# DEPENDENCE OF RADIATION SHIELDING CHARACTERISTICS AND TENSILE STRENGTH CHARACTERISTICS FOR COMPOSITE MATERIALS CONSISTING OF POLYSTYRENE AND A STEEL ADDITIVE

***E.M. Prokhorenko*[1]*, V.V. Lytvynenko*[1]*, A.A. Zakharchenko*[2]*, M.A. Khazhmuradov*[2]*,***
***S.A. Sokolov*[2]*, T.G. Prokhorenko*[3]**
**[1]*Institute of Electrophysics and Radiation Technologies NAS of Ukraine, Kharkiv, Ukraine;***
**[2]*NSC "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine;***
**[3]*Kharkiv National Automobile and Highway University, Kharkiv, Ukraine***
***E-mail: e.m.prokhorenko@gmail.com***

Radiation shielding and tensile strength on a break values were obtained for experimental samples of polystyrene-steel nano- and micro-composite materials. In these composites, the polystyrene volume is slightly larger than the metal component. Composite materials with different metal component compositions were studied. These composite materials can be used not only for shielding against ionizing radiation but also for protection against electromagnetic radiation. Particular attention was paid to the structure of composites with different component particle sizes. The attenuation of the ionizing radiation flux was determined using mathematical modeling methods (Monte Carlo (MC) method, Geant 4 v11-04 code). Ionizing radiation absorption coefficients were measured experimentally using standard gamma radiation sources (Am-241 and Eu-152). High agreement between experimental measurements and theoretical results was achieved. Tensile strength on a break measurements were conducted on composite material samples at temperatures of 250, 290, 320 K.

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## INTRODUCTION

The use of ionizing radiation in various sectors of human activity, energy, industry, agriculture, and medicine, has accelerated the development of these industries. The widespread use of ionizing radiation is justified by its high penetrating power with respect to the objects being studied.

This allows ionizing radiation to be used for medical diagnostics and therapy, material structure research, flaw detection, and more. Various types of ionizing radiation sources are widely used in science. Ionizing radiation is also used in a vast number of technological processes in manufacturing and agriculture. In addition to these sources, there are numerous other sources of ionizing radiation.

These sources can be both man-made and natural. Among them are nuclear power plants and natural deposits (sources) of radioactive elements. Of particular importance are radioactive element mining facilities, various waste rock storage facilities, and storage and disposal sites for spent nuclear fuel (SNF), radioactive waste (RAW), and decommissioned equipment.

The risk of accidents that could result in the release of various sources of ionizing radiation into the environment cannot be ruled out. These factors contribute to human exposure to ionizing radiation.

Long-term exposure of humans (biological objects) to various types of ionizing radiation leads to the development of various diseases. Ionizing radiation can also disrupt the operation of equipment operating in radiation-exposed areas. Therefore, a method for protecting against the harmful effects of ionizing radiation has been developed. This protection is achieved using various materials.

Traditional radiation shielding materials include lead, concrete, and heavy metal oxides. They are easy to manufacture and offer excellent radiation shielding properties, absorbing X-rays, gamma rays, and accelerated beams of high-energy protons, ions, and electrons. B, Br, and paraffin materials have low atomic masses and wide scattering cross-sections, offering good shielding against neutron fluxes. However, traditional materials have a number of significant drawbacks, including their heavy weight, the presence of lead, and structural rigidity. The presence of lead is associated with toxicity.

Therefore, the challenge is to create lightweight, more versatile, and wear-resistant composite materials. Lead-free polymer composite materials fully meet these requirements. They have low density, high strength, are wear-resistant, and flexible. They are also highly technologically advanced.

A significant amount of work has been completed to improve the manufacturing technology for these composites. Radiation shielding polymer composite materials are created by doping the polymer with radiation-protective particles. Materials with high atomic numbers (various metals and their oxides) can be used as radiation-protective particles. This work includes mixing, baking, and polymerization technologies. Another important task is the selection of functional particles (radiation shielding components) and the polymer matrix material. To strengthen the structure of the polymer matrix, it was doped with nanoparticles with a high coefficient of interfacial compatibility (wettability).

The main components of the composite materials we studied are polystyrene, steel powder, and aluminum powder. It's important to note that these composite materials are designed not only to protect against ionizing radiation but also to shield against electromagnetic radiation. The shielding effects vary depending on the amount of metal in the composite. With a small amount of metal, protection against electromagnetic radiation occurs due to the formation of scattering centers. The incident wave is scattered and absorbed. With a large amount of metal, the composite acquires conductive properties and acts as a conductor. Re-radiation of the incident wave may occur.

## PURPOSE OF WORK

The objectives of this work are:

1. Numerical calculation of gamma radiation absorption coefficients for layers of varying thicknesses. Measurement of the reduction in gamma radiation exposure (absorbed) dose by polystyrene-steel composite materials.
2. Measurement of tensile strength values for composites with a steel additive.
3. Refinement of the compression molding technology for polymer-based composites with a steel component. Improvement of the stability and homogeneity of the composites. Enhancement of interfacial compatibility between the base and radiation shielding functional particles.

## CONDUCTING EXPERIMENTS AND DISCUSSION OF RESULTS

The basis of the composite was polystyrene PSM-115 (GOST 20282-86). The choice of polystyrene is justified by its light weight, high wear resistance, and resistance to aggressive environments. Polystyrene is technologically advanced in processing and manufacturing of various products. Since the softening temperature is 86…92 °C, and the melting point is 198 °C, polystyrene can be used in different climatic zones and at different temperatures.

It is also important that when polystyrene is irradiated, along with the destruction process, the effect of radiation cross-linking of polystyrene molecules also works. The crosslinking process involves creating cross-linked covalent bonds between polystyrene macromolecules. In this case, a spatial grid is formed and the memory effect appears. All this only improves the performance characteristics of polystyrene.

To obtain a radiation shielding effect, functional particles with a high atomic number are added to polystyrene. In our case, these are steel microparticles. The sizes of these particles were in the range of 280 μm. The choice of steel was due to its low cost. It becomes possible to use waste from turning and grinding production. However, steel grains do not have sufficient interfacial compatibility (wettability) with the polystyrene base. Therefore, materials that have high interfacial compatibility are implanted into composite materials of this type.

In our case, aluminum powders were used, which were obtained from aluminum ASD-6, 2014, 6111 (ISO 209-1, TU 1791-007-49421776-2011). The sizes of individual aluminum nanoparticles were 10…20, 30…40, 60…90 μm. Aluminum has high interfacial compatibility with polystyrene. When nanoparticles are introduced into polystyrene, a matrix is formed. Microparticles of steel are rigidly fixed in the volume of the composite material.

**Improvement of equipment.** Several types of apparatus were used in experimental work. The main experimental work was carried out on a Windsor SP 80 horizontal injection molding machine (injection pressure – 180 MPa, injection volume – 50 $cm^3$).

The Windsor SP 80 is a conventional injection molding machine for producing polystyrene products. However, its design and layout allow for modernization and modification for the production of polystyrene-steel composite materials. The Windsor SP 80 unit was equipped with additional heating devices with control elements [1].

This refinement allowed the raw material mixture to be maintained at the required temperature. Finished product cooling was also smoother, improving the homogeneity and density of the composite. Additional devices were added to the raw material feed system. A temperature control system for both the raw material and the process was developed. Optical and IR radiometric methods were used. The Lend Ti-814, Fluke-10, and Fluke-25 [1] instruments were used.

Samples of polystyrene-steel composite materials were manufactured. The composites were produced using compression and extrusion technology. The manufacturing process is unique for each type of composite. During the process, heating and mixing modes for the raw materials and other process components were selected.

Composite materials of type C(PS08FeYYAlZZ) were manufactured. Where YY and ZZ are the volumetric amounts of steel and aluminum. Previously [1, 2] composite materials with different numbers of components and different particle sizes were studied.

**Calculation of radiation shielding characteristics.** Radiation shielding characteristics were determined using Monte Carlo (MC) mathematical modeling. The Geant4 v 11-04 software package was used. In practical medical radiology, the XMuDAT software package is used to calculate the mass absorption coefficient. For the PS8Fe4Al3 composite material, absorbed dose calculations were performed using Geant4 v 11-04 and XMuDAT. The results obtained using these two packages show high agreement (Fig. 1).

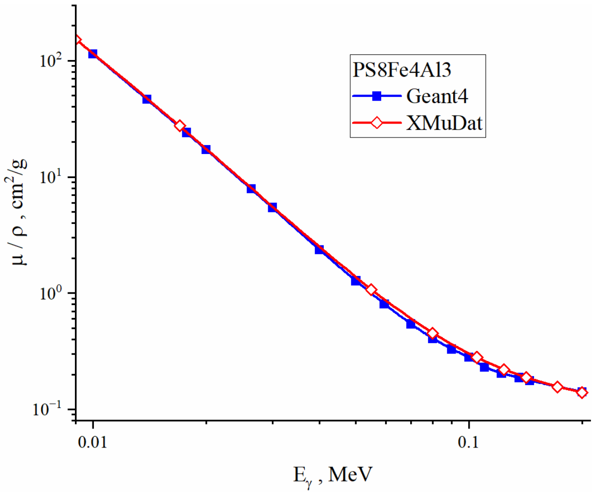

*Fig. 1. Mass absorption coefficient of polystyrene steel composite PS8Fe4Al3*

Calculations were performed for PS8FeXXAlYY composite materials. Specifically, the PS8Fe4Al3 composite was studied. This composite contains eight parts by volume of polystyrene, four parts by volume of steel, and three parts by volume of aluminum. The mass fraction was as follows: PS – 0.182, Fe – 0.6504, Al – 0.1676. The density was 3.22 g/cm$^3$.

An experimental measurement of the absorbed dose was conducted. Standard sources of ionizing radiation $^{241}$Am (gamma quantum energy 60 keV) were used for this [1, 2]. Samples of the following size – 7 × 4 × 1 cm – were used in the measurements. To experimentally determine the absorbed dose coefficients, changes in the area of the photopeak (59.54 keV) were studied. The area of the photopeak decreases with increasing absorption properties. The results of the experimental measurements are presented in [1, 2]. A high agreement between the experimental measurements and theoretical calculations was found.

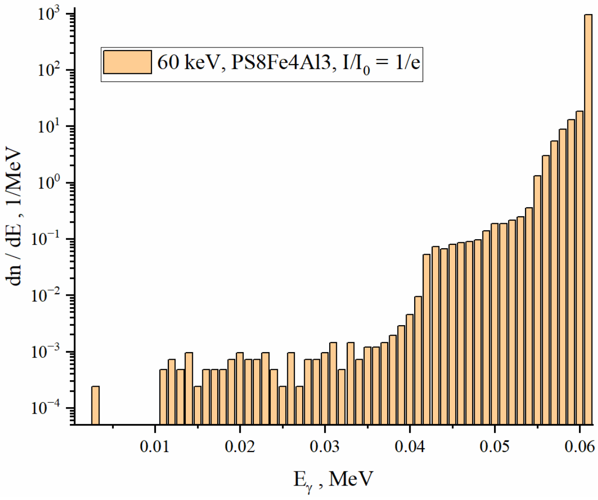

*Fig. 2. Spectrum of γ-quanta with an initial energy of 60 keV after passing through the protective layer of the PS8Fe4Al3 composite. The thickness of the protective layer is 1/μ = 3.59 mm*

The graphs revealed that when the number of gamma quanta decreases by a factor of e≈2.71828, a significant number of low-energy quanta emerge. These quanta were formed as a result of Compton scattering.

**Measuring tensile strength on a break**. Strength and wear resistance are essential properties of radiation-electromagnetic shielding composites. Tensile strength on a break is used to determine these properties.

Tensile strength was measured using a tensile testing machine. The measurements were performed in accordance with the requirements of the following regulatory documents: GOST 11262-80 "Plastics. Tensile Test Method", ASTM D638-10, and ASD-3039/D3039M. Rod-shaped specimens 12 cm long and 1 cm in diameter were used for the measurements. These experiments yield the ultimate tensile strength, relative elongation, and yield strength of the composite material. Tensile hardness measurements were performed at temperatures of 250, 290, 320 K. This range of extreme temperatures is representative of those likely to occur under natural conditions in Europe.

The PS8Fe4Al3 composite material contains a slightly higher proportion of polystyrene than the metal component mixture. This allows for maximum filling of the polystyrene matrix with nano- and micro-sized metal particles. Microscopic examination of composite sections was performed. It was found that this component composition results in a uniform distribution of metal particles throughout the polystyrene matrix.

Therefore, the tensile strength of composite materials of this type was high. At 290 K, the tensile strength was 42.8 MPa. At 320 K, the value was slightly lower, at 42.4 MPa. At 250 K, the tensile strength was 41.6 MPa. In experiments at 290 and 320 K, rupture occurred with elongation and had an elongated neck. For the 320 K experiment, the neck elongation was greater and the neck was thinner.

This effect is caused by the softening of polystyrene and the subsequent slippage of long molecules parallel to each other. At 250 K, tensile strength decreases. This occurs because polystyrene becomes brittle at low temperatures and becomes weaker. Fracture occurs as a chip along the larger steel grains. Therefore, the performance characteristics of polystyrene-steel composites decrease at extreme temperatures.

The paper [3] presents the results of compressive strength measurements for composite materials consisting of polyethylene and zinc. The results are similar to those of our experiments. Moreover, the overall strength characteristics are similar in magnitude.

## CONCLUSIONS

1. The modes of operations of equipment are experimentally determined. The basic equipment was improved. The technological process was refined to allow the production of PS8FeXXAlYY series composite materials. A pilot batch of this series of composites was manufactured. Steel powder with a particle size of 280 μm and aluminum powder with a particle size of 30…40 μm were used in production.

2. Numerical modeling of gamma-ray absorption in a PS8Fe4Al3 composite was performed. The spectrum of γ-rays (initial energy 60 keV) was determined after passing through a shielding layer of the PS8Fe4Al3 composite. It was found that with a shielding layer thickness of 1/μ = 3.59 mm, the γ-ray flux is attenuated by a factor of **e.**

3. The ultimate tensile strength on a break of the PS8Fe4Al3 composite was determined. The ultimate tensile strength on a break was determined using mechanical testing. Measurements were conducted at temperatures of 250, 290, 320 K. The maximum tensile strength on a break 42.8 MPa was obtained at 290 K.

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# ЗАЛЕЖНІСТЬ ХАРАКТЕРИСТИК РАДІАЦІЙНОГО ЗАХИСТУ І ХАРАКТЕРИСТИК МІЦНОСТІ НА РОЗРИВ ДЛЯ КОМПОЗИТНИХ МАТЕРІАЛІВ, ЩО СКЛАДАЮТЬСЯ З ПОЛІСТИРОЛУ І СТАЛЬНОЇ ДОБАВКИ

***Є.М. Прохоренко, В.В. Литвиненко, О.О. Захарченко, М.А. Хажмуратов, С.О. Соколов, Т.Г. Прохоренко***

Отримано значення радіаційно-захисних характеристик і характеристик міцності на розрив для експериментальних зразків полістирол-сталевих нанокомпозиційних матеріалів. У цих нанокомпозитів об’єм полістиролу трохи більший ніж об’єм металевої компоненти. Вивчалися композити, які мали різні склади металевих компонентів. Також окрема увага була приділена структурі композитів із різними розмірами частинок компонент. Ослаблення потоку іонізуючого випромінювання було знайдено за допомогою методів математичного моделювання (метод Монте-Карло (МК), код Geant 4 v 11-04). Експериментальними методами, за допомогою еталонних джерел гамма-випромінювання (Am-241 і Eu-152), були виміряні коефіцієнти поглинання іонізуючого випромінювання. Отримано високе співпадання експериментальних вимірів та теоретичних результатів. Визначені товщини шарів композитів, при яких відбувається ослаблення потоку іонізуючого випромінювання (60 кеВ) в **е** раз, в два рази, в 10 раз. Проведено вимірювання міцності на розрив зразків композиційних матеріалів. Міцність на розрив вимірювали при температурах 250, 290, 320 К.