


Gamma Shielding Analysis in Al 2124 Matrix Composites with EpiXS Simulation

EpiXS Simülasyonu ile Al 2124 Matrisli Kompozitlerde Gama Zırhlama Analizi

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Abstract

Composite materials theoretically designed by adding CoSO₄ ceramic material to Al 2124 alloy in proportions of 3-6-9-12% by weight were analyzed for gamma transmittance properties in the energy range of 1 keV to 1x10⁶ keV using the EpiXS program. The mean free path (MFP), half-value layer (HVL), and linear attenuation coefficient (LAC) parameters were analyzed using gamma radiation sources, including ²⁴¹Am, ¹³³Ba, ¹⁰⁹Cd, ⁵⁷Co, ⁶⁰Co, ¹⁵²Eu, and ¹³⁷Cs. As a result of the analysis, it was determined that with the increase in CoSO₄ by weight in Al 2124, the LAC values of the composite materials increased, while the HVL and MFP values decreased. In the photon energy range from 1 keV to 1x10⁶ keV, the Al 2124 material had the highest HVL value with values ranging from approximately 1.49x10⁻⁴ cm to 7.72 cm, while it had the lowest LAC values with values ranging from approximately 4661.03 cm⁻¹ to 0.09 cm⁻¹. The highest LAC values were obtained by the Al 2124+ 12% CoSO₄ composite material, which has the highest CoSO₄ ratio by weight, with LAC values ranging from approximately 6417.7 cm⁻¹ to 0.095 cm⁻¹. Due to its best photon shielding performance, its HVL had values ranging from approximately 1.08x10⁻⁴ cm to 7.3 cm.

Keywords: Al 2124, CoSO₄, gamma shielding, EpiXS

Öz

Al 2124 alaşımına ağırlıkça %3, %6, %9 ve %12 oranlarında CoSO₄ seramik malzemesi eklenerek teorik olarak tasarlanan kompozit malzemeler, EpiXS programı kullanılarak 1 keV ile 1x10⁶ keV enerji aralığında gama geçirgenlik özellikleri açısından analiz edildi. Serbest ortalama mesafe (MFP), yarı değer kalınlığı (HVL), doğrusal zayıflama katsayısı (LAC) parametreleri, ²⁴¹Am, ¹³³Ba, ¹⁰⁹Cd, ⁵⁷Co, ⁶⁰Co, ¹⁵²Eu, ¹³⁷Cs vd. gama radyasyon kaynakları kullanılarak analiz edilmiştir. Analiz sonucunda Al 2124 içerisindeki ağırlıkça CoSO₄'ün artması ile beraber kompozit malzemelerin LAC değerleri artarken HVL ve MFP değerleri azaldığı tespit edilmiştir. 1 keV ile 1x10⁶ keV foton enerji aralığında Al 2124 malzemesi yaklaşık 1.49x10⁻⁴ cm - 7.72 cm aralığında değişen değerleri ile en yüksek HVL değerini alırken yaklaşık 4661.03 cm⁻¹ - 0.09 cm⁻¹ değişen derler ile en düşük LAC değerlerini almıştır. En yüksek LAC değerlerini ise içerisinde ağırlıkça en yüksek CoSO₄ oranına sahip Al 2124+ %12 CoSO₄ kompozit malzemesi yaklaşık 6417.7 cm⁻¹- 0.095 cm⁻¹ arasında değişen LAC değerlerini almıştır. En iyi foton zırhlama performansını göstermesinden dolayı HVL değeri yaklaşık 1.08x10⁻⁴ cm- 7.3 cm arasında değişen değerler almıştır.

Anahtar Kelimeler: Al 2124, CoSO₄, gama zırhlama, EpiXS

I. INTRODUCTION

All living things on Earth are exposed to natural or artificial radiation. Some areas of use of radiation are shown in Figure 1. Artificial radio nuclides began to be produced in 1946, and radioactivity in 1934. Radioactive elements found in water, rocks, and soil in the Earth's crust, and radon gas in the air are natural radiations. These sources act as electromagnetic radiation and high-energy particles [1-2]. Gamma rays are massless, uncharged electromagnetic radiation. Due to their high frequency, they can penetrate and damage living cells. For this reason, protection against the harmful effects of gamma radiation is a critical issue. High-density and high atomic number shielding materials, such as lead, are used to protect against the harmful effects of photons. Despite the low melting points of lead and lead-based materials, they are quite successful in attenuating gamma radiation. However, lead material has toxic properties [3-6]. Al 2xxx series alloys are a lightweight material with high strength and corrosion resistance [7]. Al 2124 alloy has a melting point approximately two times that of lead and is an alloy with high strength due to the Al₂Cu phase it contains. At the same time, Al 2124 provides ease of use due to its density of 2.84 g/cm³ [8-11].

Aktas et al. [12] researched the beta, neutron and photon shielding properties of Al-B₄C-W hybrid composite materials with varying weights. Çağlar [13] researched the radiation shielding properties of materials with B₄C reinforcement added to Al 6061-40Sm₂O₃ at varying ratios of 1-5-13-17%. Gaylan et al. [14] researched the neutron shielding properties of Al-20%B₄C-x% (Sm, Sm₂O₃) composites. Kursun et al. [15] investigated the neutron shielding properties of (100-x) Al-x%Gd₂O₃ composites. Shi et al. [16] investigated the mechanical properties of B₄C_p-W_p/Al before and after radiation.

Various studies exist in the literature on the development of composite materials that can be used as alternatives to lead (Pb). In these studies, ceramic materials such as B₄C, Sm₂O₃, Bi₂O₃, Al₂O₃, and SiO₂ ceramics, etc., are generally preferred as reinforcement materials for composite matrices. However, there is a lack of sufficient studies in the literature on the radiation permeability properties of some inorganic salts commonly used in energy-electronic technologies.

In this context, the radiation attenuation performances of composite structures obtained by theoretically adding 3-6-9-12% by weight of CoSO₄, one of the inorganic salts widely used as a component of composite materials in super capacitors, electro catalysts, sensors, and lithium batteries, to the Al 2124 alloy matrix were analyzed using the EpiXS simulation program. In this study, the linear attenuation coefficient (LAC), half-value layer (HVL), and mean free path (MFP) parameters were investigated in detail to reveal the effect of CoSO₄ addition on the radiation shielding properties of the composites.

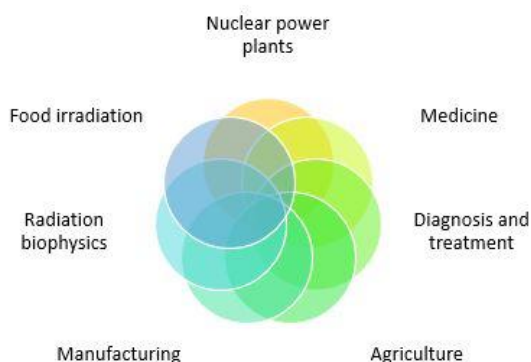


Figure 1. Areas of use of radiation.

II. MATERIALS AND RADIATION PARAMETERS

The density of Al 2124, whose chemical composition is given in Figure 2, is 2.84 g/cm³. The density value of CoSO₄ is 3.71 g/cm³ [17]. Information on the matrix and reinforcement ratios of composite materials reinforced with CoSO₄ ceramic material is given in Figure 3.

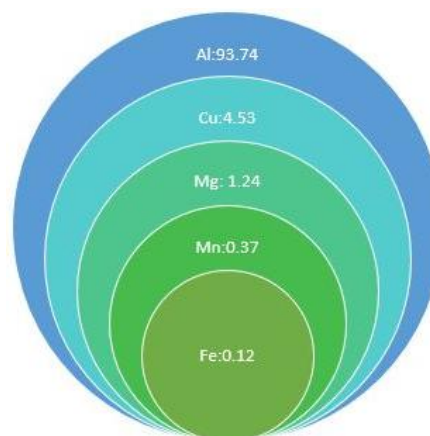


Figure 2. Chemical structure of Al 2124 [10].



Figure 3. Weight percentages of samples analyzed.

EpiXS is a simulation program that enables the theoretical modeling of photon-matter interactions. This program numerically simulates the attenuation behavior of elements, compounds, and composite materials with defined chemical compositions against photons in the energy range of 1 keV to 100 GeV, utilizing the EPICS2017 and EPDL97 data libraries. Based on the simulation outputs, fundamental parameters such as linear attenuation coefficient (LAC), half-value layer (HVL), and mean free path (MFP) of the materials are calculated, allowing for quantitative evaluation of radiation attenuation, dosimetry, and shielding properties [18]. During the analysis, ²⁴¹Am, ¹³³Ba, ¹⁰⁹Cd, ⁵⁷Co, ⁶⁰Co, ¹⁵²Eu, ¹³⁷Cs, ⁵⁵Fe, ¹³¹I, ⁵⁴Mn, ²²Na radioactive and standard gamma sources were used. Table 1 provides the parameters used to obtain information about gamma shielding.

Table 1. Radiation shielding parameters.

	Unit	Formula	References
LAC	cm ⁻¹	$I = I_0 \cdot e^{-\mu x}$	[19]
HVL	cm	$\frac{\ln 2}{\mu}$	[20]
MFP	cm	$\frac{1}{\mu}$	[21]

I: The amount of radiation passing through the matter.
I₀: Incoming radiation intensity to the matter.
μ: Linear attenuation coefficient
x: Material thickness (cm)

III. RADIATION SHIELDING RESULTS

3.1. LAC

When the LAC graph shown in Figure 4 is examined, the total LAC values of the analyzed materials decreased with increasing photon energy. At 13.81 keV (²⁴¹Am), where the photoelectric effect (PE) predominates, the total LAC values of the A0- A3-A6-A9- A12 samples were approximately 40.11 cm⁻¹, 42.26 cm⁻¹, 44.42 cm⁻¹, and 46.61 cm⁻¹, respectively. At 26.3446 keV, the total LAC values of the same gamma source were approximately 6.46 cm⁻¹, 6.82 cm⁻¹, 7.18 cm⁻¹, 7.55 cm⁻¹, and 7.93 cm⁻¹. Despite small changes in the energy of the ²⁴¹Am radioactive gamma source, the LAC changes of the material were observed to be quite rapid. In the high-energy region, LAC change rates decrease with increasing energy. The increases in the LAC values of the materials are due to the increased CoSO₄ ratio by weight. This is primarily due to the high total atomic number of the atoms forming CoSO₄, and the density of the Al 2124 alloy is 2.84 g/cm³, while the density of the added CoSO₄ is 3.71 g/cm³. This is because photons interact more strongly with materials with higher atomic numbers and higher densities. The total LAC value of the Al 2124 material was obtained as 31.68 cm at 15 keV energy. Pirez and Souza [22] determined the LAC value of the Al 7075 material as 36.4 cm at 15 keV energy. This reveals the effect of the chemical compositions and ratios of secondary elements added in trace amounts into aluminum alloys on the LAC values of the materials.

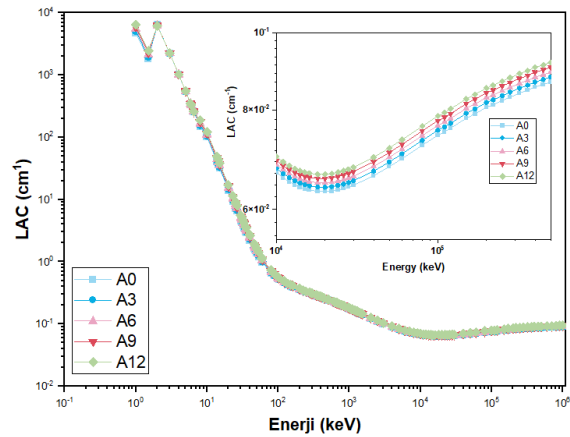


Figure 4. LAC values of samples

3.2. HVL

The HVL values of the materials also decreased with increasing CoSO₄ content. This demonstrates the positive effect of the CoSO₄ ceramic on Al 2124. The HVL values of the materials (Figure 5) increased with increasing energy. This is due to the decrease in the LAC values of the materials in the high-energy region. However, after a certain photon energy, the HVL values of the materials began to decrease again. This is thought to be due to secondary scattering resulting from the photons interacting with the electrons of the shielding material and then being absorbed by the electrons of the material. In the E < 512 keV energy region, where PE occurs dominantly, the ⁵⁷Co source has three energy peaks, approximately 14.41 keV, 122.06 keV, and 136.47 keV. The HVL values of the materials at these three energy peaks vary. This shows how significant the incident photon energy change is, even when the radiation source is the same. The A0 coded material takes values of approximately 0.019 cm - 1.52 cm - 1.63 cm at these three energies, respectively. The A3 material takes values of 0.018 cm - 1.50 cm - 1.61 cm, while the A6 material takes values of 0.017 cm - 1.47 cm - 1.58 cm; the A9 material takes values of 0.0167 cm - 1.45 cm - 1.56 cm; and the A12 material takes values of 0.016 cm - 1.43 cm - 1.54 cm.

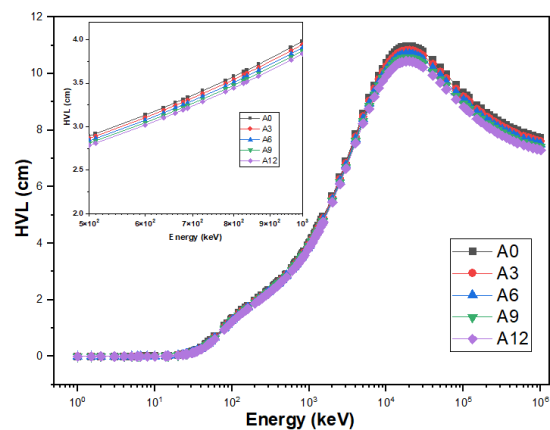


Figure 5. HVL values of samples

3.3. MPF

As seen in Figure 6, incident photons interact with CoSO_4 particles instead of propagating linearly through the voids within the material due to the CoSO_4 reinforcement. This resulted in lower MFP values for the A12 composite material, which has the highest CoSO_4 content (12%), compared to the A0 composite material without reinforcement, as shown in Figure 7. This finding suggests that the CoSO_4 reinforcement increases the probability of photon interaction within the material.

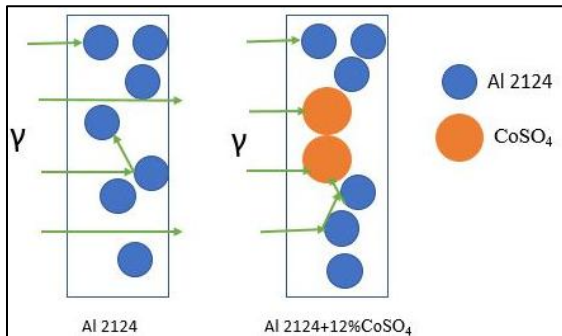


Figure 6. Interaction mechanism of Al 2124 and CoSO_4 with photon

The data presented in Table 1 reveals an inversely proportional relationship between MFP and the linear attenuation coefficient (LAC). In this context, MFP values are at their minimum in the energy ranges where LAC values are at their maximum. Furthermore, the rate of change in MFP values reaches its highest level in the high-energy regions, where pair production dominates, and remains at its lowest level in the medium-energy regions, where Compton scattering dominates. In the $511 \text{ keV} < E < 1022 \text{ keV}$ energy range, where Compton scattering occurs dominantly, the A0 coded material had values ranging from approximately 4.21 cm to 5.8 cm, while the A3 coded material had values ranging from 4.17 cm to 5.75 cm. The A6- A9 and A12 coded materials had values ranging from approximately 4.13 cm to 5.7 cm; 4.09 cm- 5.65 cm; and 4.06 cm- 5.6 cm, respectively.

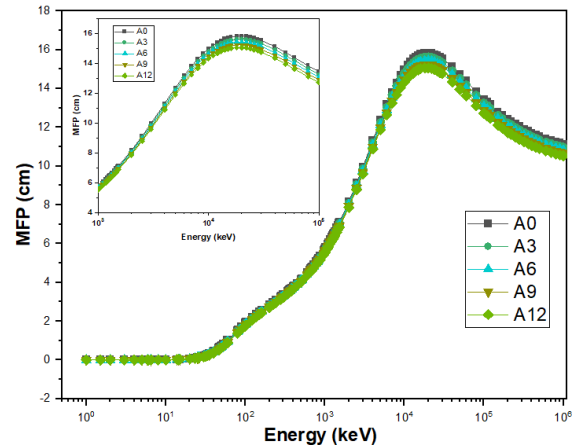


Figure 7. MFP values of samples

IV. CONCLUSIONS AND DISCUSSION

The EpiXS simulation program is an analysis tool that uses a purely mathematical modeling approach based on the chemical composition of materials. In this respect, the results obtained by the program are largely independent of the production methods, powder morphology, and size of the matrix and reinforcement materials used, composite production techniques, and manufacturing parameters. Therefore, considering the production challenges, costs, and complex manufacturing steps encountered in the experimental process, EpiXS is an extremely useful and economical simulation tool for preliminary analysis and pre-selection of a material to assess its potential for radiation shielding applications.

In this study, the effect of different amounts of CoSO_4 ceramic (3-6-9-12%) by weight added to Al 2124 in the EpiXS program on the radiation attenuation properties of materials against gamma was investigated.

- As a result of adding different amounts of CoSO_4 , the intensity values of the materials increased.
- This increased the LAC values of the materials and decreased the MFP and HVL values.
- While the LAC and values of the materials decreased with increasing photon energies, the HVL and MFP values increased.
- While it was easier for materials to stop photons in the low-energy region, it became difficult to shield them with increasing photon energy.

Table 2. Studies in the literature

Energy (keV)	Parameters	Literature Value	Ref.	This Study Value
15	LAC	29.923 cm ⁻¹ Al+5%Sm ₂ O ₃	[23]	31.68 cm ⁻¹ Al 2124
59.5	LAC	0.76 cm ⁻¹ (Al 2024+4%GNP)	[24]	1.02 cm ⁻¹ (Al 2124+3% CoSO ₄)
60	HVL	0.53 cm 0BaO (60%B ₂ O ₃ +20%Al ₂ O ₃ +20%CaF ₂)	[25]	0.71 cm Al 2124
81	LAC	7.76 cm ⁻¹ Sm(n)0	[26]	0.64 cm ⁻¹ Al 2124
276	LAC	0.63 cm ⁻¹ Sm(n)0	[6]	0.3 cm ⁻¹ Al 2124
300	LAC	0.299 cm ⁻¹ Al+5%Sm ₂ O ₃	[23]	0.3 cm ⁻¹ (Al 2124+3% CoSO ₄)
356	LAC	0.35 cm ⁻¹ (ZA27+3%GNP)	[24]	0.279 cm ⁻¹ (Al 2124+3% CoSO ₄)
356	LAC	0.47 cm ⁻¹ Sm(n)0	[26]	0.276 cm ⁻¹ Al 2124
383	LAC	0.448 cm ⁻¹ Sm(n)0	[26]	0.268 cm ⁻¹ Al 2124
662	HVL	3.4 cm HDPE+ wt. 50%Al(OH) ₃	[27]	3.15 cm (Al 2124+12% CoSO ₄)
662	LAC	0.156 cm ⁻¹ PCe- 1 (30% CeO ₂ +70 % PVC)	[28]	0.21 cm ⁻¹ Al 2124
1173	LAC	0.24 cm ⁻¹ (Cu+2%GNP)	[24]	0.16 cm ⁻¹ (Al 2124+3% CoSO ₄)
1274	LAC	0.09523 ±0.00909 cm ⁻¹ PGA/TAV-20	[3]	0.154 cm ⁻¹ Al 2124
1332	LAC	0.343 cm ⁻¹ BZ1 (50B ₂ O ₃ -5BaO-10ZnO-35Bi ₂ O ₃)	[29]	0.156 cm ⁻¹ (Al 2124+12% CoSO ₄)
1332	LAC	0.06684 cm ⁻¹ S3 (TiO ₂ reinforced PDMS composite)	[30]	0.152 cm ⁻¹ (Al 2124+3% CoSO ₄)
1332	LAC	0.21 cm ⁻¹ (theoretical) complex composite (ZABONC)	[31]	0.150 cm ⁻¹ Al 2124
1332	HVL	3.12 cm (theoretical) complex composite (ZABONC)	[31]	4.6 cm Al 2124
1332	MFP	4.51 cm (theoretical) complex composite (ZABONC)	[31]	6.64 cm Al 2124
2000	LAC	0.132 cm ⁻¹ Al+5%Sm ₂ O ₃	[23]	0.127 cm ⁻¹ (Al 2124+12% CoSO ₄)
3000	LAC	0.115 cm ⁻¹ Al+5%Sm ₂ O ₃	[23]	0.1 cm ⁻¹ Al 2124
4000	LAC	0.094 cm ⁻¹ Al+5%Sm ₂ O ₃	[23]	0.089 cm ⁻¹ (Al 2124+3% CoSO ₄)
5000	LAC	0.086 cm ⁻¹ Al+10%Sm ₂ O ₃	[23]	0.084 cm ⁻¹ (Al 2124+12% CoSO ₄)
6000	LAC	0.076 cm ⁻¹ Al+5%Sm ₂ O ₃	[23]	0.0758 cm ⁻¹ (Al 2124+3% CoSO ₄)

- In conclusion, the addition of CoSO₄, the gamma radiation shielding properties of the materials owing to the increase in density and total Z of the materials.

An examination of the data presented in Table 2 reveals that Al 2124 CoSO₄ composites have better radiation transmittance values compared to similar materials in the literature. Furthermore, a review of literature studies on Al alloy matrix composite materials reveals that small changes in the proportions of aluminum alloys have varying effects on the radiation transmittance properties of the materials.

There are limited studies in the literature on the radiation transmittance properties of inorganic salts such as BaSO₄, KNO₃, CuSO₄, and MgSO₄. Therefore, future research is recommended to utilize these inorganic salts in different ratios and combinations as shielding materials. This could offer new opportunities for the development of alternative and environmentally friendly radiation shielding materials.

REFERENCES

- [1] Hamisu, A., Khiter, O., Al-Zhrani, S., Haridh, W. S. B., Al-Hadeethi, Y., Sayyed, M. I., & Tijani, S. A. (2024). The use of nanomaterial polymeric materials as ionizing radiation shields. *Radiation Physics and Chemistry*, 216, 111448.
- [2] Babeer, A. M., Sayyed, M. I., Amin, H. Y., El-razek Mahmoud, A., & Sadeq, M. S. (2024). Composition impacts of La₂O₃ on the structure and radiation shielding parameters of NiO–BaO–B₂O₃ glasses. *Optical Materials*, 147, 114622.
- [3] Aldawood, S., Asemi, N. N., Kassim, H., Aziz, A. A., Saeed, W. S., & Al-Odayni, A. B. (2024). Gamma radiation shielding by titanium alloy reinforced by polymeric composite materials. *Journal of Radiation Research and Applied Sciences*, 17, 100793.
- [4] Ghule, P. G., Bholane, G. T., Joshi, R. P., Dahiwal, S. S., Shelke, P. N., & Dhole, S. D. (2024). Gamma radiation shielding properties of unsaturated polyester /Bi₂O₃ composites: An experimental, theoretical and simulation approach. *Radiation Physics and Chemistry*, 216, 111452.
- [5] Babeer, A. M., Sayyed, M. I., Morshidy, H. Y., El-razek Mahmoud, Abdo, M. A., & Sadeq, M. S. (2023). High transparency of PbO–BaO–Fe₂O₃–SrO–B₂O₃ glasses with improved radiation shielding properties. *Optical Materials*, 145, 114387.
- [6] Bawazeer, O., & Sadeq, M. S. (2021). Compositional dependency of transparency, optical and radiation shielding parameters inside Gd₂O₃–Fe₂O₃–Na₂O–SiO₂–B₂O₃ glass. *Ceramics International*, 50, 159–173.
- [7] Rauch, M., Nwankpa, U. V., & Hascoet, J. Y. (2021). Investigation of deposition strategy on wire and arc additive manufacturing of aluminium components. *Journal of Advanced Joining Processes*, 4, 100074.
- [8] Sukumaran, K., Ravikumar, K. K., Pillai, S. G. K., Rajan, T. P. D., Ravi, M., Pillai, R. M., & Pai, B. C. (2008). Studies on squeeze casting of Al 2124 alloy and 2124-10% SiCp metal matrix composite. *Materials Science and Engineering A*, 490, 235–241.
- [9] Lin, Y. C., Li, L. T., & Xia, Y. C. (2011). A new method to predict the metadynamic recrystallization behavior in 2124 aluminum alloy. *Computational Materials Science*, 50, 2038–2043.
- [10] Zhang, F., He, Z., Lu, K., Zhan, Z., Li, Z., & Wang, X. (2023). Interfacial microstructure and mechanical properties of 2124 aluminum alloy reinforced by AlCoCrFeNi high entropy alloy. *Journal of Materials Research and Technology*, 26, 8846-8856.
- [11] Hao, H., Ye, D., & Chen, C. (2014). Strain ratio effects on low-cycle fatigue behavior and deformation microstructure of 2124-T851 aluminum alloy. *Materials Science & Engineering A*, 605, 151–159.
- [12] Akkas, A., Tugrul, A. B., & Tazegul, O. (2025). Shielding performance of Al–B₄C–W composite materials against gamma-ray, beta and neutron radiations. *Radiation Physics and Chemistry*, 232, 112662.
- [13] Çağlar, S. (2025). Impact of B₄C reinforcement on the microstructure, wear, hardness, corrosion behavior, and radiation shielding properties of Al-40Sm₂O₃ hybrid composites. *Nuclear Engineering and Technology*, 57, 103566.
- [14] Gaylan, Y., Dag, I. E., Caglar, S., & Avar, B. (2025). Investigation of mechanical and radiation shielding properties of Sm–Sm₂O₃ reinforced Al–B₄C composite. *Radiation Physics and Chemistry*, 226, 112325.
- [15] Kursun, C., Gao, M., Yalcin, A. O., Parrey, K. A., & Gaylan, Y. (2024). Structure, mechanical, and neutron radiation shielding characteristics of mechanically milled nanostructured (100-x)Al-xGd₂O₃ metal composites. *Ceramics International*, 50, 27154–27164.
- [16] Shi, J., Lv, Z., Wang, J., Tang, W., Liu, Y., Yang, Z., Yang, J., Yang, Z., & Ma, S. (2025). A finite element study on the irradiation-induced mechanical behaviors of aluminum-matrix radiation-shielding composites. *Journal of Nuclear Materials*, 603, 155440.
- [17] Patnaik, P. (2002). *Handbook of Inorganic Chemicals*. McGraw-Hill Professional, 1 edition. <https://rushim.ru/books/spravochniki/handbook-of-inorganic-chemicals.pdf>

- [18] Hila, F. C., Asuncion-Astronomo, A., Dingle, C. A. M., Jecong, J. F. M., Javier-Hila, A. M. V., Gili, M. B. Z., Balderas, C. V., Lopez, G. E. P., Guillermo, N. R. D., & Amorsolo, A. V., Jr. (2021). EpiXS: A Windows-based program for photon attenuation, dosimetry and shielding based on EPICS2017 (ENDF/B-VIII) and EPDL97 (ENDF/B-VI.8). *Radiation Physics and Chemistry*, 182, 109331.
- [19] Sayyed, M. I., Kamışlıoğlu, M., & Jecong, J. F. M. (2022). Investigation of photon attenuation factors for TeO₂-Bi₂O₃-B₂O₃ glass systems using SRIM codes, EPICS2017 library and Phy-X/ PSD2. *Optik - International Journal for Light and Electron Optics*, 257, 168832.
- [20] Acikgoz, A., Demircan, G., Yılmaz, D., Aktas, B., Yalcin, S., & Yorulmaz, N. (2022). Structural, mechanical, radiation shielding properties and albedoparameters of alumina borate glasses: Role of CeO₂ and Er₂O₃. *Materials Science and Engineering B*, 276, 115519.
- [21] Prabhu, N. S., Sayyed, M. I., Almuqrin, A. H., Khandaker, M. U., Mahmoud, K. A., Yasmin, S., & Kamath, S. D. (2021). Network-modifying role of Er³⁺ ions on the structural, optical, mechanical, and radiation shielding properties of ZnF₂-BaO-Al₂O₃-Li₂O-B₂O₃ glass. *Radiation Physics and Chemistry*, 200, 110228.
- [22] Pires, L. F., & Souza, G. B. D. (2025). Radiation shielding properties of materials used in the aeronautical industry. *Radiation Physics and Chemistry*, 235, 112820.
- [23] Gaylan, Y., & Caglar, S. (2025). Effect of Sm₂O₃ on radiation shielding and mechanical properties of Al-Sm₂O₃ composites. *Ceramics International*, 51, 10133-10142.
- [24] Uyar, E., Akay, D., & Pul, M. (2025). Investigation of radiation shielding properties of Al₂O₃, ZrO₂ (Zamac) and Cu composites reinforced with nano graphene and multi-walled carbon nanotubes. *Radiation Physics and Chemistry*, 237, 113129.
- [25] Mutuwong, C., Bootjomchai, C., Chaiphaksa, W., Cheewasukhanont, W., Sommat, V., Kaewjaeng, S., Ornkhetphon, O., Intachai, N., Kothan, S., Kim, H. J., & Kaewkhao, J. (2025). Photon and thermal neutron shielding behaviors of aluminum calcium fluoroborate glass modified with barium oxide: FLUKA Monte Carlo, XCOM and experimental investigations. *Annals of Nuclear Energy*, 210, 110863.
- [26] Kilic, G., Durmus, H., Birdogan, S., Ilik, E., Perişanoğlu, E. K., Saltık, S., Guler, Ö., ALMisned, G., & Tekin, H. O. (2025). Nanoarchitectonics and radiation mitigation in Sm₂O₃-doped lithium borotellurite glass systems: From amorphous harmony to localized order. *Journal of Non-Crystalline Solids*, 666, 123674.
- [27] Khozemy, E. E., Salem, E. F., & Ali, A. E. H. (2022). Radiation shielding and enhanced thermal characteristics of high-density polyethylene reinforced with Al (OH)₃/Pb₂O₃ for radioactive waste management. *Radiation Physics and Chemistry*, 193, 109976.
- [28] Nasrabadi, M., Anbaran, H. K., & Ebrahimibasabi, E. (2025). Experimental study of radiation shielding and mechanical properties of polymer nanocomposite reinforced with CeO₂ NPs. *Materials Today Communications*, 48, 113369.
- [29] Yaghi, M. A., Sayyed, M. I., Manjunatha, Mhareb, M. H. A., Bennal, A. S., & Hamad, M. Kh. (2026). Radiation shielding and mechanical performance of lead-free novel glasses: Insights from Geant4 Monte Carlo simulations. *Radiation Physics and Chemistry*, 239, 113335.
- [30] Urooge, S., Shahzad, K., Fazil, S., Liaqat, K., Irshad, A., Khan, A., Hassan, R., & Alam, M. (2026). Fabrication and characterization of TiO₂ reinforced polydimethylsiloxane nanocomposite for simulation based gamma radiation shielding. *Radiation Physics and Chemistry*, 239, 113270.
- [31] Sathish, K. V., Sridhar, K. N., Seenappa, L., Manjunatha, H. C., Vidya, Y. S., Reddy, B. C., Manjunatha, S., Santhosh, A. N., Munirathnam, R., Raj, A. C., Gupta, P. S. D., & Sankarshan, B. M. (2023). X-ray/gamma radiation shielding properties of Aluminium- BariumZinc Oxide nanoparticles synthesized via low temperature solution combustion method. *Nuclear Engineering and Technology*, 55, 1519-1526