International Journal of Advanced and Applied Sciences, 9(11) 2022, Pages: 160-168

Contents lists available at Science-Gate

International Journal of Advanced and Applied Sciences

Journal homepage: http://www.science-gate.com/IJAAS.html

Estimation of electromagnetic shielding properties of wire mesh with AL6061 composite material for oblique incidence

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ARTICLE INFO

Article history:
Received 20 April 2022
Received in revised form
19 July 2022
Accepted 11 August 2022

Keywords:
AL6061
Fly ash
Shielding effectiveness
Lightning strike protection
Wire mesh

ABSTRACT

Since composite materials were initially used in airplanes a few decades ago, substantial research has been done on problems such as lightning strike protection (LSP) and electromagnetic interference (EMI) shielding. In the current state of technology, the aerospace industry needs cutting-edge materials to meet requirements like lower weight and higher values of strength and stiffness and protect against electromagnetic interference. On the other hand, the metallic mesh performs poorly at high frequencies (UHF and SHF). Many present and future equipment on airplanes can only operate in the frequency range referred to above. Metal wire mesh matrix composite (MWMMC) materials may be employed to shield airplanes against electromagnetic interference (EMI) as a result of this research. In this work, we made three different MWMMCs represented as MMC-1 with 95% AL6061+5% Fly ash, MMC-2 with 90% AL6061+10% Fly ash, and MMC-3 with 85% AL6061+15% Fly ash. In this article, a stir-casting method was used to try to make Al6061 metal matrix composites that were made stronger with different amounts of fly ash particles. With fly ash, the AL6061 metal matrix composite protects against lightning strikes. So that it may serve as an aircraft surface MWMMC. The material's thickness should be maintained as low as possible. It decided to explore oblique incidence with a different mix of fly ash, reinforced to pure AL6061, to provide more significant shielding to better approximate the signal toward the practical case. Compared to the plane sheet, the shielding effectiveness of the materials and the weight of the material will be reduced. In other words, the maximum shielding effectiveness obtained was 37dB and 20 dB. The shielding effectiveness of 40.5 dB of the manufactured composite is obtained, and it is beneficial for aerospace applications.

1. Introduction

Lightning strikes are a frequent issue. Aircraft may anticipate one lightning hit per 1000 to 10000 flights, or approximately once a year for a commercial aircraft. A lightning strike that discharges a large quantity of electrical current always goes toward the composite structure's weakest points (Yoshikawa and Ushio, 2019; Zhao et al., 2018). As a result, aircraft composite constructions that are not adequately shielded from lightning strikes or electromagnetic interference may suffer severe effects, such as the vaporization of metal control wires. Aircraft structures are damaged by the delamination and vaporization of composite resin systems. Each electrical and electronic system that allows it to act whose failure would impede the airplane from continuing to fly and land safely reduces the aircraft or the ability of the flight crew to respond to an adverse operating condition (Gagné and Therriault, 2014). The lightning strike effect minimizes the efficiency of the aircraft, increasing accidents and hazards to the environment.

The Faraday cage is a device that is used to protect metallic airplanes from electromagnetic interference (EMI). However, without significant modifications, the new composite planes will not be able to achieve the desired radiation deflection or absorption. Metallic foils, integrated metallic wires and filaments, and conductive coatings are currently being used to increase electromagnetic shielding (Pandey et al., 2020; Asmatulu et al., 2020). Metal mesh (usually made of aluminum or copper) is the most often utilized method of shielding. Weight,

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manufacturing complexity, corrosion, and low-frequency shielding are the key downsides of this technique, which are also the most expensive. Therefore, a lightweight way of shielding for higher frequencies is urgently required, particularly in the aerospace and aeronautics industries. Many aircraft applications no longer require metal components because newer production techniques have evolved from simple handcraft to highly automated processes, which employ computer-controlled equipment to lay up prepreg material (Nayak, 2014; Sardiwal et al., 2014).

Composite materials have increasingly been used in aircraft, automotive, and wind energy structures. Using expanded metal as a shield offers excellent protection from Lightning to Composite materials. This material has several benefits but does not correctly channel the electrical currents that result from lightning strikes. A method of dissipating the electromagnetic energy created by lightning is required in composite constructions susceptible to lightning strikes (Kumar et al., 2020).

Composite materials negatively impact LSP instead of conductive metals. According to Chu et al. (2019), CFRP composites have been widely employed in aviation parts for several applications because of their exceptional strength and stiffness, making them an excellent choice when weight, strength, and resistance to erosion are critical factors to consider. Gulzar et al. (2020) worked on improving the electromagnetic SE of composite materials. EMI is one of the significant problems that affect electronic circuits in aircraft and commercial applications. Fly ash is doped into various composite materials to circumvent this difficulty. This significantly. A few electromagnetic climate pollution studies relevant studies have focused on the recovery of fly ash as a hazardous waste from thermoelectric power stations in advance (Lingvay et al., 2018).

The electromagnetic SE of fly ash particles reinforced with pure Al6061 at 5%, 10%, and 15%were examined independently in the current exploration. The stir casting process is employed to manufacture the composite material, and the electrical parameter values were determined using a vector network analyzer. SE is determined based on the electrical parameters.

2. Importance of fly ash

If the thickness is less than one, it is called a Siliceous empty particle. If the density is between 2 and 2.5 g/cm3, it is called a precipitator-round particle. Precipitator particles have been used to enhance wear resistance, thickness, stiffness, and strength. Because of their low density compared to matrix density, Siliceous fly ash particles are used to construct ultra-light composite materials (Matsunaga et al., 2002; Cao and Chung, 2004). Over the last thirty years, analysts have developed new composite materials with improved SE and mechanical characteristics for contemporary applications. Because of its cheap cost and density, fly ash is a typical recent by-product of coal power plants; it supports the production of low-cost composites with enhanced Electromagnetic characteristics for a broad range of modern applications at X-band frequencies. The percentage composition of fly ash is represented in Table 1.

3. Methodology

3.1. Stir casting process

Liquid-state composite material production techniques such as stir casting are examples. In the classic approach, a molten metal matrix is used to agitate the dispersed phase before it is cast as a composite. Fly ash melted at 600^0C is combined with 700^0C -heated pure Al6061 in this experiment. This combination is transformed into the desired specimens using various techniques. These considerations must be taken into account while manufacturing composites for the stir casting process in order to ensure that they are evenly distributed, that two major ingredients are wettable, and that cast composites are less prone to porosity. Fig. 1 illustrates the use of stir casting for reinforcing. Hybrid Composites, described in Table 2, are composed of a mix of material properties.

Fig. 1: Stir casting set up for reinforcement

Table 1: Chemical composition of fly ash

Compound	Al_2O_3	Na_2O	K_2O	SiO_2	Cao	Fe_2O_3	SO_3	MgO
Wt%	26.23	0.21	0.95	53.1	4.59	3.17	0.62	1.10

Table 2: Combination of specimens reinforced with fly ash

Material Used	Specimens fabricated
AL6061, Fly ash	MMC-1-Al6061+ 5% Fly ash MMC-2-Al6061+ 10% Fly ash MMC-3-Al6061+ 15% Fly ash

4. Electrical properties

Electrical Parameters related to materials, as demonstrated in Fig. 2, the VNA (Vector Network Analyzer) can assess MMC's permeability, permittivity, and conductivity using the Transmission/Reflection technique. It is possible to obtain an electromagnetic field incident by inserting a piece of MMC into the waveguide (Hasar, 2009; Alegaonkar and Alegaonkar, 2019; Budumuru and Mosa, 2021).

The shielding efficacy of the manufactured samples is evaluated using the waveguide approach and a VNA (ZVB20). To ensure that the guide does not have any air gaps, all specimens are ground down to a size of 22.86 mm X 10.16 mm. At room temperature, the samples are subjected to electromagnetic waves with a frequency range from 8 to 12 GHz. It is possible to measure the electrical properties of a material (permittivity, permeability, and conductivity) using a VNA that utilizes waveguide technology. Using this information, the shielding efficacy of all MMCs is hypothetically estimated using MATLAB. The vector network analyzer calculates the material's permittivity, permeability, and conductivity. The electrical parameters acquired by the VNA are shown in Figs. 3-6.

5. Shielding mechanism

Reflection and absorption are the two EMI protection methods most often used in practice. A robust electrical conductivity throughout the shielding material is required to obtain a large quantity of electromagnetic radiation reflection. EMI SE is achieved primarily by the Reflection of electromagnetic waves by metals, which are the most often employed materials. This is accomplished through the presence of free electrons in the metal. Electromagnetic shields offer superior protection from external electromagnetic fields because they reflect waves instead of allowing the waves to pass through the mesh of the shield. While shielding is effective throughout this time, it is considered to be an "auxiliary phase" (Raj et al., 2010). SE computed for the wire mesh in an oblique direction. Consider the rectangular mesh with the following dimensions: The mesh radius is denoted by the letter *rw* (Jayasree et al., 2010; Casey, 1988; Lovat et al., 2008; Cheraku et al., 2010).

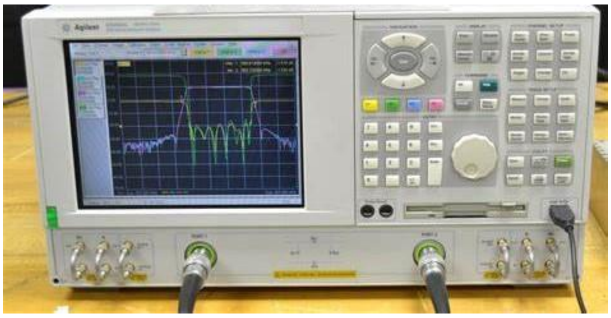
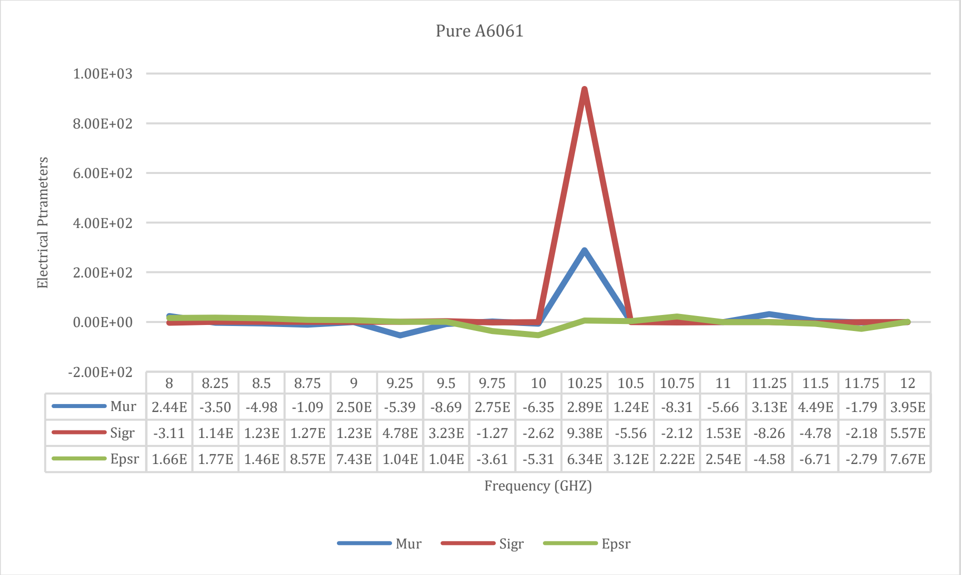
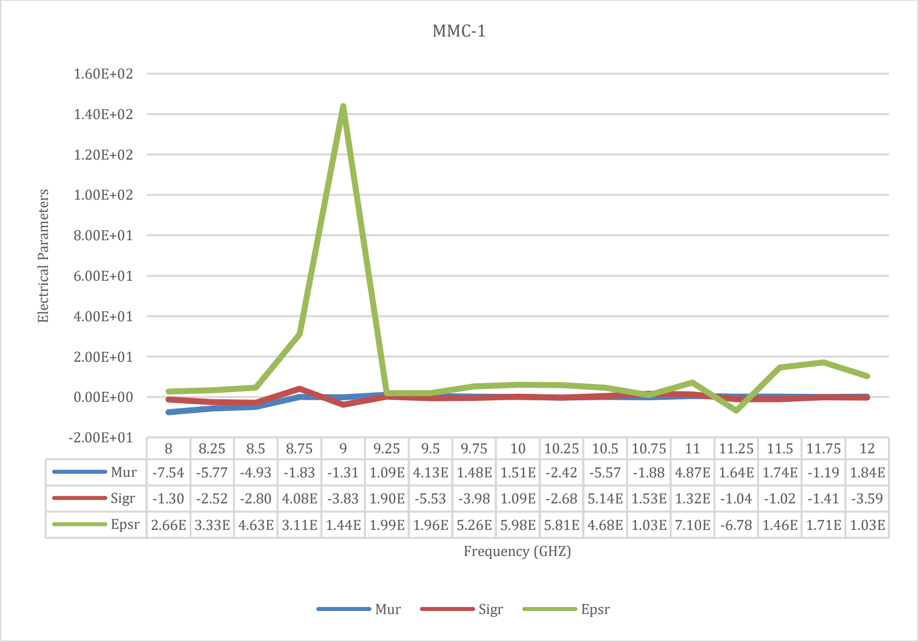


Fig. 2: Experimentation setup of transmission/reflection method



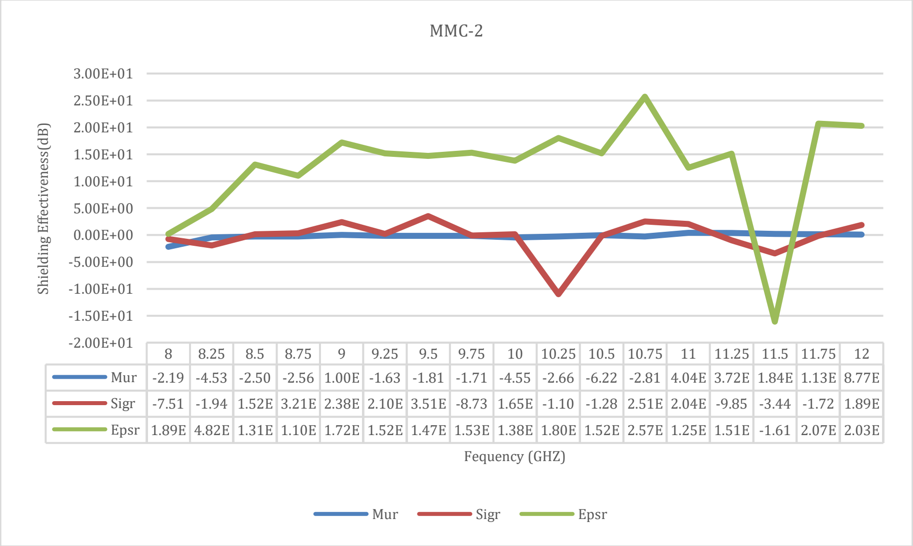
	8	8.25	8.5	8.75	9	9.25	9.5	9.75	10	10.25	10.5	10.75	11	11.25	11.5	11.75	12
Mur	2.44E	-3.50	-4.98	-1.09	2.50E	-5.39	-8.69	2.75E	-6.35	2.89E	1.24E	-8.31	-5.66	3.13E	4.49E	-1.79	3.95E
Sigr	-3.11	1.14E	1.23E	1.27E	1.23E	4.78E	3.23E	-1.27	-2.62	9.38E	-5.56	-2.12	1.53E	-8.26	-4.78	-2.18	5.57E
Epsr	1.66E	1.77E	1.46E	8.57E	7.43E	1.04E	1.04E	-3.61	-5.31	6.34E	3.12E	2.22E	2.54E	-4.58	-6.71	-2.79	7.67E

Fig. 3: Electrical parameters of pure Al6061. Mur: Relative permeability of the material; Sigr: Relative conductivity of the material; Espr: Relative permittivity of the material



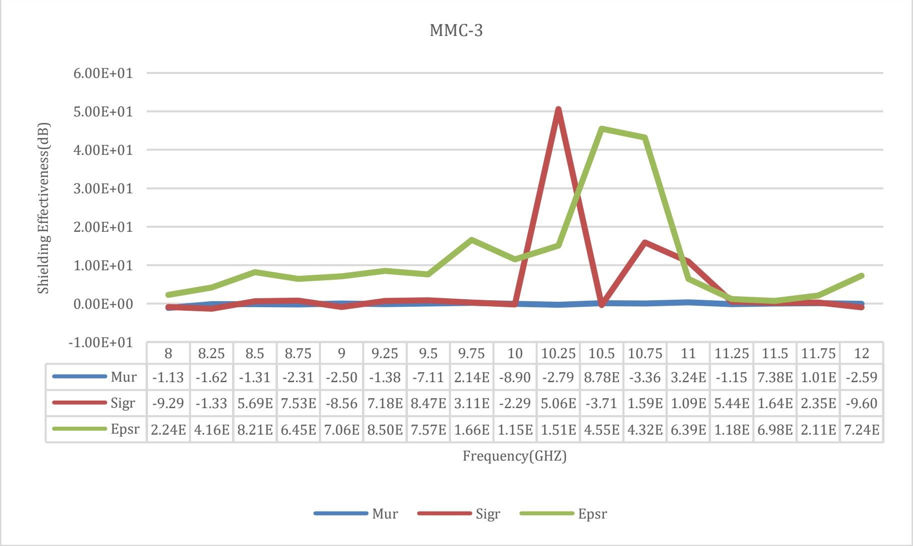
	8	8.25	8.5	8.75	9	9.25	9.5	9.75	10	10.25	10.5	10.75	11	11.25	11.5	11.75	12
Mur	-7.54	-5.77	-4.93	-1.83	-1.31	1.09E	4.13E	1.48E	1.51E	-2.42	-5.57	-1.88	4.87E	1.64E	1.74E	-1.19	1.84E
Sigr	-1.30	-2.52	-2.80	4.08E	-3.83	1.90E	-5.53	-3.98	1.09E	-2.68	5.14E	1.53E	1.32E	-1.04	-1.02	-1.41	-3.59
Epsr	2.66E	3.33E	4.63E	3.11E	1.44E	1.99E	1.96E	5.26E	5.98E	5.81E	4.68E	1.03E	7.10E	-6.78	1.46E	1.71E	1.03E

Fig. 4: Electrical parameters of MMC-1. Mur: Relative permeability of the material; Sigr: Relative conductivity of the material; Espr: Relative permittivity of the material



	8	8.25	8.5	8.75	9	9.25	9.5	9.75	10	10.25	10.5	10.75	11	11.25	11.5	11.75	12
Mur	-2.19	-4.53	-2.50	-2.56	1.00E	-1.63	-1.81	-1.71	-4.55	-2.66	-6.22	-2.81	4.04E	3.72E	1.84E	1.13E	8.77E
Sigr	-7.51	-1.94	1.52E	3.21E	2.38E	2.10E	3.51E	-8.73	1.65E	-1.10	-1.28	2.51E	2.04E	-9.85	-3.44	-1.72	1.89E
Epsr	1.89E	4.82E	1.31E	1.10E	1.72E	1.52E	1.47E	1.53E	1.38E	1.80E	1.52E	2.57E	1.25E	1.51E	-1.61	2.07E	2.03E

Fig. 5: Electrical parameters of MMC-2. Mur: Relative permeability of the material; Sigr: Relative conductivity of the material; Espr: Relative permittivity of the material



	8	8.25	8.5	8.75	9	9.25	9.5	9.75	10	10.25	10.5	10.75	11	11.25	11.5	11.75	12
Mur	-1.13	-1.62	-1.31	-2.31	-2.50	-1.38	-7.11	2.14E	-8.90	-2.79	8.78E	-3.36	3.24E	-1.15	7.38E	1.01E	-2.59
Sigr	-9.29	-1.33	5.69E	7.53E	-8.56	7.18E	8.47E	3.11E	-2.29	5.06E	-3.71	1.59E	1.09E	5.44E	1.64E	2.35E	-9.60
Epsr	2.24E	4.16E	8.21E	6.45E	7.06E	8.50E	7.57E	1.66E	1.15E	1.51E	4.55E	4.32E	6.39E	1.18E	6.98E	2.11E	7.24E

Fig. 6: Electrical parameters of MMC-3. Mur: Relative permeability of the material; Sigr: Relative conductivity of the material; Espr: Relative permittivity of the material

The mesh structure is shown in Fig. 7 and Fig. 8. The sheet inductances of the mesh are denoted by the letter $L_s$in the notation. In this case, L_s is dependent on the radius of the wire and the permeability of the open space around the wire:

$$L_s = \frac{\mu_0 . a_s}{2\pi} \ln(1 - e^{-\frac{2\pi r_s}{a_s}})^{-1} \tag{1}$$

There is a way to show the internal impedance of the wire: z'_w. There are a lot of z'_w. The resistance per unit length, the time constant, and the first kind of the Bessel function all play a role in how much resistance there is in a given length.

$$z'_w = r'_w \frac{(\sqrt{jw\tau_w}) I_0(\sqrt{jw\tau_w})}{2I_1(\sqrt{jw\tau_w})} \tag{2}$$

From Eq. 3 we are considering the resistance per unit length is r'_w *and* τ_w is considered as the time constant. $I_n(.)$ Represent the first kind of the Bessel function.

$$r'_w = (\pi r_w^2 \sigma_w)^{-1} \tag{3}$$
$$\tau_w = \mu_w \sigma_w r_w^2 \tag{4}$$

The sheet impedances are represented as z_{s1} and z_{s2}:

$$z_{s1} = z'_w a_s + j\omega L_S \tag{5}$$
$$z_{s2} = z_s - \frac{j\omega L_S}{2} sin\theta^2 \tag{6}$$

The angle of incidence (θ) is shown below, and the transmission (T) is shown at that angle. Plane waves with perpendicular polarisation have a sheet impedance that is the same as z_s= z_{s1} andz_{s2}.

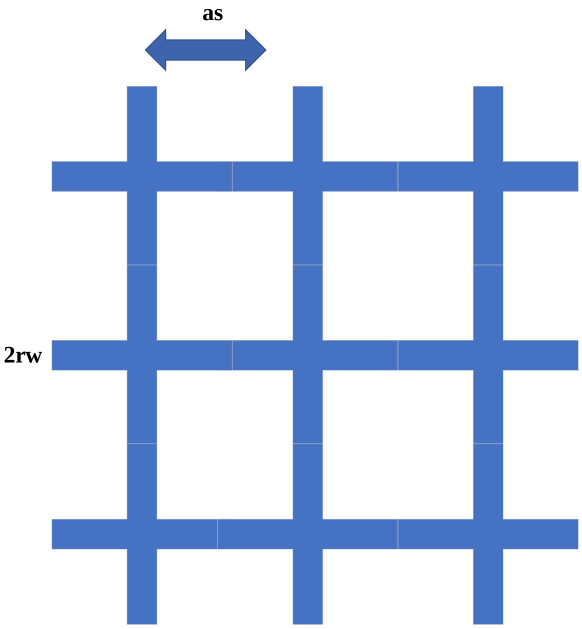


Fig. 7: Composite mesh depiction using a square mesh of size a_s and radius of r_w

Eq. 7 represents the TE Polarization, and Eq. 8 represents the TM Polarization:

$$T_1 = \frac{2\left(\frac{z_{s1}}{z_0}\right)cos\theta}{1+2\left(\frac{z_{s1}}{z_0}\right) cos\ \theta} \tag{7}$$
$$T_2 = \frac{2\left(\frac{z_{s2}}{z_0}\right)cos\theta}{1+2\left(\frac{z_{s2}}{z_0}\right)cos\theta} \tag{8}$$

From Eqs. 7 and 8, the SE is determined as given below:

$$SE = -10log_{10}\left(\left(\frac{1}{2}T_1^2\right) + \left(\frac{1}{2}T_2^2\right)\right) \tag{9}$$

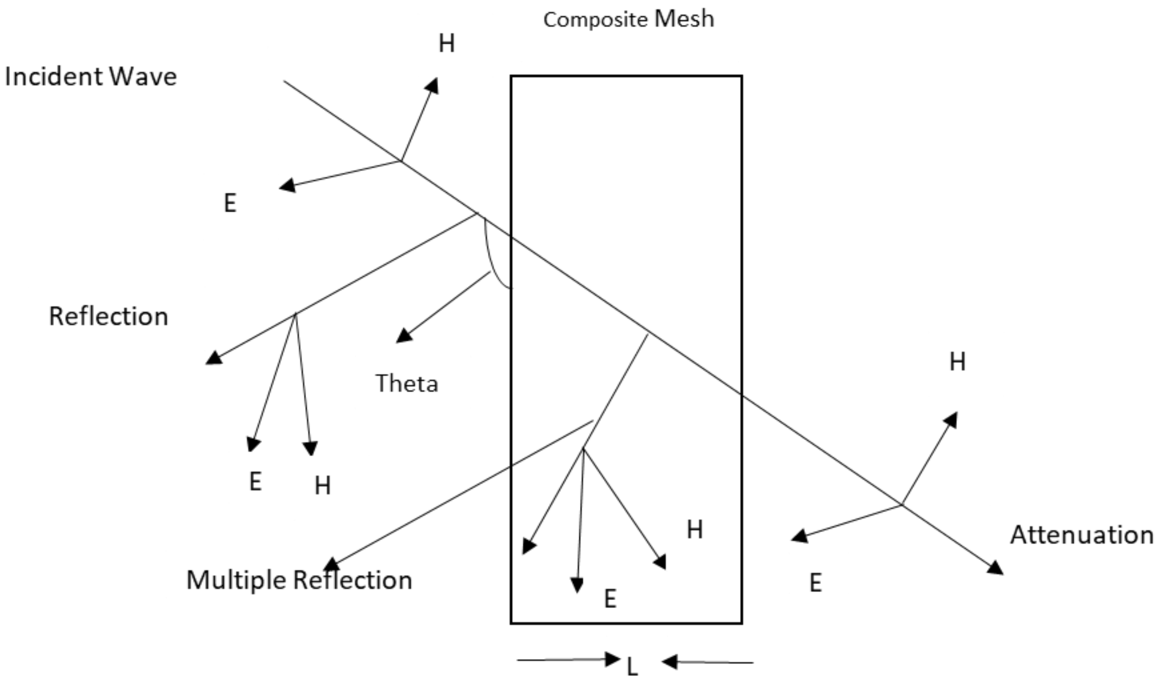


Fig. 8: Oblique incidence of E. M. wave on mesh wire

6. Results

The results included the oblique incidence of electromagnetic waves on the composite wire mesh of pure Al6061 material reinforced with fly ash at 5%, 10%, and 15%. The SE of these MMCs is varied by the electrical parameters (μ, ϵ, σ) which are shown in Figs. 3-6. The analysis included the oblique incidence of electromagnetic waves on the composite wire mesh material of Al6061 with fly ash. As the angle of incidence increases, the Shielding Effectiveness will decrease. Fig. 9 showed the SE of the pure Al6061 and obtained the 32.6dB. Figs. 10-13 represent the SE. of Al6061 reinforced with fly ash. The SE values of MMC1, MMC2 and MMC3 are 36.26dB, 36.8dB and 38.64 dB. As the content of fly ash increases, the SE value will increase. The main reason for an increase in the value SE is due to the contents of Fe_2O_3 in fly ash. From the discussion it confirmed that the SE is due to absorption which is linked to oxide components present in fly ash. The above discussion shows that Reflection makes fly ash an effective shield; it's also absorption linked to the oxide components. Tables 3 to 7 show the SE values for different angles for all specimens. In this analysis, the maximum shielding of 38.64dB is attained. Fig. 13 represents the comparison graph with pure Al6061 with different percentages of fly ash reinforcement.

Table 3: Shielding effectiveness of pure AL6061for different angles of incidences

Material	Angle of incidences	Shielding effectiveness (dB)
AL6061	20^0	32.62
	45^0	23.48
	60^0	22.72
	70^0	17.86
	85^0	11.77

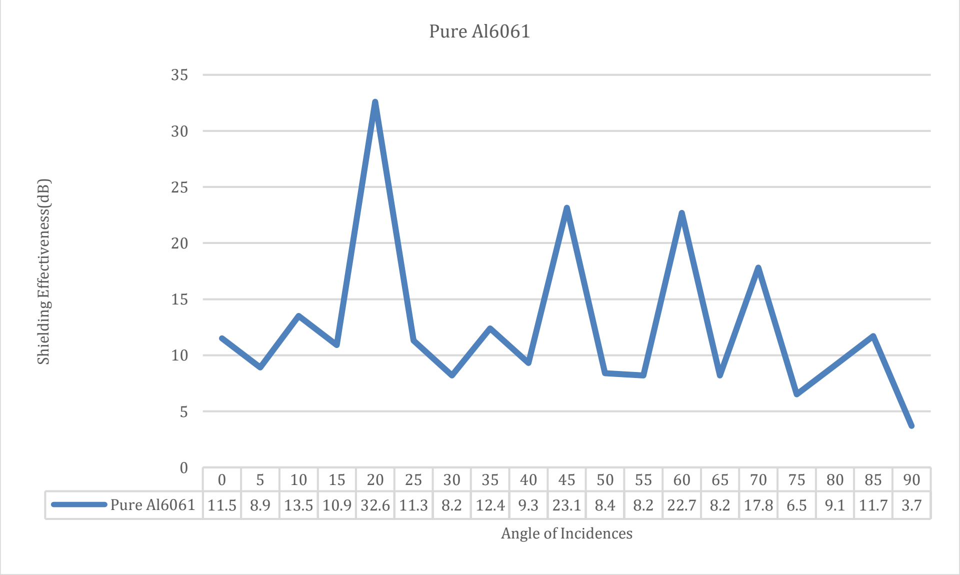


Fig. 9: Electromagnetic shielding effectiveness of Pure Al6061

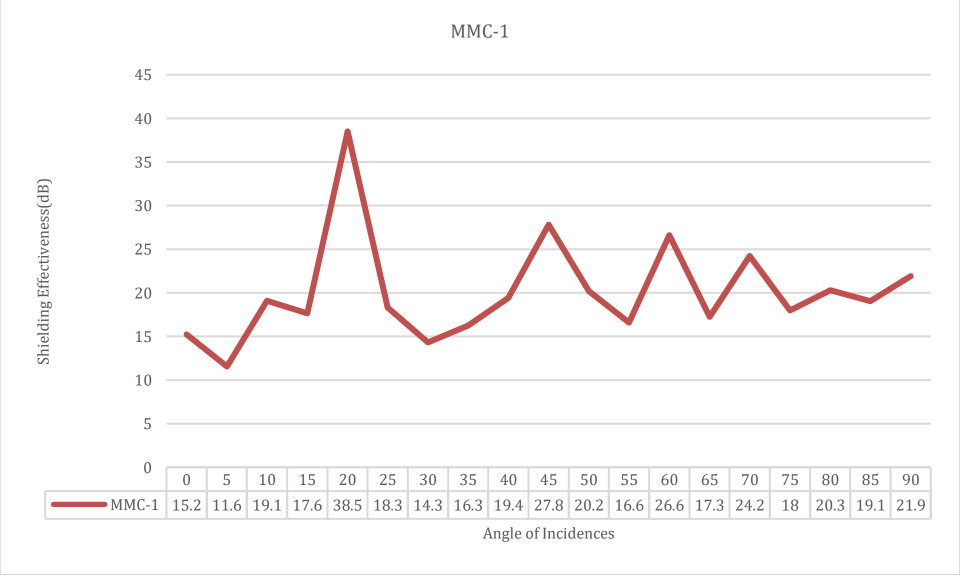


Fig. 10: Electromagnetic shielding effectiveness of MMC1

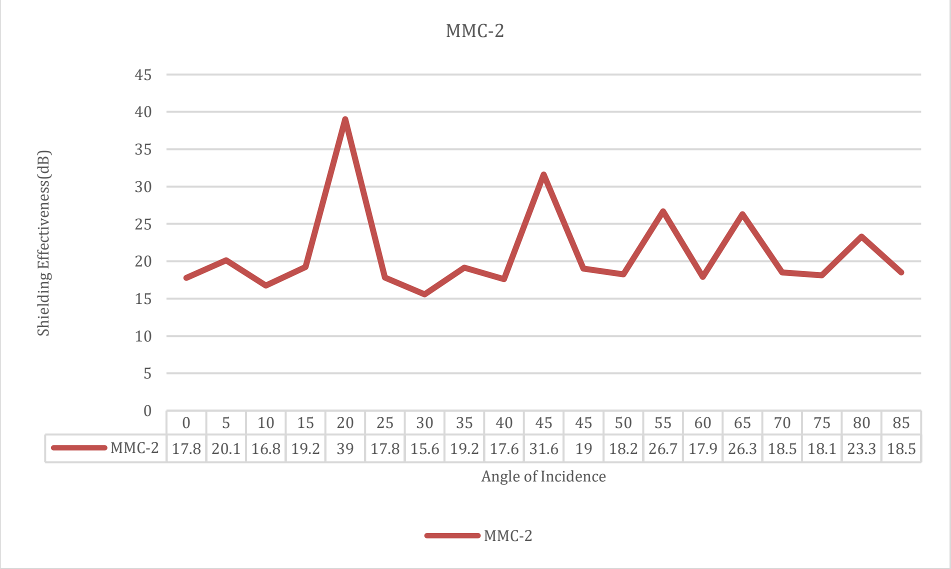


Fig. 11: Electromagnetic shielding effectiveness of MMC2

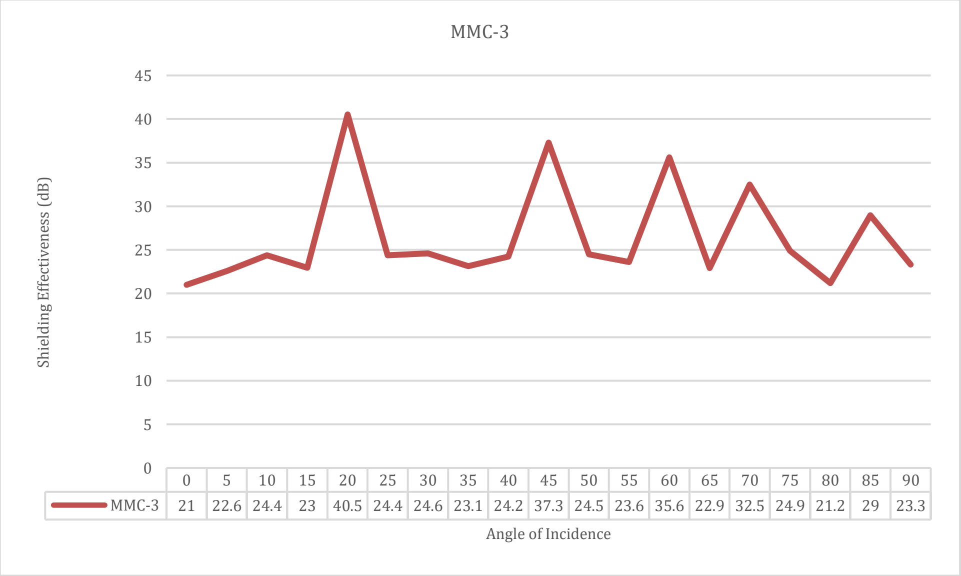


Fig. 12: Electromagnetic shielding effectiveness of MMC3

7. Conclusion

Findings from this study show that the metal matrix material composite AL6061 is successful at varying levels of fly ash reinforcement. Using fly ash-reinforced Al6061 composite as a shielding material has been proven successful. Increasing the proportion of fly ash reinforcement makes it more efficient. Composite shielding effectiveness of 36.26dB and 38.64dB may be achieved using fly ash-reinforced Al6061 composites of 5% and 15% by weight. In this investigation, the maximum shielding attained is 38.64dB. MMCs are increasingly in demand for aeronautical engineering applications due to their superior electrical properties versus standard composite materials. In structural applications in aeronautical engineering, fiber-reinforced MMCs played a critical part in achieving the dual objectives of decreasing weight. Fly-by-wire control systems are used to provide flight control and navigation duties in modern aircraft. The electromagnetic interference caused by lightning must thus be guarded. It is essential to prioritize materials with electrical qualities to ensure their long-term performance. When it comes to selecting the materials that will be utilized in the manufacturing of aerospace and military applications, it is essential to pay close attention to detail. This material has the potential to be used as an EMI protection layer in aviation applications.

Table 4: Shielding effectiveness of MMC1for different angles of incidences

Material	Angle of incidences	Shielding effectiveness (dB)
MMC1	20^0	38.50
	45^0	27.82
	60^0	26.62
	70^0	24.72
	85^0	19.06

Table 5: Shielding effectiveness of MMC2for different angles of incidences

Material	Angle of incidences	Shielding effectiveness (dB)
MMC2	20^0	39.05
	45^0	31.6
	60^0	26.76
	70^0	26.33
	85^0	23.33

Table 6: Shielding effectiveness of MMC3for different angles of incidences

Material	Angle of Incidences	Shielding Effectiveness (dB)
MMC3	20^0	40.5
	45^0	37.29
	60^0	35.65
	70^0	32.48
	85^0	28.97

Table 7: Comparison of maximum shielding effectiveness of different percentages of Fly ash

material	Maximum shielding (dB)
Gulzar et al. (2020)	37
Patel et al. (2022)	20
Pure Al6061	32.62
MMC 1	38.50
MMC 2	39.05
MMC 3	40.5

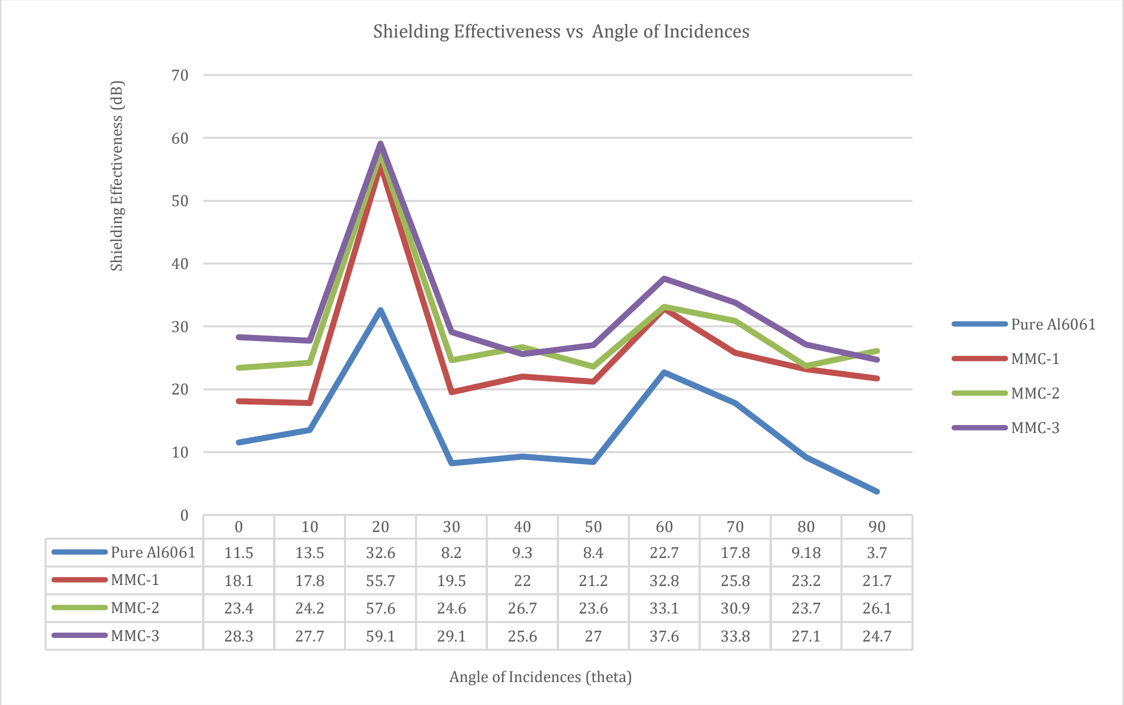


Fig. 13: Comparison graph of pure AL6061 with different percentages of fly ash

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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