



Analysis of Electromagnetic Shielding Effectiveness of Multilayer to Protect Against Lightning Strike Effect on Aerospace Applications

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Abstract: When lightning strikes in aerospace applications, the structural integrity and electrical systems of aircraft are put at great risk. Lightning creates very powerful electromagnetic pulses that conventional aluminium structures can't handle. This work examines how well mesh topologies protect multilayer metal matrix composites (MMCs) that include conductive and ceramic reinforcements, such as Al_2O_3 , SiC, and fly ash, within an Al6061 matrix. The composite structure has layers of metallic mesh coated with nickel to improve electromagnetic shielding and heat dissipation further. This investigation presents a theoretical and computational analysis of the efficacy of electromagnetic shielding, utilising Schelkunoff's theory in conjunction with a transmission-line model to evaluate multilayer MMC mesh structures. The suggested multilayer Al6061-based metal matrix composite (MMC) structures reinforced with SiC, Al_2O_3 , and fly ash exhibit improved electromagnetic shielding effectiveness in the X-band frequency range (8-12 GHz). The shielding performance is around 96.12dB better than that of regular aluminium structures due to improved absorption and impedance mismatch. This work demonstrates a useful way to build sophisticated aeronautical structures utilising lightweight, highly effective shielding materials.

Keywords: Lightning strike protection; shielding effectiveness (SE); transmission line model; fly ash reinforcement.

1. Introduction

The electronic parts and communication systems used in today's aeroplanes make them vulnerable to electromagnetic interference. There are three primary locations where electromagnetic interference may affect aircraft. Lightning is one thing that may trigger them. a) Emissions from radio waves, radar, and other electromagnetic sources; b) Items on board the aircraft that cause circuit spark discharges; and c) External parts [1]. Aeroplanes and passenger safety are jeopardised by electromagnetic interference (EMI), which can cause communication problems and major equipment failures. Electromagnetic shielding technologies are urgently required to lessen the negative effects of electromagnetic interference. Lightning EMPS and other pulsed intense electromagnetic radiations are non-nuclear EMPS that may

disrupt electronic devices. This issue gravely threatens the normal functioning of the concerned devices. The costs associated with these threats may be reduced by implementing electromagnetic protection measures [2].

Meshes and plates made of MMCs are used extensively as primary shielding structures in electromagnetic protection engineering. MMC's mesh structures have become more common in place of plate structures due to their many advantages in areas such as ventilation, illumination, weight, and cost [3-5]. The requirement for electromagnetic shielding is another factor that cannot be ignored. Metal meshes with only one layer cannot provide electromagnetic shielding. The research provides an overview of the practical use of double- and multilayer MMC mesh systems in electromagnetic protection. A few scientific models were introduced to assess the viability of single-layer metal cross sections for providing security. Casey (1988) [5] presented a technique for deciding the typical impedance of a metal lattice with square openings. This strategy uses the typical field hypothesis. The estimation approach assumes that the rate frequency and the metal lattice size are much larger than the width of the metal wire [6-8]. Hyun et al. (2016) conducted a review in which they made numerical changes to the Casey model. The motivation behind these changes was to explicitly upgrade the exactness of calculation results for denser metal lattices. It is critical to note that these changes were made while keeping the recurrence consistent [9].

Precisely determining the shielding efficacy of double-layer metal meshes using analytical methods poses significant challenges. The insightful model created by Losito et al. in 2010 [10] was utilised to appraise the protective adequacy of single-layer metal froths. The Casey model evaluated the viability of twofold-layer metal lattices as a safeguard across various frequencies. In any case, it didn't give an exact evaluation of their viability. In 2019, Wang et al. conducted an investigation into the protective performance of double-layer metal lattices. They used the same transmission line approach [11-13] for their investigation. The development of the insightful model was obtained from Casey's work. The scientists encountered difficulties performing precise computations across an extensive range of frequencies, as in the model referenced in [14]. In many examinations investigating the adequacy of multi-facet metal cross sections for safeguarding, mathematical models are typically preferred over analytical models [15]. The test of achieving quick outcomes across different designs and sizes arises from the sluggish performance of reenactments and the extensive resource use. Previous research has suggested that accurately assessing the shielding effectiveness of single- and double-layer metal meshes using the Casey model [5] poses a significant challenge. Determining the shielding efficacy of multilayer meshes is a challenging and intricate undertaking. This study presents an analytical model that expands on the Hyun model [9]. This model aims to assess the efficiency of double- and multilayer metal meshes in providing effective shielding. The initial presentation highlights an MMC's single-layer mesh model, which exhibits a plane impedance. The extension of shielding theory to multilayer metal plates has been applied to a technique involving multilayer meshes. Now, let's analyse the factors that affect the precision of the calculations used to evaluate the efficacy of double- and multilayer metal meshes as protective shields.

The study examines improvements in electromagnetic shielding coatings for aircraft applications, emphasizing materials such as ZrB₂ and composites. These coatings enhance longevity and efficiency, ensuring the reliability and safety of aviation equipment for both crew and passengers [16-17]. Electromagnetic environmental shielding is essential in aerospace to safeguard equipment and personnel from space radiation, including solar particle events, cosmic rays, and proton-electron radiation. Recent advancements in materials aim to improve reliability for upcoming space missions [18]. To improve system reliability and minimise errors caused by external electromagnetic sources, this paper investigates the optimisation of electromagnetic shielding techniques for aerospace systems. It focuses on a dual-layer shielding approach that uses aluminium foil to augment protection against high-frequency EMC [19]. For some aerospace applications, you need electromagnetic interference (EMI) shielding materials that can suit your particular functional needs while also efficiently reducing EMI. The article delves into composite EMI shielding materials optimized for aircraft applications through careful consideration of structural design and raw material selection [20]. Investigating how various infinite sheet metals can attain varying shielding effectiveness (SE) to fulfil the rigorous 40 dB SE criterion for electromagnetic compatibility, the study highlights the critical role of electromagnetic interference (EMI) shielding in aerospace, especially for space vehicles [21]. This paper presents a braided sheath for electromagnetically shielded cables suitable for aerospace applications. The sheath is composed of a

polytetrafluoroethylene film, aluminum, and copper shielding layers, all of which contribute to the cable's excellent mechanical properties, insulation, and shielding effectiveness, ensuring stable signal transmission even in electromagnetic environments [22]. The electromagnetic environment and onboard equipment may cause interference with aerospace applications, electromagnetic shielding is necessary. Optimizing protection while reducing weight, advanced materials, especially nanomaterials, increase shielding efficiency over a frequency range from Hz to THz [23].

Even though materials for electromagnetic shielding have advanced, accurately analysing multilayer metal-mesh-based metal-matrix composites (MMCs) remains challenging due to the complexity of impedance interactions and frequency-dependent behaviour. Most current investigations are either on single-layer shielding setups or numerical simulations. There aren't many analytical methods that can effectively anticipate how multilayer systems would behave across a wide range of frequencies [24-25]. The main purpose of this research is to create and evaluate multilayer Al6061-based MMC mesh structures fortified with SiC, Al₂O₃, and fly ash, to improve electromagnetic shielding efficacy for aerospace applications. This study uses Schelkunoff's theory of electromagnetic shielding and a transmission-line modelling approach to look at the theoretical and computational aspects of shielding mechanisms. It focuses on reflection and absorption losses in the X-band frequency range (8–12 GHz). The research seeks to assess the impact of reinforcement composition and multilayer architecture on shielding efficacy, and to propose lightweight composite solutions suitable for aeronautical electromagnetic conditions.

2. Materials and Methods

When designing sophisticated multilayer metal-matrix composites (MMCs) that can withstand lightning strikes in aerospace applications, it is crucial to use the right materials. This research uses a hybrid material system to find a balance between mechanical performance, thermal stability, electrical conductivity, and light weight. The suggested system comprises an Al6061 alloy matrix strengthened with a blend of fly ash particles, silicon carbide (SiC), and aluminium oxide (Al₂O₃). Also, conductive nickel-coated mesh layers are placed between the MMC layers to enhance electromagnetic shielding effectiveness (SE). Al6061 was selected as the base matrix material. It is a common aluminium alloy utilised in aerospace applications. Al6061 is known for being very strong for its weight, highly corrosion-resistant, and having a high thermal conductivity. It can absorb lightning-induced currents due to its relatively high electrical conductivity (approximately 40% IACS) [26]. It also works very well with ceramic reinforcements and is suitable for casting and extrusion, both of which are important for making multilayer composite structures. Adding ceramic reinforcements such as Al₂O₃ and SiC makes the composite stronger and better at withstanding heat. Al₂O₃ (10 wt%) was selected because it is very strong, resistant to wear and tear, and very stable at high temperatures. These properties help it withstand erosion and deterioration after a lightning strike. Silicon carbide (5 wt%) is added to improve heat conduction and mechanical strength while maintaining the material's excellent oxidation resistance. The ceramic particles act as thermal barriers, making the composite better able to withstand the very high temperatures associated with lightning strikes [27–28]. Fly ash is a cheap and light filler made from industrial waste that is high in alumino-silicate compounds. It is utilised at a concentration of 10 wt%. Adding this element lowers the composite's overall density while improving its ability to insulate against heat and resist deformation at high temperatures. In addition, using fly ash to make aeroplane parts from trash helps develop sustainable materials [29]. To meet the demand for improved electromagnetic shielding, layers of nickel-coated stainless steel mesh are inserted between the composite layers. The mesh structures have several uses: they allow electrical current to flow through them with little resistance, reflect incoming electromagnetic radiation, and improve energy absorption by reflecting it multiple times. Nickel plating makes the surface more conductive and corrosion-resistant, both of which are important for long-lasting performance in aviation applications [30]. Nickel-coated stainless-steel meshes (200 mesh per inch, ~150 µm wire thickness) with a nickel coating thickness of approximately 3–5 µm were employed as conductive interlayers to enhance electromagnetic shielding performance. The multilayer architecture features MMC layers and nickel-mesh interfaces that alternate. This setup improves performance by improving reflection and absorption processes and fixing impedance mismatches between layers. This makes high-frequency electromagnetic waves less

powerful. The concept combines mechanical performance with electromagnetic shielding, making it suitable for aircraft skin, unmanned aerial vehicles (UAVs), and other aerospace components that are struck by high-energy lightning [31].

2.1 Fabrication Process

Utilising the stir-casting method, we fabricated multilayer Al6061-based metal-matrix composite (MMC) structures reinforced with ceramic and industrial byproduct particles. Stir casting is an economical and scalable technique for manufacturing aluminium matrix composites in their molten form. This technique offers exceptional control over particle dispersion and is optimal for generating a large number of particles [32]. The selection of commercial-grade Al6061 alloy as the matrix material was based on its superior casting characteristics, moderate strength, corrosion resistance, and appropriateness for aerospace applications. Aluminium oxide (Al_2O_3) and silicon carbide (SiC) were used as ceramic particles, while fly ash was employed as a low-density industrial waste filler. All reinforcements were filtered to guarantee that the particles were fewer than $50\text{ }\mu\text{m}$ in size. The materials were further heated to 300°C for 2 hours to remove moisture, improve wettability, and prevent hydrogen gas from being trapped during casting [24]. Nickel-coated stainless steel mesh (200 mesh per inch, approximately $150\text{ }\mu\text{m}$ thick) was used as the conductive substrate between the layers. Before casting, the meshes were ultrasonically cleaned in acetone and then dried to enhance their adhesion to the matrix during layer integration. A resistance furnace with a graphite crucible was used for the stir casting process. The Al6061 alloy was melted at a processing temperature between 700 and 750°C , which is sufficiently above its liquidus temperature to ensure complete melting and effective reinforcement incorporation. A little proportion (1 wt%) of magnesium (Mg) was integrated into the melt to improve the adherence of the molten matrix to the ceramic and fly ash particles [25]. Upon achieving stability in the mixture, the heated reinforcements (10% Al_2O_3 , 10% SiC, and 5% fly ash) were meticulously incorporated into the molten aluminium, which was agitated at 450 rpm for 10 minutes using a graphite-coated impeller. An argon gas purge was maintained while stirring to prevent oxidation of the mixture and to remove dissolved gases. This guaranteed homogeneous particle distribution and minimised voids in the final casting [33].

Table 1. Percentage combination of materials

Material	Name of Specimen
AL6061+5% Al_2O_3 +5%SiC+5%FA	MMCs-10
AL606+7.5% Al_2O_3 +7.5%SiC+5%FA	MMCs-11
AL606+10% Al_2O_3 +10%SiC+5%FA	MMCs-12

2.2 Analysis of Multilayer MMC Meshes

The calculation of shielding efficiency for multilayer MMC meshes. To accomplish this, we modify the plane impedance model originally developed for a single-layer MMC mesh to apply it to shielding theory for multilayer conductors.

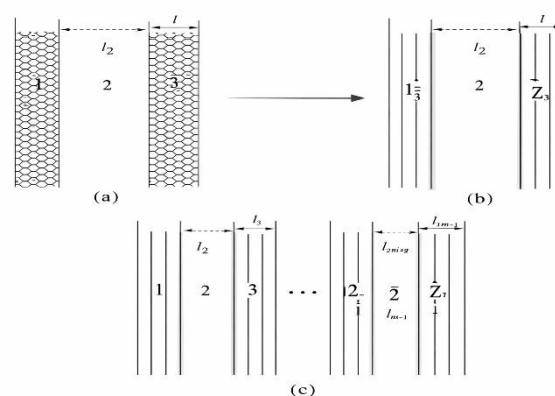


Figure 1. Electromagnetic Shielding model of a multilayer sheet and mesh

The initial step of this process involves examining an MMC's plate, which consists of only one layer. Figure 1: Electromagnetic Shielding model of a multilayer sheet and mesh. The formula provided can be used to calculate the shielding efficiency of a single plate [34].

$$SE = A + R + M \quad (1)$$

$$SE = \underbrace{20 \log_{10} e^{l/\delta}}_A + \underbrace{20 \log_{10} \left| \frac{(\eta_0 + \eta)^2}{4\eta_0\eta} \right|}_R + \underbrace{20 \log_{10} \left| 1 - \left(\frac{\eta_0 - \eta}{\eta_0 + \eta} \right)^2 e^{-2\gamma l} \right|}_M \quad (2)$$

In the given context, absorption loss is represented by the symbol "A," reflection loss by "R," and multiple reflection loss by "M." The effectiveness of using a single-layer MMC plate as a conveyor is often attributed to its inherent impedance (η), which is lower than the impedance of free space (η_0). Additionally, it is important to acknowledge that the thickness (l) of the MMC's plate generally exceeds the skin depth.

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (3)$$

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\epsilon)} \quad (4)$$

The equation includes variables that represent different properties of the MMC's plate. γ represents the propagation constant, which describes how waves propagate through the plate. ϵ , μ , and σ represent the plate's permittivity, permeability, and conductivity, respectively. The variable "f" represents the frequency of the incident wave. The M worth is far less critical than the benefits of the first two boundaries (A and R). Thus, the safeguarding viability of a solitary MMC's plate can be communicated as follows.

$$SE_{single\ plate} = A + R \quad (5)$$

Figure 1(a) shows the game plan of twofold-layer MMC plates, with each plate having thickness and material properties similar to those of a solitary-layer plate. The client has determined the interlayer between the metal plates as "l₂." To thoroughly examine the safeguarding viability of the twofold-layer plate structure, the design has been partitioned into three distinct regions, designated as locales 1, 2, and 3, as shown in Figure 1(a). To discover the composite design's general protective adequacy, it is essential to process the combined safeguarding viability values for these three individual locales

$$SE_{Double\ plate} = SE_1 + SE_2 + SE_3 \quad (6)$$

The MMC's plates in this arrangement have similar safeguarding adequacy because of their reliable mathematical and electromagnetic properties, addressed as $SE_1 = SE_3$. It's essential to note that the safeguarding adequacy (SE) of the air interlayer doesn't adhere to the two suspicions applied to the MMC's plates. The methodology for registering misfortunes due to various reflections within the air interlayer (district 2) can be outlined as follows. The image λ_0 It is utilized to address the frequency in free space.

$$M_2 = 20 \log_{10} \left| 1 - \left(\frac{z_0 - z_s}{z_0 + z_s} \right)^2 e^{-2\gamma_2 l_2} \right| \quad (7)$$

$$M_2 = 20 \log_{10} \left| 1 - \left(\frac{z_0 - z_s}{z_0 + z_s} \right)^2 \left(\cos 4\pi \frac{l_2}{\lambda_0} - j \sin 4\pi \frac{l_2}{\lambda_0} \right) \right| \quad (8)$$

In Figure 1(b), a twofold-layer structure is delineated, where the MMC plates in locales 1 and 3 are subbed with networks made of the same material and having the same thickness. The thickness of an MMC's plate (l) rises to the thickness of an MMC's cross-section. Ultimately, the configuration of multilayer metal meshes, as illustrated in Fig. 1(c), can be achieved by extending horizontally the configuration of a dual-layer mesh is illustrated in Fig. 1(b). Since the porosity of the lattice is higher than that of the MMC's plate, its

assimilation misfortune is unimportant. The strategy for registering the protective adequacy of the twofold layer MMC's lattice is framed as follows:

$$\text{SE Double Mesh} = \text{Reflection loss for first layer} + \text{Reflection loss for second layer} + \text{Multiple Reflection loss for second layer} \quad (9)$$

$$A_{\text{first layer}} = \exp\left(\frac{t_m}{\sqrt{2}} \sqrt{k_0 \sigma_m \mu_m}\right) \quad (10)$$

$$R_{\text{first layer}} = 20 \log_{10} \left| \frac{(z_0 + z_s)^2}{4z_0 z_s} \right| \quad (11)$$

$$M_2 = 20 \log_{10} \left| 1 - \left(\frac{z_0 - z_s}{z_0 + z_s} \right)^2 e^{-2\gamma_2 l_2} \right| \quad (12)$$

$$z_{s1} = z'_w a_s + j\omega L_s \quad (13)$$

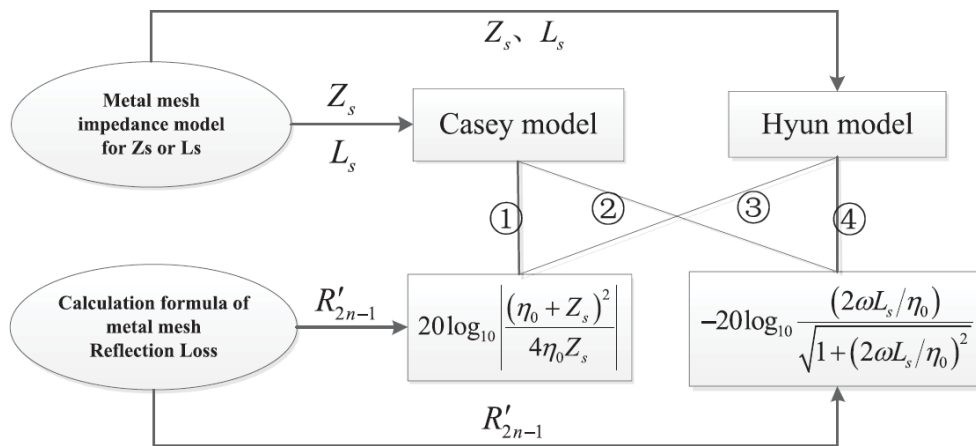


Figure 2. Overview of the various calculation methods used to determine the reflection loss [31].

The k_0 is used to address the free-space wave number. z'_w represents the normalised wave impedance of the multilayer structure relative to that of open space. a_s The attenuation coefficient (Np/m) shows how the field weakens within a conductive medium.

The impedance model for a metal mesh is depicted in Figure 2, providing a succinct representation. Additionally, the approach used to compute the metal-mesh reflection losses is outlined. To ensure high accuracy in shielding effectiveness calculations, it is crucial to implement stringent measures and methodologies. The user emphasises the importance of using precise and reliable mathematical models, advanced simulation techniques, and accurate input parameters and data. In addition, it is important to emphasise the need for comprehensive validation and verification procedures to ensure the accuracy and reliability of the calculations. The accuracy of the shielding effectiveness calculations can be improved by implementing these analytical approaches. An examination is underway to assess the use of multilayer meshes across a wide range of frequencies. Analysing data is crucial for making well-informed decisions. The figure depicts the visibility of both Casey and Hyun. The use of models is a common practice in computing the impedance Z_s or L_s of a system. A single-layer metal mesh is a material composed of interwoven metal wires or threads arranged in a single layer. Furthermore, it is important to acknowledge that there are two separate schemes for calculating the reflection loss of a metal mesh, which is essential for determining its shielding effectiveness.

3. Results and Discussion

Figure 3 portrays the protective viability of a miniature absorbing material supported by an Al6061 composite at 1 mm for the ordinary frequency of electromagnetic waves in the X-band. Nickel was the most engrossing material, with the most extreme shielding of 51 dB and the least shielding of 39.9 dB at 8 GHz and 12 GHz, respectively. Figure 4 illustrates the effectiveness of a Miniature retaining material supported by an 85% Al6061 + 5% Sic + 5% Al_2O_3 + 5% FA composite at a thickness of 1 mm for typical electromagnetic wave occurrences in the X-band. The chosen retaining material is nickel, which provides a maximum shielding of 79.3 dB and a minimum shielding of 40.2 dB at frequencies of 8 GHz and 12 GHz, respectively.

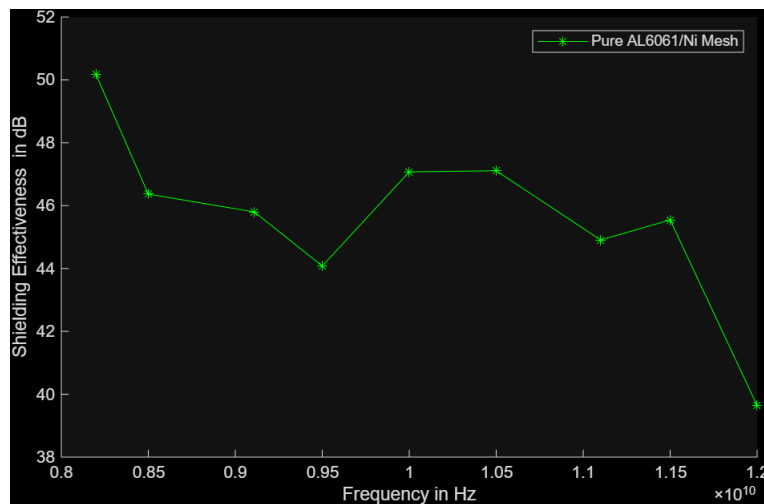


Figure 3. Shielding Effectiveness of Multilayer Pure Al6061/ Ni Mesh

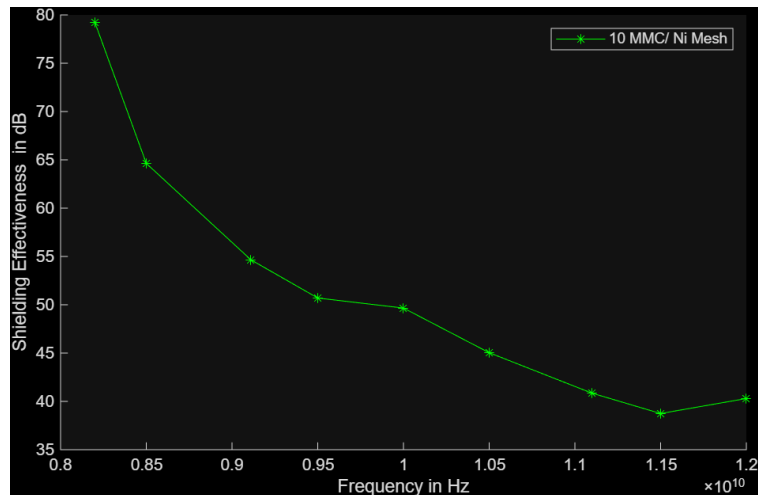


Figure 4. Shielding Effectiveness of Multilayer MMC-10/ Ni Mesh

Figure 5 illustrates the effectiveness of a Miniature absorbing material, which is reinforced by an 80% Al6061, 7.5% Sic, 7.5% Al_2O_3 , and 5% FA composite. The material's ability to protect against X-band electromagnetic waves is evaluated at a thickness of 1 mm. The choice of nickel as the engrossing material was based on its maximum shielding of 83.33 dB and minimum shielding of 42.2 dB at frequencies of 8 GHz and 12 GHz, respectively. Figure 6 illustrates the effectiveness of a Miniature absorbing material, which is reinforced by a composite consisting of 75% Al6061, 10% Sic, 10% Al_2O_3 , and 5% FA. The material's ability to protect against X-band electromagnetic waves is evaluated at a thickness of 1 mm. The chosen material for

engrossing purposes is nickel, which exhibits a maximum shielding effectiveness of 95.20 dB and a minimum of 42.2 dB at 8 GHz and 12 GHz, respectively.

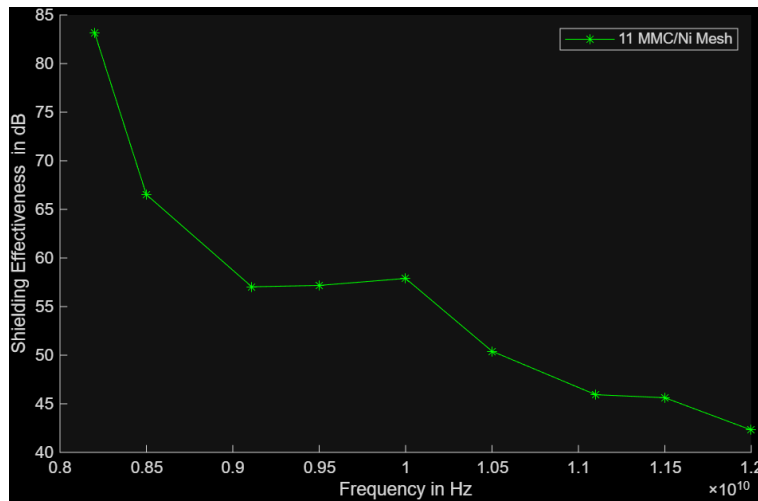


Figure 5. Shielding Effectiveness of Multilayer MMC-11/ Ni Mesh

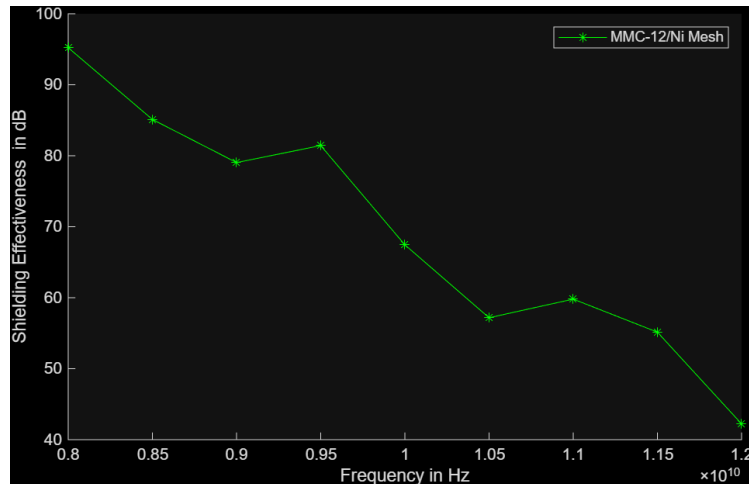


Figure 6. Shielding Effectiveness of Multilayer MMC-12/ Ni Mesh

A clear trend is observed in Figure 7, wherein the shielding effectiveness improves with increasing reinforcement concentration. The ceramics (SiC and Al_2O_3) enhance the dielectric properties and interfacial area, contributing to both absorption and reflection losses. The presence of fly ash, with its lightweight, porous nature, may help impede EM wave propagation through internal scattering and impedance mismatch.

Table 2. Comparison of MMC with Ni mesh

References	Frequency range	Existing work
35	8-12 GHz	59.4dB
36	8-12 GHz	89.23dB
37	1-9 GHz	38.9
Proposed	8-12 GHz	95.20

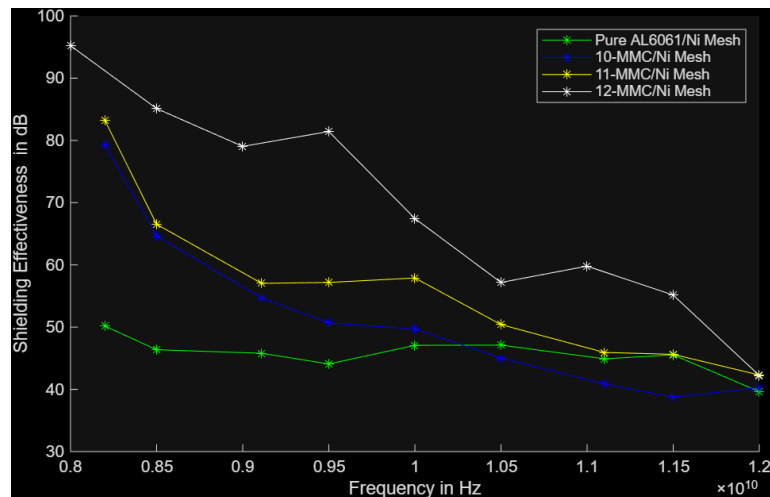


Figure 7. Comparison of Shielding Effectiveness of different materials.

4. Conclusions

This study examined the electromagnetic shielding capabilities of multilayer Al6061-based metal matrix composites (MMCs) enhanced with different ratios of SiC, Al₂O₃, and fly ash, incorporating nickel as a surface-absorbing layer. The analysis of shielding effectiveness (SE) was conducted across the X-band frequency range (8–12 GHz) with a uniform composite thickness of 1 mm, focusing on conditions pertinent to lightning strike protection in aerospace settings. The findings indicate a clear correlation between the type and proportion of reinforcements and the material's shielding behaviour. In the study, pure Al6061 and low-reinforcement configurations reached moderate SE values of approximately 51 dB at 8 GHz. However, with increased reinforcement levels, particularly the composition of 75% Al6061, 10% SiC, 10% Al₂O₃, and 5% FA, a significant improvement in shielding was observed, resulting in a maximum SE of 96.21 dB at 8 GHz. The enhancement can be linked to heightened interfacial polarisation, dielectric loss, and various internal scattering facilitated by the ceramic and fly ash components. The study's findings indicate that the strategic design of multilayer MMCs can greatly enhance electromagnetic shielding while maintaining both weight and structural performance. The refined formulation offers a robust approach for cutting-edge aerospace uses, particularly in addressing the challenges posed by high-intensity electromagnetic pulses and lightning strikes.

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