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RADIATION SHIELDING CHARACTERISTICS AND CHARACTERISTICS OF STRENGTH FROM POLYSTYRENE STEEL COMPOSITE MATERIALS WITH HIGH METAL CONTENT

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Experimental samples of composite materials with a polystyrene base were manufactured. Steel powder with a grain size of 230 µm was used for radiation shielding. Aluminum powder with a grain size of 20, 40 µm was used as a reinforcing additive. Using a ^{241}Am ionizing radiation source (gamma quanta with energy 59.54 keV), measurements of the radiation shielding characteristics of these composite materials were carried out. Also, numerical calculations of the relative attenuation of the absorbed dose were performed. Experimental results and calculated data have a high coincidence. These composite materials effectively absorb gamma radiation with energies of up to 150 keV. Work was performed to determine the tensile strength of these samples at temperatures of 250, 290, 320 K. It was found that the maximum tensile strength (24.4 MPa) at a temperature of 290 K was for samples with the maximum amount of aluminum additive.

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INTRODUCTION

Currently, energy, industry, medicine, and science widely use devices and equipment that are sources of ionizing radiation. In addition, areas of very high risk include enterprises manufacturing various sources of ionizing radiation, deposits of radioactive elements, quarries for storing waste rock, storage and disposal sites for spent nuclear fuel (SNF), radioactive waste (RAW), and spent equipment.

Thus, a large number of people are exposed to ionizing radiation. Also, the probability of occurrence of emergency and accident situations increases. There may be a release of radioactive substances into the environment.

All these factors require the use of means of shielding against ionizing radiation. The principle of creating shielding that reduces radiation to a safe level is considered.

Currently, various radiation shielding materials are used. Among them are materials with a large atomic mass (Pb, W). These materials absorb X-rays, gamma radiation, beams of protons, ions, electrons. Materials with a low atomic mass (B, Br) have a wide scattering cross-section and are effective protection against flows of neutrons.

For maximum efficiency of shielding against ionizing radiation, materials are used in which several different protective components. These composite materials allow for maximum weakening of ionizing radiation and may also have additional properties.

At present, much attention is paid to the study of radiation shielding materials based on polymers with the addition of various fillers [1-3]. Various radiation shielding additives were used as fillers. The choice of a radiation shielding protective component is determined by the intensity of radiation and its type.

Previously, we studied composites with a radiation shielding component made of powder of tungsten [4-6]. These composite materials have a wide range of applications.

Composites that use of powder of steel are of great interest [7–9]. Of powder of steel is obtained during the production of various products [10, 11]. Since of powder of steel is obtained from production waste, the cost of composites is low. The radiation shielding properties of powder of steel are low, so the thickness of the shielding layer must be large.

Therefore, the use of such composites is advisable in cases where the thickness of the shielding layer is not limited. These composite materials will also be effective for radiation shielding of radioactive waste (RAW) and spent nuclear fuel (SNF) storage facilities [12].

Composition materials are characterized by several parameters. For our purposes, the most important parameters are: radiation shielding characteristics; strength and hardness characteristics. These characteristics were studied in this paper. The characteristics of polystyrene metal composite materials with a high content of steel components were considered.

PURPOSE OF WORK

1. Measurement and numerical calculation of radiation shielding characteristics of materials with an increased content of steel components.

2. Obtaining strength characteristics, at break, for composites with a steel component.

3. Improvement of the technology of manufacturing composite materials based on polystyrene with a steel component.

CONDUCTING EXPERIMENTS AND DISCUSSION OF RESULTS

As a result of the work performed, experimental samples of polystyrene metal composite materials were manufactured, which are intended for shielding against ionizing radiation [4-6, 8]. Some of these composites have already passed laboratory tests and have been used in practical activities. It was found that these composites have high performance characteristics. The creation of composite materials requires solving a number of problems.

It is necessary to select the base material. Depending on the type of radiation, it is necessary to determine the radiation shielding additive. It is also necessary to select the material for reinforcing the composite and creating its matrix. An important part of the work in creating composite materials is the development of technological processes for the production of composites.

Polystyrene PSM-115 (GOST 20282-86) was used as a base. Polystyrene is suitable for work in a wide range of temperatures. Its softening point is 86…92 °C, melting point is 196…200 °C. Polystyrene has low hygroscopicity, high water resistance, and is resistant to acids and alkalis.

It should be noted that polystyrene is resistant to ionizing radiation (electrons, ions, X-rays, gamma rays, neutrons). This is due to the fact that as a result of irradiation, two opposite processes occur in polystyrene: the process of destruction of polystyrene molecules and the process of cross-linking of polystyrene molecules. The rate of cross-linking processes of polystyrene molecules is slower than the processes of destruction. However, the processes of cross-linking of radicals have a significant effect on the restoration of polystyrene. Strengthening of composites also occurs due to the stretching and reorientation of polystyrene chains.

To create a radiation shielding composite, it is necessary to add a radiation shielding additive to polystyrene. Powder of steel [8, 10, 11] of the S235J0, A570-36, Fe37B3FN type was used as a radiation shielding component. These steels comply with the standards given in the ISO 570-36, GOST 977-75 documents. However, the bond between individual particles of steel and polystyrene is insufficient, since steel is poorly wetted by polystyrene. Therefore, another additive was used to reinforce the composite.

When creating the matrix of the composite material, highly dispersed powder of aluminum was used. Powder of aluminum obtained from aluminum of the ASD-6, 2014, 6111 type were used [12–14]. Powder of aluminum obtained complies with the standards given in the documents: ISO 209-1, TU 1791-007-49421776-2011. Aluminum particles can have the following sizes: 10…20, 30…40, 60…90 μm.

For highly dispersed powder of aluminum we have, and high mechanical interaction with polystyrene. Also, the presence of powder of aluminum improves the volume distribution of radiation shielding component powders.

Improvement of equipment. The following units were used in the production of composite materials: Kuasy 100/25, Windsor SP 80. The Kuasy 100/25-1 and Windsor SP 80 units are horizontal injection molding machines. Composite materials are produced on them using the extrusion method. This equipment was used not only to produce reinforced polystyrene products, but also to refine the technology for producing composite materials [4–6, 8].

There are certified technological processes for the production of reinforced polystyrene products for these units. The technology for producing radiation-protective composite was improved using the Kuasy 100/25-1, as it has lower characteristics (injection pressure – 180 MPa, injection volume – 50 cm^3). The production of composite material, taking into account modifications and improvements, was carried out using the Windsor SP 80. Its productivity is higher (injection pressure – 300 MPa, injection volume – 187 cm^3).

The production of radiation of shielding composites is a complex process. Therefore, the equipment was improved and refined. The raw material supply system was refined and an additional device for mixing the components was added. Additional heaters installed. The temperature control system was also improved. Optical and IR radiometry methods were used to control the uniformity of mixing. For this purpose, thermal imaging devices Lend Ti-814, Fluke-10, Fluke-25 were used [15].

The photograph (Fig. 1) shows the equipment that has been improved.

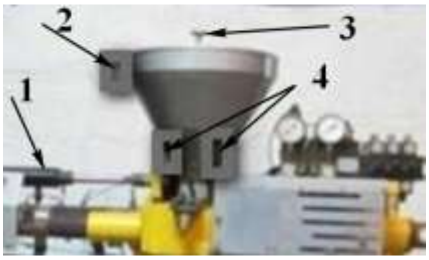

Fig. 1. Photograph of feedstock feed system and bunker with improvements: 1 – feedstock feed motor and system of rotation; 2 – mixing system motor; 3 – IR camera for control of heating; 4 – heaters

Calculation of radiation shielding characteristics. In case of real use of composites, it is necessary to know their radiation shielding characteristics.

For experimental measurement of gamma radiation absorption coefficients, a setup developed at NSC “KIPT” [16] was used. The “Amptek” spectrometric tract was used [17]. It includes a preamplifier, a CdTe detector “XR-100T”, and a microprocessor signal processing unit “PX5” [18]. For high statistical reliability of the results, the spectra were collected for 20 min.

The absorption coefficients were calculated using a standard technique. The absorption spectra from the reference gamma radiation source ^{241}Am (gamma quanta with an energy of 60 keV) were compared.

Experimentally, absorbed dose measurements were performed. For calculations and measurements, we assume that the decay model of ^{241}Am isotopes has the following form Fig. 2.

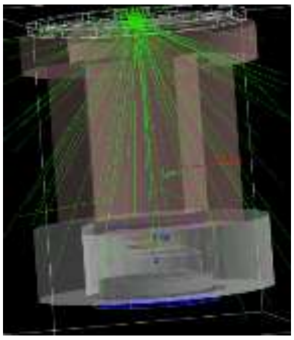

Fig. 2. Visualization of the decay model of isotopes of ^{241}Am

The simulated trajectories of gamma quanta are shown in green lines, and those of electrons in red. To confirm the accuracy of the measuring equipment, we compare the calculated and experimental spectra of the source of ionizing radiation ^{241}Am. The measurements were performed without using samples of composite materials.

The total area of the spectra of source of ^{241}Am was obtained. The results of the experimental and simulated of spectra of source of ^{241}Am are given in Table 1.

Table 1

Total area of the experimental and simulated of spectra of source of ^{241}Am

Experiment (Countdown)	Model (Countdown)	Model / Experiment
259597	212342	0.818

A comparison of the calculated and experimental spectrum of the source of standard radiation of ^{41}Am for the XR-100T-CdTe detector was carried out (Fig. 3).

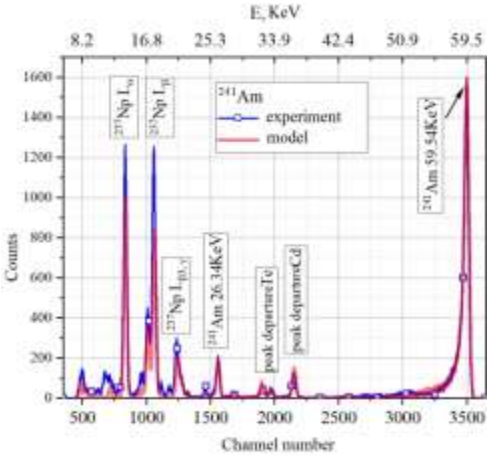

Fig. 3. Comparison of the experimental and calculated spectrum of the source of standard radiation of ^{241}Am for the XR-100T-CdTe detector

Based on the analysis of the curves (see Fig. 3), we can state that the calculation model corresponds to the experimental results. The theoretical curves display the experimentally measured spectrum of ^{241}Am. However, it was not possible to obtain a high correspondence in the region of low energies of 13…18 keV. In this region there is characteristic radiation of Np-237 L_{α} and Np-237 L_{β}. The areas and amplitudes that were calculated are 20…30% smaller than those obtained in the experiments. For energies of 26.34 and 59.54 keV, the areas of the calculated peaks are in good agreement with the experimental data.

To compare coefficients of absorption, it is necessary to bring the samples to the same thickness (linear coefficient of absorption μ_{60}). In practical work, the mass coefficient of absorption (μ_{60}/ρ) is used. The necessary parameter is also the thickness of the tenfold attenuation of stream of the gamma of quanta (L_{10}).

Previously, experimental measurements were carried out and theoretical calculations of radiation shielding characteristics for composite materials with a low content of components of steel were performed [8]. A high agreement between the experimental and calculated results was obtained.

This paper presents the calculated results and experimental results for composite materials with a high content of metallic components. They are designated as CFe05YYZZ. These composites contain five volume parts of polystyrene and ten volume parts of metallic components. The appearance of the CFe050901 sample is shown in Fig. 4.

Fig. 4. Original appearance of sample of CFe050901. Size of grains of component: Al – 10…20 μm; Fe – 230…280 μm

Composites of type of CFe05YYZZ have an appearance close to that of the CFe050901 sample (see Fig. 1). The mass values and density of the composite materials are given in Table 2.

Table 2

Mass quantity of components in composite materials of type of CFe05YYZZ

Material/ Density, g/cm^3	Polystyrene (PS), mass. %/ amount, g in 15 cm^3	Steel (Fe), mass. %/ amount, g in 15 cm^3	Aluminum (Al), mass. %/ amount, g in 15 cm^3
CFe050109/ 2.51	14.6/ 5.5	7.86/ 20.87	24.3/ 64.52
CFe050505/ 3.89	9.43/ 5.5	39.3/ 67.41	13.5/ 23.16
CFe050901/ 5.26	6.97/ 5.5	70.74/ 89.61	2.7/ 3.42

The experiments used composite samples with dimensions of ~ 7 × 4 × 1 cm. The samples had different contents of polystyrene, powder of steel, and powder of aluminum.

Several types of composite materials were studied. The characteristics of samples CFe050109 and CFe050901 were compared. Sample CFe050109 contains nine parts of aluminum and one part of steel. Sample CFe050901 contains nine parts of steel and one part of aluminum. Experimental values of the characteristics of attenuation of stream of ionizing radiation (μ_{60}, μ_{60}/ρ, L_{10}) were obtained (Table 3).

Also, computer modeling was carried out to study the dependence of the coefficients μ_{60}, μ_{60}/ρ, L_{10} on the mass content of powder of steel. The experimental results and calculated values of the gamma radiation of coefficients of attenuation are given in Table 3.

Table 3

Comparison of experimental and calculated characteristics of attenuation of stream of the gamma of quanta with an energy of 59.54 keV

№ sample	Experiment			Calculation		
	μ_{60}, 1/cm	μ_{60}/ρ, cm^2/g	L_{10}, cm	μ_{60}, 1/cm	μ_{60}/ρ, cm^2/g	L_{10}, cm
050109	0.365	0.279	6.3	0.347	0.265	6.6
050901	0.975	0.545	2.4	0.948	0.530	2.4

The results of experimental measurements for different samples have a form close to the graphs shown in Fig. 5.

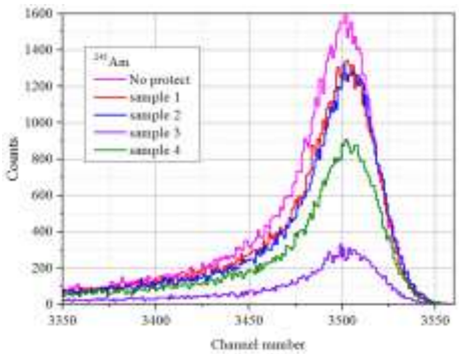

Fig. 5. Graphs of change of photopeak from the source of ^{241}Am

The change in the graphs depended on the type of composite material. For control, the protective properties of pure polystyrene were measured (light pink curve). With an increase in the amount of component of steel, the protective properties of composites also increase. The maximum absorption was obtained for the composite material, which had the maximum amount of component of metal in its composition (violet curve, sample №3). The measurement results have a high coincidence with the results of numerical calculation.

An radiation spectrum was obtained for the CFe050901 sample. The spectrum was measured after the radiation passed through the sample. An XR-100T-CdTe detector was used to measure the spectrum. The radiation was obtained from a standard ^{241}Am source (Fig. 6).

We observe a high coincidence of the spectra in the energy range of 59.54 keV. This peak makes the main contribution to the spectrum of radiation. In experimental measurements, we have minor peaks in the region of the characteristic radiation of Np-237 L_α. However, they do not make a significant contribution to the total area of the peak of radiation.

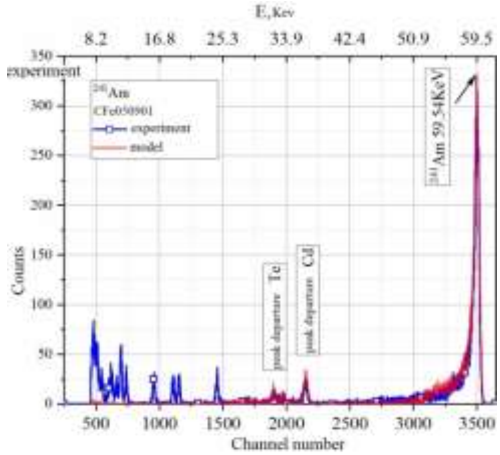

Fig. 6. Experimental and calculated response of the XR-100T-CdTe detector on the radiation of the source of ^{241}A, after the CFe050901 sample

Practical measurement of protective characteristics is a long and labor intensive process. Therefore, software packages were developed to calculate the attenuation of ionizing radiation. The Geant4 v 4.9.6p03 software package was used for the calculation [19, 20]. For our purposes, the package was modified [21].

As a result of numerical modeling, we obtained the relative weakening of the dose of ionizing radiation *(η)*. The curve of changes in η was found from the expression:

$$\eta = 1 - \frac{D}{D_{air}},$$

D_{air} – is the calculated dose, in the absence of protection; D – is the calculated dose when protected; η – is the degree of relative attenuation of the absorbed dose of gamma radiation by a layer of protection made of a composite material. In these calculations, the effect of ionizing radiation on a biological phantom was considered.

Curves of changes of protective characteristics were obtained. Calculations were performed for samples with a thickness of 1 cm. For comparison, numerical modeling of other types of composite materials was performed. The samples were solid. The results of the numerical calculation are shown in Fig. 7.

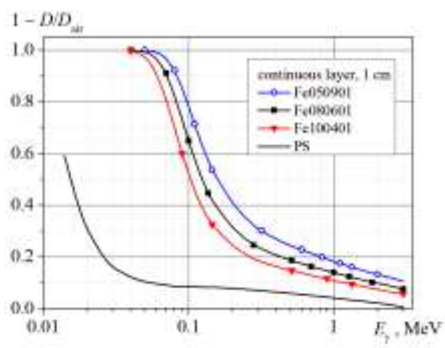

Fig. 7. Graphs of attenuation, dose of absorbed of ionizing radiation for the composites of CFeXXYYZZ

As follows from the graphs (see Fig. 5), composite materials have fairly high radiation shielding characteristics. The best shielding indicators are demonstrated by composite CFe050901. Radiation shielding characteristics of composites CFe080601 and CFe100401 are lower.

In the composite material CFe050901 the maximum amount of powder of steel. Half attenuation occurs at gamma quantum energies of no more than 150 keV. At gamma of quantum energies of 300 keV no more than 30% stream of the gamma of radiation.

To control the accuracy of the tensile testing machine, tensile tests were performed on pure polystyrene samples. The tests were performed at a temperature of 290 K. The rupture occurred with stretching. In this case, a neck was formed. The modulus of elastic was 2.1 GPa. The relative elongation was equal to 95…96%. Pure polystyrene had a high limit of fluidity, which is equal to the value of 24…25 MPa. The value of tensile strength was equal 22…23 MPa. At a temperature of 320 K, polystyrene softens, so the elongation is greater.

In the next stages of the research, the tensile strength on the break of composite materials of class CFe05YYZZ were measured.

Since composites are used in various weather conditions, the testing of a break machine (tensile) was carried out at three fixed temperatures (250, 290, 320 K). The size of grains of aluminum was 10…20 μm. The size of grains of steel was 230…280 μm.

The numerical results of the measurements are given in Table 4.

Table 4

Tensile of strength of composite materials of type CFe05YYZZ

Tape \T,K	250 K, MPa	290 K, MPa	320 K, MPa
PS	26.0	23.0	22.0
CFe050901	23.1	23.4	23.2
CFe050505	23.5	23.8	23.6
CFe050109	24.0	24.4	24.3

It was found that the maximum tensile strength is at a temperature of 290 K. At temperatures of 250 K, polystyrene becomes embrittled and a brittle break (rupture) of the composite material occurs. Therefore, their strength is low.

Due to the low polystyrene content, the strength of the C05YYZZ composites is low. Destruction occurs without formation of neck. For the C05YYZZ composite material, the break had a highly structured form. Since the C05YYZZ material is formed from lumps of the composite material, the break occurred along the surface of these lumps. The relative elongation did not exceed 1%.

At temperatures of 320 K, polystyrene softens. However, the break occurs along the surface of the lumps of composite.

It should be noted that the maximum tensile strength is that of the CFe050109 composite. It contains the maximum amount of finely dispersed of powder of aluminum and the minimum amount of powder of steel. Increasing the dispersion of the components increases the strength of the composite.

Aluminum powder is well wetted by polystyrene, and accordingly the connection between individual particles of the components in the composite is quite high. Therefore, the strength of composites with a larger amount of components of aluminum is the maximum for this class of composites.

It was found that for composites of the CFe050109 type, the tensile strength on a break is minimal, since they have the maximum amount of components of steel. It was also found that the tensile strength on a break depends on the size of the grains of the metal component. With an increase in the dispersion of the metal component, the tensile strength also increases.

In the work [22] the values of the compressive strength limit are given. The analysis of these results and their comparison with our data shows their similarity, allows us to determine how the strength characteristics change.

Composite materials of this type do not have high strength characteristics. However, they have fairly high radiation shielding properties. All this allows for the wide use of composites of this type for radiation shielding of various objects.

CONCLUSIONS

1. Experimental samples of composite materials of the CFe05YYZZ series have been manufactured. Equipment operating modes and temperature conditions have been selected experimentally.
2. Using a standard ^{241}Am, radiation source, the attenuation characteristics of the ionizing radiation flux were measured after it passed through samples of composite materials.
3. Numerical calculations of coefficients of the attenuation of ionizing radiation for composites with a radiation shielding component in the form of powder of steel were performed. Cases were considered when the amount of the component of metal was greater than the polystyrene component. It was found that the composite material CFe050901 had the maximum radiation shielding characteristics.
4. Mechanical tests of tensile strength on a break were carried out for composites CFe050109, CFe050505, CFe050901. The tests were carried out at temperatures of 250, 290, 320 K. It was found that the maximum tensile strength on a break occurs at a temperature of 290 K.
5. It was found that the tensile strength increased with the increase in the amount of aluminum component. It was determined that composites with the smallest particle sizes of the components had the highest tensile strength on a break.

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РАДІАЦІЙНО-ЗАХИСНІ ХАРАКТЕРИСТИКИ І ХАРАКТЕРИСТИКИ МІЦНОСТІ ПОЛІСТИРОЛ СТАЛЕВИХ КОМПОЗИЦІЙНИХ МАТЕРІАЛІВ З ВЕЛИКИМ ВМІСТОМ МЕТАЛЕВОЇ КОМПОНЕНТИ

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Виготовлено експериментальні зразки композиційних матеріалів із основою з полістиролу. Для радіаційного захисту використовували порошок сталі з розміром крупин 230 мкм. Як компоненту для армування композита застосовували порошок алюмінію з розміром крупинок 20, 40 мкм. За допомогою джерела іонізуючого випромінювання ^{241}Am (гамма-кванти з енергіями 59,54 кеВ) проведено вимірювання радіаційно-захисних характеристик цих композиційних матеріалів. Виконані чисельні розрахунки відносного ослаблення поглиненої дози. Експериментальні результати та розрахункові дані мають високий збіг. Такі композиційні матеріали ефективно поглинають гамма-випромінювання з енергіями до 150 кеВ. Виконано роботи з визначенням міцності на розрив цих зразків при температурах 250, 290, 320 К. Отримано, що максимальна межа міцності (24,4 МПа) при температурі 290 К була для зразків з максимальною кількістю алюмінієвої добавки.