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Effect of Increasing Weight of SiC Ceramic on Radiation Shielding of Al 2219

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Anahtar Kelimeler

Al 2219
SiC
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Radyasyon Zırhlama

Graphical/Tabular Abstract (Grafik Özet)

In this study, the effect of SiC ceramics varying in weight on the radiation shielding properties of Al 2219 was investigated. / Bu çalışma ile ağırlıkça değişen SiC seramiklerin Al 2219'un radyasyon zırhlama özelliklerine etkisi incelenmiştir.

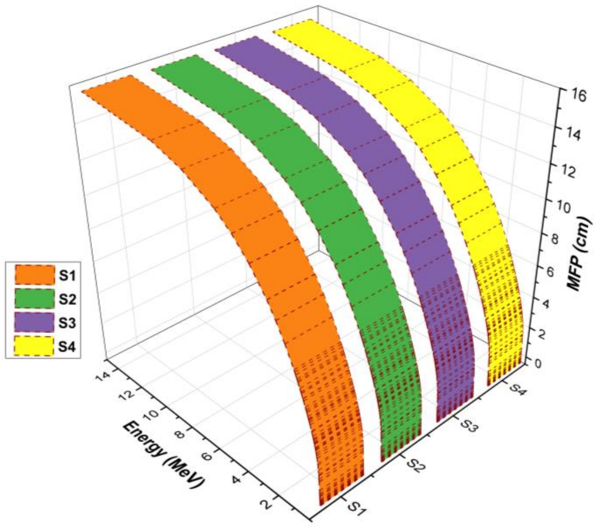

***Figure A**: MFP values of samples **Şekil A:** Örneklerin MFP değerleri*

Highlights (Önemli noktalar)

- *Effect of increasing SiC weight on gamma linear attenuation coefficient/ Ağırlıkça artan SiC'ün gama lineer zayıflatma katsayısına etkisi*
- *Effect of increasing SiC weight on gamma shielding material thickness/ Ağırlıkça artan SiC'ün gama zırhlam malzemesinin kalınlığına etkisi*
- *The effect of weight-varying SiC on the fast neutron cross section of alloy Al 2219/ Ağırlıkça değişen SiC'nin Al 2219 alaşımının hızlı nötron tesir kesiti üzerindeki etkisi*

***Aim (Amaç):** To increase the shielding properties of Al 2219 material. / Al 2219 malzemesinin zırhlama özelliklerini artırmak.*

***Originality (Özgünlük):** There has been no previous attempt to improve the shielding properties of Al 2219 material with SiC ceramics. / Daha önce Al 2219 malzemesinin zırhlama özelliklerini SiC seramiği ile geliştirmeye çalışılmamıştır.*

***Results (Bulgular):** With increasing weight of SiC ceramic, the possibility of Al 2219 to interact with fast neutrons increased. / Ağırlıkça artan SiC seramiği ile Al 2219'un hızlı nötronlar ile etkileşime girme olasılığı artmıştır.*

***Conclusion (Sonuç):** Among the Al 2219, Al 2219 + 5% SiC, Al 2219 + 10% SiC and Al 2219 + 15% SiC samples, the material with the highest LAC value was the Al 2219 + 15% SiC composite, while the Al 2219 material had the lowest LAC values. /Al 2219, Al 2219 + %5 SiC, Al 2219 + %10 SiC ve Al 2219 + %15 SiC numuneleri arasında en yüksek LAC değerine sahip malzeme Al 2219 + %15 SiC kompozit olurken, Al 2219 malzemesi en düşük LAC değerlerine sahip malzeme olmuştur.*

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Abstract

Artificial radiation has many disadvantages as well as benefits. In order to eliminate or minimize these disadvantages and to be an alternative to radiation shield materials used, Al 2219 alloy material, Al 2219+% 5 SiC, Al 2219+% 10 SiC and Al 2219+% 15 SiC metal matrix composite materials' mass attenuation coefficient (MAC), mean free path (MFP), linear attenuation coefficient (LAC), half value layer (HVL), fast neutron cross section (FNRCS) and tenth value layer (TVL) parameters were analyzed in Phy-x/PSD program. Powder grain structure of Al 2219 and SiC powders was analyzed by scanning electron microscopy (SEM) and powder grain size analysis was performed by Malvern Mastersizer 3000 device. After looking at fast neutron and gamma radiations, the materials' linear attenuation values against photons went up as the reinforcement ratio went up, while HVL, TVL, and MFP values went down. The FNRCS values of Al 2219 alloy material, Al 2219+5% SiC, Al 2219+10% SiC, Al 2219+15% SiC materials were calculated as 0.081 cm-1, 0.083 cm-1, 0.084 cm-1 and 0.084 cm^{-1} respectively.

SiC Seramiğin Artan Ağırlığının Al 2219'un Radyasyon Zırhlamasına Etkisi

Makale Bilgisi

Araştırma makalesi
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Anahtar Kelimeler

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Radyasyon Zırhlama

Öz

Yapay radyasyonun faydalarının yanı sıra birçok dezavantajı da bulunmaktadır. Bu dezavantajları ortadan kaldırmak veya en aza indirmek ve kullanılan radyasyon zırh malzemelerine alternatif olmak amacıyla Al 2219 alaşım malzemesi, Al 2219+% 5 SiC, Al 2219+% 10 SiC ve Al 2219+% 15 SiC metal matrisli kompozit malzemelerin kütle zayıflama katsayısı (MAC), ortalama serbest yol (MFP), doğrusal zayıflama katsayısı (LAC), yarı değer kalınlığı (HVL), hızlı nötron kesiti (FNRCS) ve onda bir değer kalınlığı (TVL) parametreleri Phy-x/PSD programında analiz edilmiştir. Al 2219 ve SiC tozlarının toz tane yapısı taramalı elektron mikroskobu (SEM) ile incelenmiş ve toz tane boyutu analizi Malvern Mastersizer 3000 cihazı ile yapılmıştır. Hızlı nötron ve gama radyasyonlarına bakıldığında, takviye oranı arttıkça malzemelerin fotonlara karşı doğrusal zayıflama değerleri artarken, HVL, TVL ve MFP değerleri azalmıştır. Al 2219 alaşım malzemesi, Al 2219+5% SiC, Al 2219+10% SiC, Al 2219+15% SiC malzemelerinin FNRCS değerleri sırasıyla 0,081 cm^{-1}, 0,083 cm^{-1}, 0,084 cm^{-1} ve 0,084 cm^{-1} olarak hesaplandı.

1. INTRODUCTION (GİRİŞ)

Despite the ongoing global transformation toward sustainable and renewable energy sources, the importance and contribution of nuclear energy to energy production worldwide cannot be ignored or underestimated [1]. Nuclear power plants, with their high energy output capacity accounting for approximately 11% of global electricity production, their low CO_2 emissions, and their ability to bridge the energy gap in countries lacking renewable resources, have garnered significant attention [2]. Therefore, as a consequence of the advancement of nuclear energy utilization, the use of X-rays and gamma rays as ionizing radiation is now prevalent in various fields, including nuclear reactors and nuclear medicine, radiological imaging, research centers, as well as industry. Thus, individuals are subjected to various forms of ionizing radiation, including gamma radiation. Due to the higher penetrating ability of gamma radiation compared to other particles, there is an increasing need to create appropriate shielding materials to prevent laborers and the population from harmful exposure. This potentially harmful radiation must be carefully contained so as not to harm human tissue and the environment [3-4]. As a result, reducing radiation exposure in the environment by shielding nuclear

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power plants has become an urgent priority, and extensive research on radiation protection has been conducted for many years to address these risks. This is primarily due to the need to sustain sensitive equipment and human wellbeing.

Current developments in gamma radiation shielding focus on the creation of new materials and composites that can efficiently reduce radiation, and this suggests that the presence of high atomic number elements, such as heavy metal oxides, in different matrices can greatly improve shielding capabilities [2-5]. Scientists have observed that incorporating SiC as a reinforced particle with AMMCs enhances mechanical and machinability properties, finding that a higher reinforcement ratio boosts hardness, tensile strength, and density, but decreases impact toughness [6-7].

In the mechanical analysis of Al 2024 / B_4C / SiC composites produced by the powder metallurgy method, Hua et al. [8] found that SiC nanowires increased the temperature resistance of Al 2024 material by 92.2%. They also obtained significant increases in neutron absorption. Lian et al. [9] found that the neutron shielding performance of 5 mm thick SiC/ Gd_2O_3/ 6061 Al material (0 wt%-25 wt%) SiC/ 5 wt% Gd_2O_3/ 6061 Al reached over 99.5% in MCNP5 software. Al-mugren et al. [10] investigated the radiation shielding properties of the materials they produced by doping WC, SiC and MoC into HDPE polymers against X-rays. Uzun [11] performed radiation shield analyses using Phy-x software commonly used Zircaloy, TiC, FeCrAl, ZrC, and SiC coating materials.

In industry, 2xxx aluminum alloy materials are widely used as SiC ceramics due to their mechanical properties. Since there are not enough studies in the literature on the effect of SiC on the radiation transmittance of Al 2xxx materials, Al 2219 reinforced with SiC metal matrix composite was analyzed in order to evaluate the radiation attenuation properties by incorporating different SiC ceramic materials into the matrix at 0-5-10-15% by weight. The Phy-x/PSD program investigated the tenth value layer (TVL), tenth value layer (HVL), fast neutron cross section (FNRCS), mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), and mean free path (MFP) parameters.

2. MATERIALS AND RADIATION PARAMETERS (MALZEMELER VE RADYASYON PARAMETRELERİ)

2.1. Materials (Mazlemeler)

After analyzing the powder dimensional analysis and SEM images of Al 2219 and SiC powders, the radiation parameters were theoretically examined in the Phy-x/PSD program. Table 1 shows the chemical distribution of Al 2219 alloy material by weight. It is understood that the main element in Al 2219 is aluminum and the primary alloying element is copper. One of the important parameters in the production of composite materials is the size distribution of the powder grains of the materials used. Dv (50), Dv (90), and Dv (10) values give the size of the powders at 50, 90, 10% by volume of the analyzed powders. The Malvern Mastersizer 3000 device was used to do the analysis. The Dv (90), Dv (50), and Dv (10) values for the Al 2219 material were 156 µm, 89.4 µm, and 14.5 µm, respectively. For the SiC material, they were 32.7 µm, 11.0 µm, and 2.40 µm.

It is very important to determine the powder materials used at the beginning of the process, as the sinterability and pressability properties of the materials change in relation to the shape of the powder grains. In powder metallurgy, reducing the powder grain size generally improves the mechanical properties of composite materials, but excessively small grain sizes can lead to sintering and machinability problems. Therefore, it is very important to determine the powder sizes of the powders to be used during production before production.

The powder particle shape of SiC ceramic material shown in Figure 1 generally has sharp corners, while some powder particles are also spherical. The SEM image of SiC ceramic supports the powder particle size analysis and reveals the size differences of powder particles. The dimensional distribution of the powder grains of the Al 2219 alloy material is shown in Figure 2. The SEM image supports the dimensional distribution of the powder grains mentioned in Table 2. Al 2219 powder particles are generally seen to have a pear-shaped or teardrop shape, as well as being spherical. Information about the SiC ceramic material and Al 2219 alloy material varying by weight among the analyzed materials is given in Table 3.

Table 1. Chemical composition of the Al 2219 alloy [12] (Al 2219 alaşımının kimyasal bileşimi)

wt. %	Cu	Ti	Mn	V	Zr	Al
Al 2219	6.3	0.06	0.3	0.10	0.18	Balance

Table 2. Powder grain size of Al 2219 and SiC (Al 2219 ve SiC'nin toz tane boyutu)

	Dv (90)	Dv (50)	Dv (10)
Al 2219	156 µm	89.4 µm	14.5 µm
SiC	32.7 µm	11.0 µm	2.40 µm

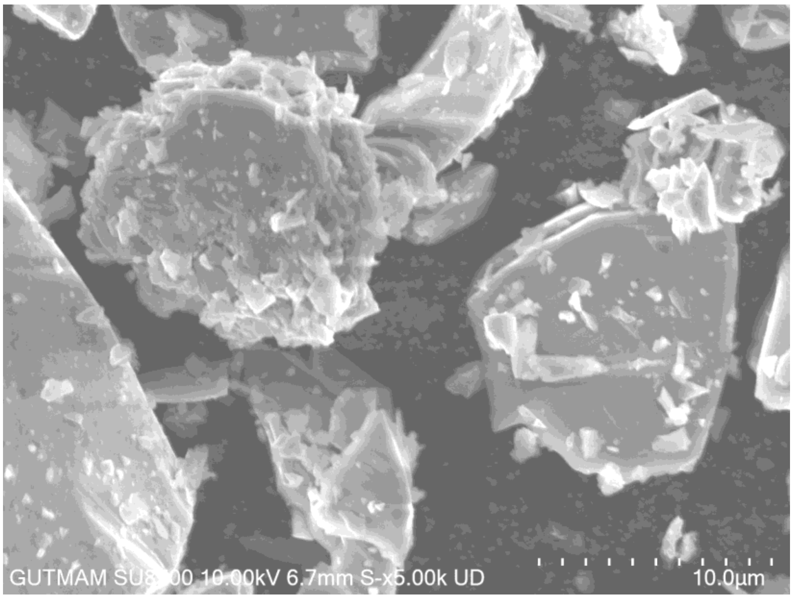

Figure 1. SEM image of SiC ceramic (SiC seramiğinin SEM görüntüsü)

Figure 2. SEM image of Al 2219 alloy (Al 2219 alaşımının SEM görüntüsü)

Table 3. Materials chemical composition (Malzemelerin kimyasal kompozisyonları)

Names of specimens	Composition
S1	Al 2219
S2	95% Al 2219+5% SiC
S3	90% Al 2219+10% SiC
S4	85% Al 2219+15% SiC

2.2. Radiation parameters (Radyasyon parametreleri)

The term linear attenuation coefficient (μ) (Equation 1) is a crucial indicator for gamma rays to show how well a material is able to absorb or weaken radiation as it moves through, thus being a proportion indicating how much incoming radiation is absorbed for each unit thickness of the material. The capacity of radiation to permeate a material relies upon both its energy level and the properties of the material itself. Higher energy radiation is generally more penetrating and therefore has a lower μ, whereas materials with higher atomic numbers or densities tend to have higher μ due to increased absorption. In Equation 2, the mass attenuation coefficient, which is the attenuation coefficient per density of the material, is given. The symbol x signifies the material's thickness [5]

$$I = l_o\, e^{-\mu x} \quad (1)$$

$$\mu_m = \mu/\rho \quad (2)$$

The half-value layer (Equation 3) is a metric employed to determine the quantity of substance needed to cut the radiation level in half [5].

$$HVL = (\ln(2))/\mu \quad (3)$$

These elements play a crucial role in assessing the effectiveness of different materials in offering shielding against gamma radiation.

The tenth value layer (Equation 4) is the thickness required to decrease the intensity by ninety percent, while the mean free path (Equation 5) is the average distance a photon travels between interactions, calculated using the linear attenuation coefficient (μ) [5,13]. The FNRCS parameter given in Equation 6 indicates the probability of fast neutrons interacting with the target material and ρ, represents the density of the material.

$$TVL = \ln(10)/\mu \quad (4)$$

$$MFP = 1/\mu \quad (5)$$

$$\Sigma_R = \Sigma_i\, \rho_i\, (\Sigma_R/\rho)_i \quad (6)$$

3. RESULTS (BULGULAR)

Using the Phy-x/PSD program [14], the parameters providing information about the gamma and fast neutron permeability of the S1-S2-S3-S4 coded samples were examined. In Figure 3, linear attenuation coefficients of materials against photon energy are given depending on increasing photon energy. The photon absorption of materials decreased depending on increasing photon energy. Since the theoretical density value of Al 2219 (2.84 g/cm^3) is lower than the theoretical density value of SiC (3.21 g/cm^3), the LAC values of the materials increased as the weight of the SiC ceramic material in Al 2219 increased. One of the main reasons for this is that dense materials have better gamma ray shielding. A certain region was selected in the graph given in Figure 3 and LAC graph which changes depending on energy increase in this region was drawn by focusing on approximately 0.867 MeV-1.6 MeV energy range. Pair formation occurs dominantly in the focused 1.022 MeV-1.5 MeV energy range. In the energy range of 1.022 MeV to 1.5 MeV, the LAC values of the S1-S2-S3-S4 coded samples are about 0.174 cm^{-1} to 0.142 cm^{-1}, 0.175 cm^{-1} to 0.143 cm^{-1}, 0.177 cm^{-1} to 0.144 cm^{-1}, and 0.178 cm^{-1} to 0.145 cm^{-1}. As can be understood from the LAC values, although the shielding property of the material against photons is improved with the addition of SiC, the raise in the LAC values is low. The reason for this is that the atomic number, which is one of the main parameters for radiation shielding, decreases connecting on the increasing SiC ratio by weight.

The MAC values of the S1-S2-S3-S4 coded samples in the energy range of 0.005888 MeV-15 MeV connecting on the changing photon energy are given in Figure 4. While the density values of the composite materials raise with the rise in SiC by weight, the attenuation coefficient per unit density decreases with the change in the chemical compound within the material and the decrease in the atomic number. Therefore, the MAC value of the Al 2219 (Al: 13 Cu: 29 Zr: 40) material with the code number S1 and without SiC reinforcement is maximum. The MAC value of the S4 coded sample containing 15% SiC (Si:14 C:6) reinforcement is the minimum. The MAC changes as the photon energy does because of the way the photoelectric effect (PE), pair production (PP), and Compton scattering (CS) interact with each other at different energy levels. The MAC values of the S1-S2-S3-S4 coded samples in the energy range of 0.0221 MeV (^{47}Ag) and 0.0358 MeV (^{133}Ba), where the PE occurs dominantly, have taken the values of 4.198 cm^2/g- 1.143 cm^2/g; 4.111 cm^2/g- 1.121 cm^2/g; 4.024 cm^2/g- 1.099 cm^2/g; 3.937 cm^2/g- 1.078 cm^2/g. As a result of the increases in photon energy, the MAC values decreased rapidly in the energy region where the PE occurs dominantly, while the decrease rates of the MAC values decreased in the energy region where CS occurs.

The HVL of the samples coded S1-S2-S3-S4, which varies relying on the changing photon energy, is given in Figure 5. Ba-133 is a gamma source with different photon energies. The HVL values of the samples coded S1-S2-S3-S4 at the photon energies of 0.03082 MeV, 0.05316 MeV, 0.3839 MeV, where the photoelectric event predominately occurred, were 0.145 cm- 0.147 cm- 0.149 cm- 0.151 cm; 0.526 cm- 0.530 cm- 0.535 cm- 0.539 cm; 2.583 cm- it is 2.562 cm- 2.542 cm-2.521 cm. The rise in the HVL values of materials with boosting photon energy shows us that the ability of materials to absorb photons decreases with boosting photon energy. The decrease in the HVL values of materials with increased SiC indicates that the SiC ceramic material enhances the radiation permeability properties of the Al 2219 material. At 15 MeV energy, which is the end energy of the analysis, the HVL values of the samples with S1-S2-S3-S4 codes are 10.765 cm- 10.722 cm- 10.679 cm- 10.637 cm respectively. It is seen that the difference between the HVL values is very small. However, it is quite important for the areas of use where the thickness value is important.

The distance value required for the S1-S2-S3-S4 coded materials to reduce incident photon congestion to 10% is similar to the HVL graph in Figure 5. While the increase in TVL values in the energy region where the photoelectric effect occurs is less, the rise in TVL values increased linearly with increasing photon energy, especially in the high energy region where PP dominantly occurs. The TVL values of the 60Co S1-S2-S3-S4 coded materials with 1.173 MeV energy are 14.328 cm- 14.208 cm- 14.090 cm- 13.973 cm, respectively, while at 2.506 MeV 60Co photon energy they took the values of 20.985 cm- 20.817 cm- 20.650 cm- 20.486 cm, respectively. Here, the effect of the incident photon energy on the thickness value of the material is clearly seen. It shows that the shielding properties of materials toward gamma radiation decrease with increasing photon energies.

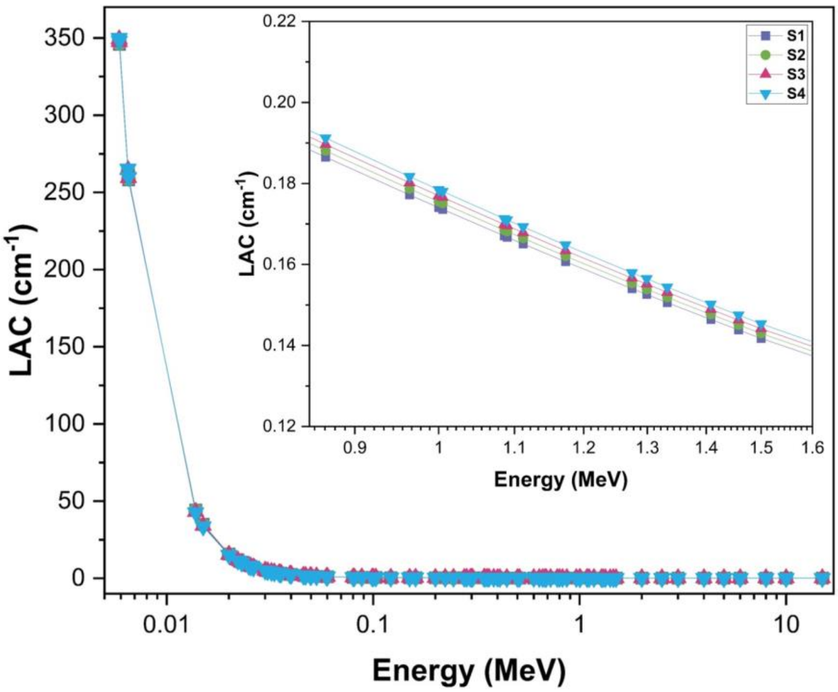

Figure 3. LAC values of samples (Malzemelerin LAC değerleri)

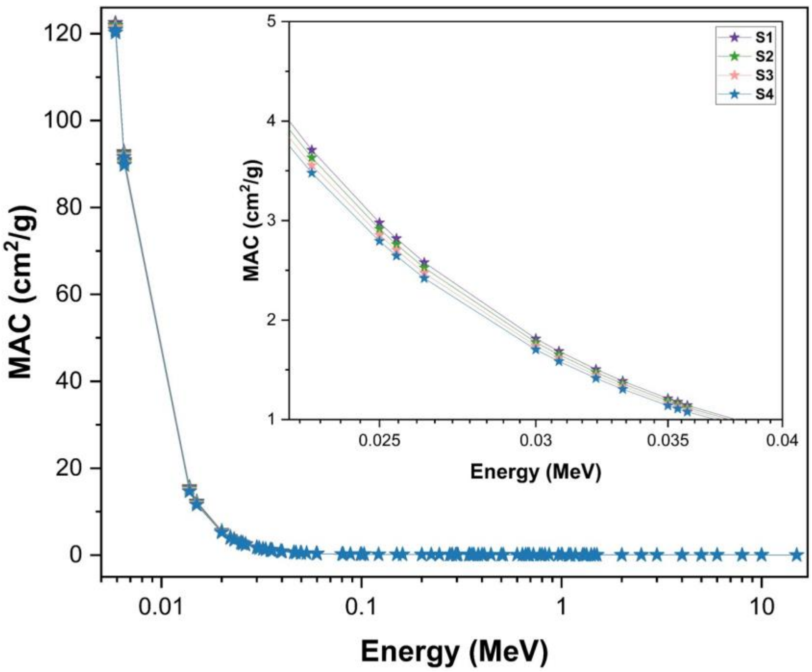

Figure 4. MAC values of samples (Malzemelerin MAC değerleri)

The MFP parameter shows the distance traveled by a photon during two successive interactions within the S1-S2-S3-S4 coded numbers. The material with the lowest MFP value is S4-coded material, while the material with the lowest MFP value is S1-coded material. The reason why S4 material comes out the best is because it has a higher density value and atomic number than Al 2219. While the MFP value is minimum at E< 0.015 MeV photon energy, the required distance values increase rapidly with increasing photon energy. Eu-152 radioactive nucleus emits gamma radiation in the energy regions where pair production, CS and PE occur. At 0.0358 MeV (Eu-152) energy, the MFP values of the samples coded S1-S2-S3-S4 are 0.308 cm- 0.312 cm- 0.316 cm- 0.321 cm, respectively, while at 0.6887 MeV (Eu-152) energy they are 4.812 cm- 4.772 cm- 4.733 cm- 4.694 cm, respectively, and at 1.408 MeV (Eu-152) energy they are 6.829 cm- 6.772 cm-6.715 cm- 6.660 cm, respectively.

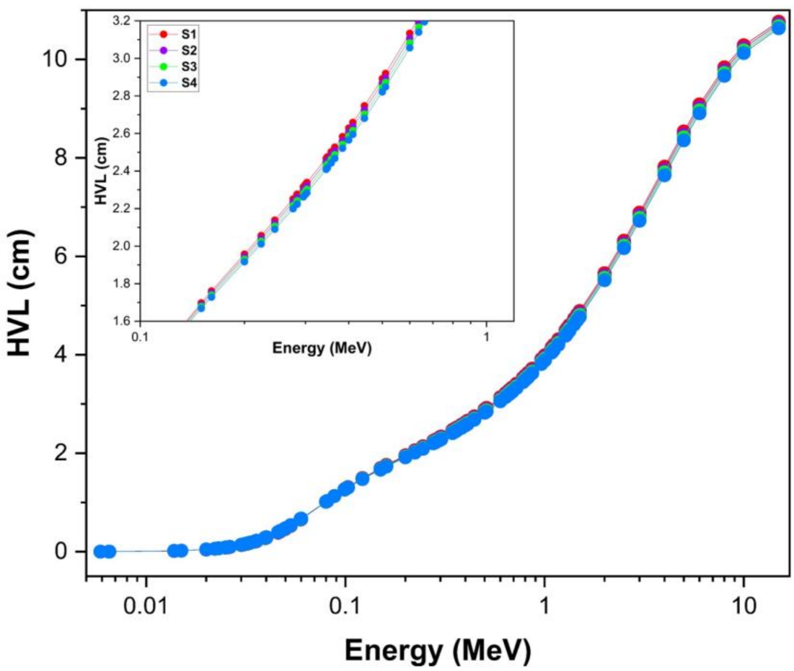

Figure 5. HVL values of samples (Malzemelerin HVL değerleri)

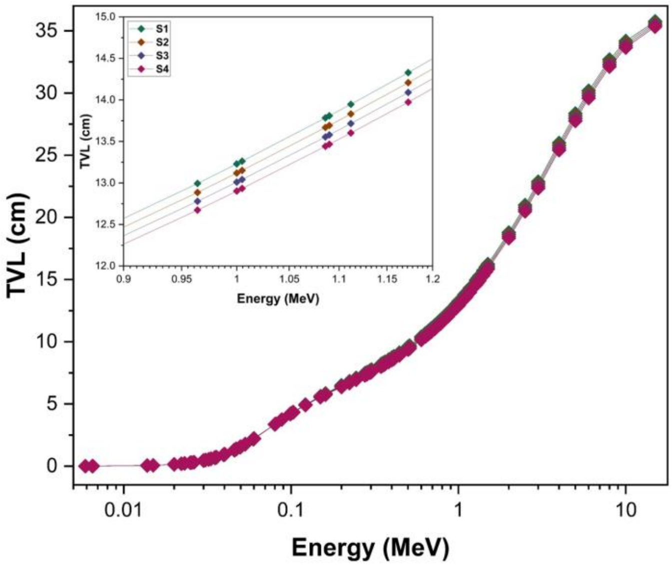

Figure 6. TVL values of samples (Malzemelerin TVL değerleri)

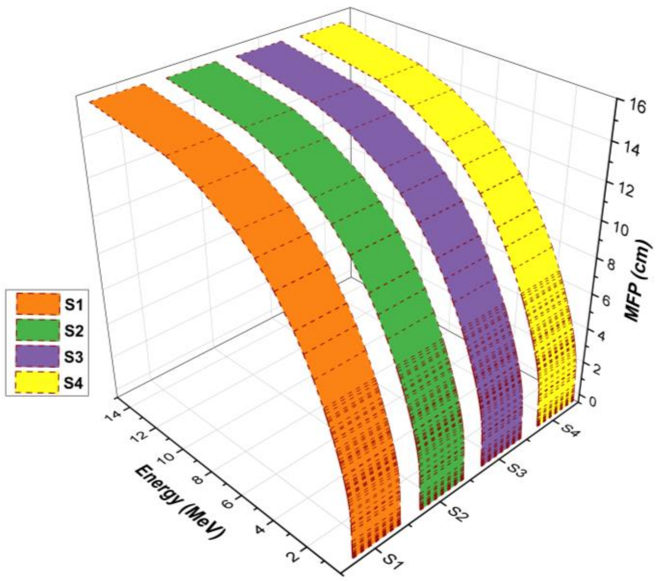

Figure 7. MFP values of samples (Malzemelerin MFP değerleri)

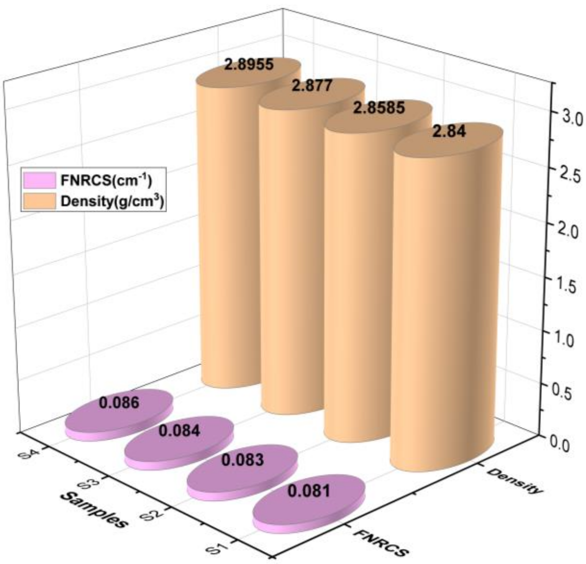

Figure 8. FNRCSS values of samples (Malzemelerin FNRCSS değerleri)

The FNRCSS values of the S1-S2-S3-S4 coded samples, that is, the FNRCSS value showing the probability of a fast neutron interacting with the target material, and the density values of the materials are given in Figure 8. The fast neutron cross section value is different for S1-S2-S3-S4 target materials because the changing chemical composition and ratios change the possibility of the materials interacting with fast neutrons. Due to the increasing SiC ratio by weight, the probability of materials interacting with fast neutrons has increased. As a result of adding SiC by 15% by weight to Al 2219, it increased the density value by approximately 2.09% and caused the FNRCSS value to increase by approximately 6.17%. The main reasons for the analysis result are that aluminum has an atomic number of 13, silicon, which forms the SiC ceramic, has an atomic number of 14, and carbon has an atomic number of 6. This shows that SiC has a heavier nucleus than aluminum and that SiC is more likely to interact with fast neutrons. Another reason is that SiC ceramics are denser than the aluminum element, which is the main material of the Al 2219 alloy, and this increases the possibility of interacting with fast neutrons [15-16]. The higher density of the target material means that there are more nuclei per unit volume that fast neutrons can interact with.

4. CONCLUSIONS (SONUÇLAR)

Radiation shielding is very important in terms of protecting human health (reducing the possibility of long-term health effects, cancer, indirect acute radiation syndrome, etc.), occupational safety (equipment, work environment, etc.), environmental safety (extinction of animals and plants, disruption of their genetic structure, etc.) and storage of radioactive waste (preventing contact with soil, preventing mixing with groundwater, etc.).

In this study, powder grain size distribution and SEM analysis of the matrix and reinforcement elements used were performed to determine the production parameters in the powder metallurgy production method. Al 2219 metal alloy 5-10-15 wt. % SiC ceramic material distribution metal matrix composite materials Phy-x/PSD program also produced important information about radiation recording properties depending on the photon energy TVL, LAC, MFP, HVL, and MAC were analyzed. In addition, the probability of target interaction with fast neutrons was analyzed. Among the Al 2219, Al 2219 + 5% SiC, Al 2219 + 10% SiC and Al 2219 + 15% SiC samples, the material with the highest LAC value was the Al 2219 + 15% SiC composite, while the Al 2219 material had the lowest LAC values. While LAC values increased, HVL, TVL and MFP values decreased. SiC reinforced metal composites FNRCSS values change with increasing SiC ratio. According to the results of this study, SiC ceramics in Al 2219 improved the radiation shielding properties used for protection from ionizing radiation. Aluminum alloy materials frequently use SiC ceramics due to their hardness, high strength, and mechanical properties at high temperatures. For this reason, this study on the effect of SiC ceramics on radiation shielding is very important for showing the contribution of SiC, which is used in many industries, to radiation shielding.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.

Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

***Kubilay AKGÜL*:** He conducted the experiments.

Deneysel çalışmaları yapmıştır.

***Berkay ÇAKIR*:** He conducted the literature review and checked the manuscript writing.

Literatür taramasını ve makalenin yazımını kontrol etmiştir.

***Seda GÜRGEN AVŞAR*:** She carried out theoretical analyses and experimental studies.

Teorik analizleri ve deneysel çalışmaları yapmıştır.

***Zübeyde ÖZKAN*:** She analyzed the results and performed the writing process.

Sonuçları analiz edip yazma sürecini gerçekleştirdi.

Uğur GÖKMEN**:** He analyzed the results and performed the writing process.

Sonuçlarını analiz etmiş ve maklenin yazım işlemini gerçekleştirmiştir.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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