+}O_4]$	0,31	1,58
	1,0	$[Fe^{3+}O_6]$	1,04	1,61
	1,0	$[Fe^{3+}O_4]$	0,35	1,69
	1,0	$[Fe^{2+}O_6]$	1,33	2,68
	2,0	$[Fe^{3+}O_6]$	1,20	1,70
	2,0	$[Fe^{2+}O_6]$	1,43	2,92

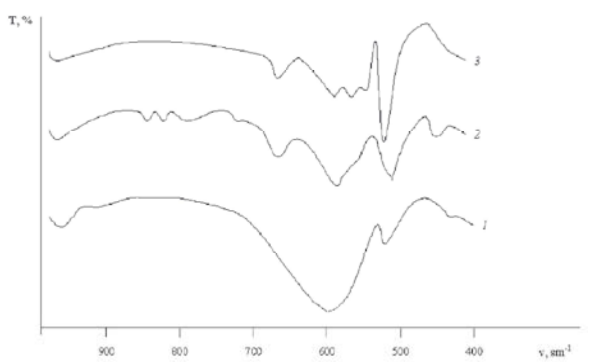


Fig. 2: The hematite infrared spectra before (*1*) and after the electron irradiation with the absorbed dose: 0,2 MGy (*2*); 2,0 MGy (*3*)

The intensity of absorption bands is reduced abruptly. The appearance of the spectrum indicates that at increasing the irradiation dose, the quantity of hematite phase decreases and magnetite (Fe_3O_4) is formed. This is demonstrated by the increase of the absorption band intensity in the range 500-700 cm^{-1}, the shift of maximum to the low-frequency range (from 560-585 cm^{-1} to 555 cm^{-1} at the increase of electron irradiation absorbed dose). The intensity of the absorption band at 470-480 cm^{-1} is reduced. There appears an absorption band at 630 cm^{-1}, which refers to the magnetic phase γ-Fe_2O_3.So, the presence of the newly formed magnetite phase Fe_3O_4 indicates the partial rearrangement of the initial hematite's structure, due to reallocation of Fe^{3+} atoms from tetrahedral $[FeO_4]$ to octahedral $[FeO_6]$ position and alteration of their stoichiometry to $Fe_{1-\delta}O$ [11].

The structure of hematite, treated with fast electrons flow, was also studied by method of nuclear gamma resonance. Parameters of the received Mossbauer spectra, isomer shift, quadrupolar splitting and the width of spectrum lines on $h_{1/2}$ are given in Table 2.

In nuclear gamma resonance spectra (Fig. 3) there appear the "paramagnetic" doubles. The asymmetry of double's lines, which refers to iron ions Fe^{3+} is indicative of two its coordination states. The paramagnetic double's formation in the spectra also indicates the closing-in of Fe3+ ions to the distance more than 15 Å. In this case there takes place the transition of pre-cluster formations to magnetite-oriented clusters with indirect exchange interaction between ions of iron, which is typical for them.

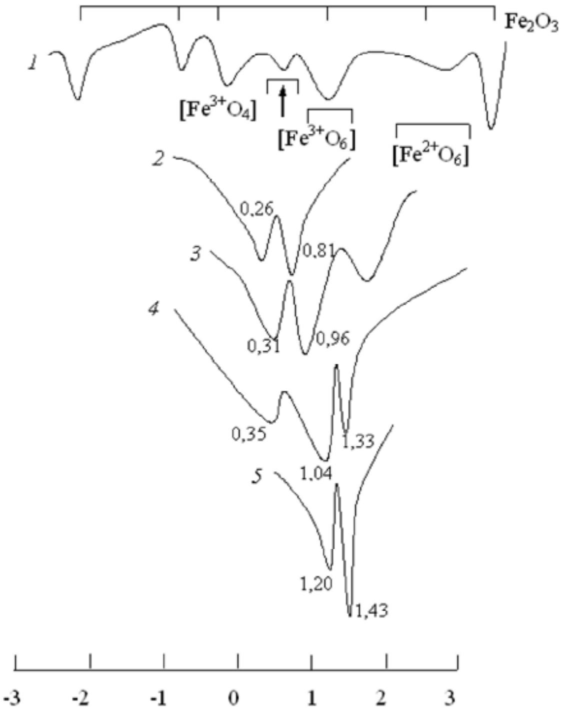


Fig. 3: Nuclear gamma resonance spectra of the modified hematite before (*1*) and after (*2-5*) the fast electrons irradiation with the absorbed dose (MGy): *2* – 0,2; *3* – 0,66; *4* – 1,0; *5* – 2,0

After the treatment of modified hematite with electrons flow of 0,2-0,66 MGy, in nuclear gamma resonance spectra there appears an extra "paramagnetic" double, which is characterized by chemical isomer shift 0,26-0,31 mm/s and quadrupolar splitting 1,41-1,58 mm/s, which corresponds to Fe^{3+} ions in tetrahedral coordination (Table 2). The decrease of the metal atom's coordination number at the permanent valency is accompanied by shortening of interatomic spacing and increase of the quantity of valence electrons for one bond, i.e. increase of bond order. At escalating the electron irradiation dose to 1-2 MGy there appears a double, corresponding to Fe^{2+} ions with a deformed octahedral coordination and characterized by the following parameters: isomer shift 1,33-1,43 mm/s and quadrupolar splitting 2,68 mm/s (Fig. 3). At the dose of 2 MGy there is observed more than twofold widening of spectrum lines (to 0,72-1,08 mm/s) in comparison with the initial sample (before the electron irradiation). So, it may be assumed that during the high-energy fast electrons treatment at dose 2 MGy there takes place the most intensive structural reorganization of iron atoms, which results in the restructuring (amorphisation) of iron oxide crystals.

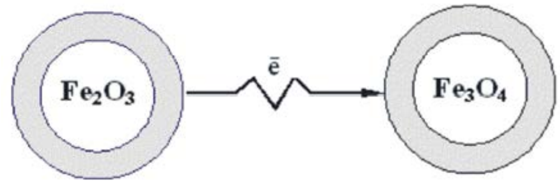


Fig. 4: The scheme of restructuring process in hematite during irradiating it with fast electrons flow

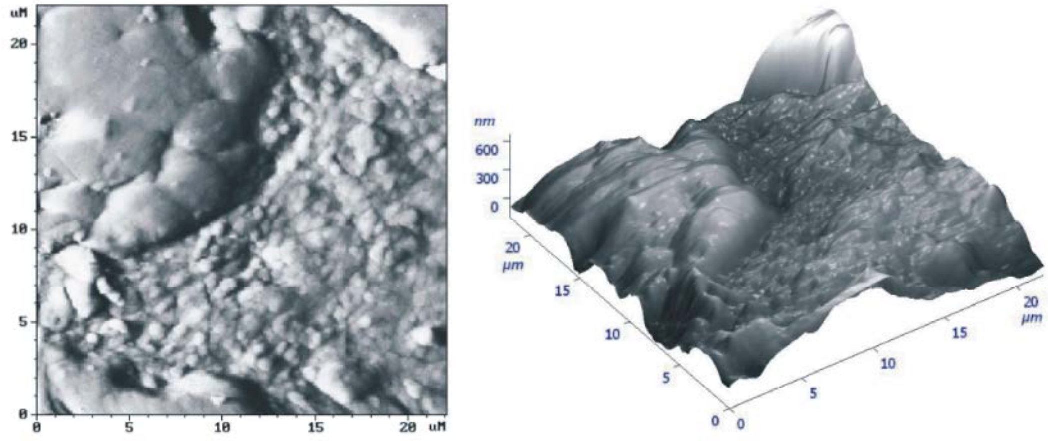
The hematite phase transfers into magnetite with a deformed tetrahedral lattice of iron atoms [12]. The restructuring process in the modified hematite under study can be represented as in Fig. 4.

So, the nuclear gamma resonance research confirms the data of infrared spectroscopy concerning the generation and development of structural transformations in the iron atomic groupings, which results in forming of magnetite.

The surface structure of the modified iron-containing composite material has been studied by method of scanning atomic force probe microscopy before and after bombarding it with gamma-quanta (radioactive isotope ^{60}Co).

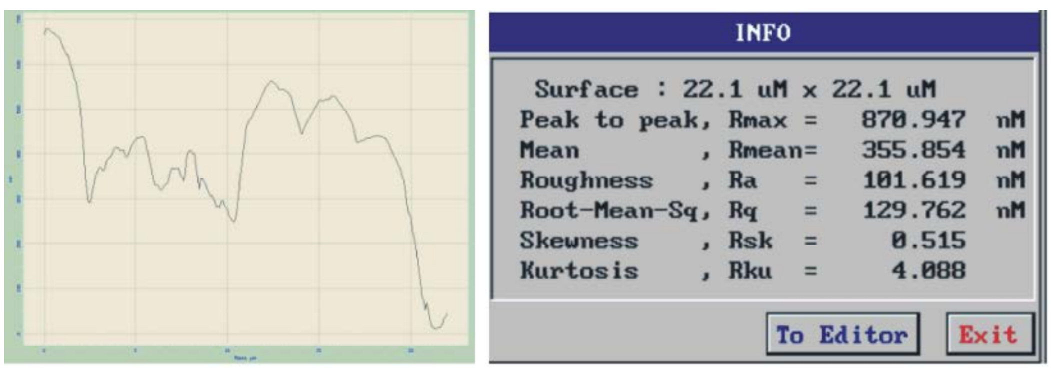
In Figure 5 (*a, b*) there are shown micrographs of the composite material's surface before gamma-quanta bombarding. After studying the composite material surface properties around all the scanned area and the profilogram of a separately selected area of the surface (Fig. 6, *a*), there were determined the statistically important characteristics of the surface within the area under research (Fig. 6, *b*): the difference between maximum and minimum value of coordinate Z on the surface (R_{max}), amounting to 870,947 nm; the mean value of coordinate Z on the surface (R_{mean}), amounting to 355,854 nm; the average value of surface roughness (R_a), amounting to 101,619 nm; the value of root-mean-square deviation of coordinate Z on the surface (R_q), amounting to 129,762 nm; the coefficients of skewness (R_{sk}) and kurtosis (R_{ku}) of the sample's surface, amounting to 0,515 and 4,088 respectively.

In Figure 7 (*a, b*) there are shown micrographs of the composite material's surface after bombarding with gamma-quanta with energy 1,2 MeV and absorbed dose to 1 MGy. After studying the surface properties of the composite material treated with gamma-quanta, around all the scanned area and the profilogram of a separately selected area of the surface (Fig. 8, *a*), there were determined the statistically important characteristics of the surface within the area under research (Fig. 8, *b*): the difference between maximum and minimum value of



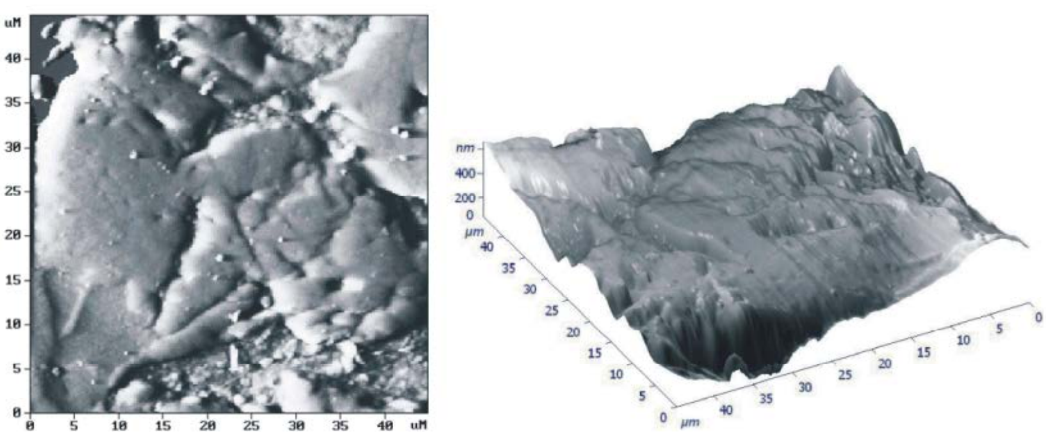
(a) (b)

Fig. 5: The surface of the composite material before gamma-quanta bombarding:
a) 2D 22,1×22,1 μm; b) 3D 22,1×22,1 μm ×600 nm



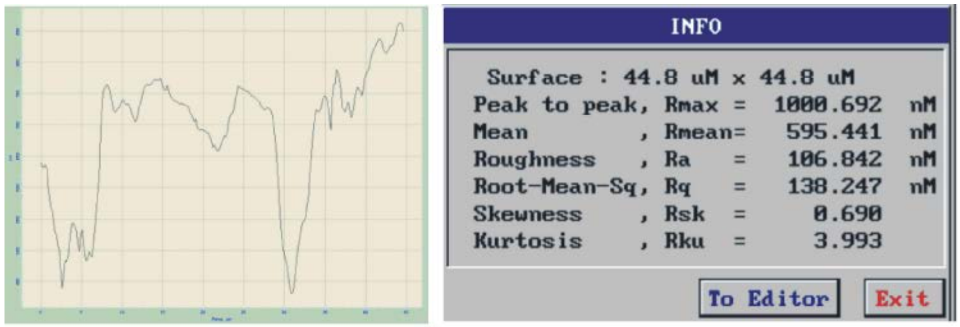
(a) (b)

Fig. 6: The surface of the composite material before gamma-quanta bombarding:
a) profilogram of a separately selected area; b) statistical characteristics of the surface



(a) (b)

Fig. 7: The surface of the composite material after gamma-quanta bombarding:
a) 2D 44,8×44,8 μm; *b*) 3D 44,8×44,8 μm ×600 nm



(a) (b)

Fig. 8: The surface of the composite material after gamma-quanta bombarding:
a) profilogram of a separately selected area; b) statistical characteristics of the surface

coordinate Z on the surface (R_{max}), amounting to 1000,692 nm; the mean value of coordinate Z on the surface (R_{mean}), amounting to 595,441 nm; the average value of surface roughness (R_a), amounting to 106,842 nm; the value of root-mean-square deviation of coordinate Z on the surface (R_q), amounting to 138,247 nm; the coefficients of skewness (R_{sk}) and kurtosis (R_{ku}) of the sample's surface, amounting to 0,690 and 3,993 respectively.

At comparing the above listed basic properties of the composite material surface around all the scanned area before and after gamma-quanta bombarding it is evident, that after treating the composite material with gamma-quanta, the structure of its surface undergoes no pronounced alterations. The difference between values of difference between maximum and minimum peak of coordinate Z by 12,5 %, mean values of coordinate Z by 40 %, average values of surface roughness by 5 %, values of root-mean-square deviation of coordinate Z by 6 %, coefficients of skewness by 25% and coefficients of kurtosis by 2 %, results from the twofold increase of the researched surface's geometrical dimensions after the gamma-quanta bombardment.

CONCLUSION

The modified iron-containing composite material on the base of hematite and metallic aluminum is stable in its basic physical and mechanical properties at bombarding it with gamma-quanta with energy to 1,2 MeV and absorbed dose to 1 MGy.

Conclusions: There are considered the peculiarities of the composite material's iron atoms structural condition under the action of fast electrons flow: the research by means of infrared spectroscopy and nuclear gamma resonance indicate the generation and development of structural transformations in the iron atomic groupings, which results in forming of magnetite. The surface structure of the modified iron-containing composite material has been studied by method of scanning atomic force probe microscopy before and after bombarding it with gamma-quanta: at comparing the basic properties of the composite material surface around all the scanned area before and after gamma-quanta bombarding it was proved, that after treating the composite material with gamma-quanta, the structure of its surface undergoes no evident alterations. So, it can be stated with assurance, that the modified iron-containing composite material on the base of hematite and metallic aluminum remains stable in its basic physical and mechanical properties under the action of fast electrons flow with energy 6,2 MeV, fluence 10^{18} el/cm^2 and absorbed dose to 2 MGy and at bombarding it with gamma-quanta with energy to 1,2 MeV and absorbed dose to 1 Mgy.

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