

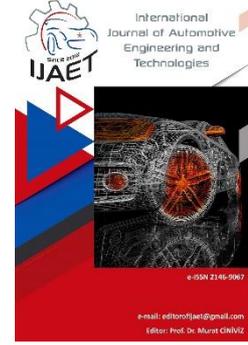


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Original Research Article

### Multifunctional titanium-carbon fiber metal laminates for next-generation automotive EMI shielding: the role of polyimide veil interleaving



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#### ABSTRACT

As the automotive industry shifts toward electric vehicle (EV) architectures and autonomous driving systems, there is an urgent demand for multifunctional structural materials that offer both superior crashworthiness and high-frequency electromagnetic interference (EMI) shielding. While fiber-reinforced polymers (FRPs) facilitate lightweighting, their inherent brittleness and limited shielding capabilities often necessitate hybridization. This study investigates the synergistic integration of Ti-6Al-4V titanium alloy sheets and unidirectional carbon fiber plies in a 3/2 Fiber Metal Laminate (FML) configuration. To address interlaminar delamination and enhance functional performance, neat thermoplastic polyimide (PI) veils were incorporated as interleaves. The EMI shielding effectiveness (SE) of the fabricated FMLs was rigorously characterized in the X-band (8.2–12.4 GHz). Results indicate that the PI veil-integrated FMLs achieved a SE exceeding 30 dB, surpassing the industrial requirement for commercial electronic protection. The enhanced performance is attributed to the PI veil acting as a dielectric interlayer that facilitates multiple internal reflections between the conductive titanium and carbon fiber phases, thereby shifting the primary shielding mechanism toward absorption. Skin depth analysis further substantiated that the neat veil optimizes the electromagnetic interaction within the hybrid structure. This research demonstrates that Ti/CF FMLs interleaved with neat PI veils provide a robust, dual-purpose solution for next-generation automotive engineering, ensuring structural integrity while shielding sensitive autonomous systems from electromagnetic disruption.

**Keywords:** Carbon Fiber, EMI, FML, Titanium

### 1. Introduction

The modern automotive industry is currently navigating a transformative era, primarily

driven by the imperatives of lightweighting, emission reduction, and the rapid electrification of vehicle fleets [1]. In this

pursuit, Fiber-Reinforced Polymers (FRPs), particularly carbon fiber composites, have become central to high-performance vehicle design due to their exceptional specific strength and design flexibility [2]. By replacing traditional heavy steel components with FRPs, manufacturers can achieve substantial weight savings, which directly translates to improved range and performance in electric vehicles (EVs) [3]. However, despite their advantages, pure fiber composites are inherently limited by their brittle failure modes and relatively low impact energy absorption. To mitigate these drawbacks while retaining the lightweight benefits of composites, the strategy of hybridizing metals with fibers has emerged as a superior engineering solution. Fiber Metal Laminates (FMLs) represent this synergy, combining the high fracture toughness and durability of metallic layers with the lightweight and fatigue-resistant nature of composites [4]. A hallmark example of this advanced hybridization in the high-performance automotive sector is Carbotanium<sup>®</sup>, a patented material utilized by Pagani Automobili. By integrating titanium alloys into a carbon fiber weave, Pagani developed a material that possesses the extreme rigidity of carbon fiber while gaining the non-shattering, energy-absorbing characteristics of titanium—essential for the safety cells of hypercars like the Huayra and Zonda.

Following this industrial precedent, Hybrid Titanium Composite Laminates (HTCLs) have gained significant interest as a high-performance frontier in FML technology. HTCLs offer remarkable technical advantages over aluminum-based hybrids, including superior high-temperature stability and excellent galvanic corrosion resistance [5]. Nevertheless, a persistent challenge in these hybrid systems is the mechanical property mismatch at the interface between the metallic sheet and the composite ply, which often leads to delamination. To resolve this, interleaving with thermoplastic veils, such as Polyimide (PI), has been proposed [6]. PI veils are highly regarded for their ability to enhance interlaminar fracture toughness and provide crucial vibration damping control [7], a key comfort factor in luxury and performance

vehicles.

Beyond structural integrity, the rapid shift toward Electric Vehicles (EVs) and Autonomous Driving Systems (ADS) has introduced a critical new requirement: Electromagnetic Interference (EMI) shielding [8]. The increasing density of high-frequency sensors, radar units, and high-voltage electronics within vehicle architectures necessitates effective shielding to ensure operational safety and signal integrity [9]. Furthermore, occupant well-being is emerging as a critical factor; as passengers in EVs are positioned in close proximity to high-current power electronics, protecting them from prolonged exposure to electromagnetic radiation [10] is becoming a fundamental safety standard. While carbon fiber composites provide a baseline level of shielding [11], transitioning to an FML architecture significantly elevates this performance. The metallic layers act as highly conductive surfaces that dominate electromagnetic reflection, while the carbon fiber plies and the resulting metal-composite interfaces facilitate absorption and multiple internal reflections.

Despite the growing use of thermoplastic veils in traditional composites, their integration into FMLs—especially for multifunctional EMI protection—remains largely unexplored. Most of the research focuses exclusively on the mechanical benefits of these veils [6,12–14]. Furthermore, while EMI shielding can be boosted by adding conductive fillers [15] to these veils, such additives often complicate manufacturing and may compromise interfacial bonding. Consequently, there is a significant gap in understanding the intrinsic (neat) contribution of these veils to the electromagnetic shielding of hybrid laminates. This study aims to bridge this gap by investigating the synergistic EMI shielding performance of a 3/2 Titanium/Carbon Fiber FML configuration in the X-band (8.2–12.4 GHz). This frequency range is critical for protecting high-speed on-board processing units and V2X communication links [16]. Distinct from filler-heavy approaches, this research evaluates the influence of a neat polyimide veil interleaf. By utilizing the PI veil as a dielectric layer between the highly conductive titanium and carbon fiber phases,

this work establishes a baseline for a dual-purpose hybrid material that meets both the structural and electromagnetic protection demands of next-generation automotive engineering.

## 2. Materials and Methods

### 2.1. FML fabrication

In this study, Grade 5 Ti-6Al-4V titanium alloy sheets with a nominal thickness of 0.55 mm were utilized as the metallic phase, supplied by TSM Technology Co. Ltd. (China). The composite reinforcement layers were prepared using unidirectional (UD) carbon fiber fabric with an areal density of 300 g/m<sup>2</sup>, impregnated with a matrix system consisting of LR160 epoxy resin and LH160 hardener, both sourced from Dost Kimya (Türkiye). To facilitate the interleaving process, a nonwoven polyimide (PI) thermoplastic veil with an areal weight of 8 g/m<sup>2</sup> was procured from Technical Fiber Products Ltd. (UK).

To improve interfacial bonding, the titanium sheets were mechanically abraded using 180-grit sandpaper. Following the grinding process, the surfaces were thoroughly cleaned with ethanol to eliminate any residual debris or contaminants and subsequently dried on a hotplate at 90 °C for 15 minutes. The UD carbon fiber fabrics and PI veils were then precision-cut to the dimensions required for the 3/2 FML configuration. The specific stacking sequence of the veil-incorporated hybrid laminates is schematically illustrated in Fig. 1.



**Fig. 1.** Schematic view of fabricated FMLs consisting of three layers of titanium and two layers of UD carbon fiber fabric interleaved with four layers of polyimide veils

The epoxy matrix was prepared by blending the resin and hardener at a stoichiometric ratio of 100:25 by weight, as per the manufacturer's instructions. The mixture was mechanically agitated for 10 minutes to achieve a homogeneous state, followed by a degassing process at -0.97 bar for 15 minutes to remove entrapped air bubbles. The hybrid laminates were then assembled using the conventional hand lay-up technique. To ensure uniform

consolidation and minimize void formation, the assembly was covered with a mold release film and cured under a constant external pressure of 90 kPa. The curing cycle was maintained at room temperature for 24 hours. Upon completion of the cure, the specimens were demolded and trimmed to their final dimensions for characterization (25 x 25 x 2.5 mm). It is noteworthy that the non-woven polyimide veil has a nominal thickness of 12 μm. Due to its highly porous nature and the applied consolidation pressure during curing, the veil was fully impregnated by the epoxy resin. Consequently, the incorporation of the PI veil resulted in a negligible change in the total thickness of the FMLs, staying within the standard manufacturing tolerances of the hand lay-up process.

### 2.2. EMI Shielding Tests

Electromagnetic shielding effectiveness (EMSE) measurements were conducted at X-band (8.2–12.4 GHz) using a vector network analyzer configured with a two WR-90 waveguide setup. Prior to measurement, using SOLT method a full two-port calibration was implemented, and scattering parameters (*S*-parameters) were measured. All reported values are the average of three measurements of each sample. Total shielding effectiveness ( $SE_{Tot}$ ) was determined using Eq. 1.  $SE_{Tot}$  is defined as the sum of shielding effectiveness due to reflectance ( $SE_R$ ), absorbance ( $SE_A$ ), and multiple internal reflections ( $SE_M$ ).  $SE_M$  is considered negligible when the  $SE_{Tot}$  exceeds ±10 dB [17].

$$SE_{Tot} (dB) = SE_R + SE_A + SE_M = 10 \log\left(\frac{P_t}{P_i}\right) \quad (1)$$

Here,  $P_i$  represents the power of the incident EM waves, and  $P_t$  represents the power of the transmitted EM waves. The required  $SE_A$ ,  $SE_R$ , and  $SE_T$  parameters were calculated using Eq. 2 through 4, based on the measured *S*-parameters obtained with the network analyzer [18,19].

Here, *A* represents absorbance, *R* represents reflectance, and *T* represents transmittance. To ensure the validity of the measurement system, the sum of the absorption (*A*), reflection (*R*), and transmission (*T*) coefficients must equal unity [18,19].

$$SE_A(dB) = 10 \log\left(\frac{1-S_{11}^2}{S_{12}^2}\right) = 10 \log\left(\frac{1-S_{22}^2}{S_{21}^2}\right) = 10 \log\left(\frac{1-R}{T}\right) \quad (2)$$

$$SE_R(dB) = 10 \log\left(\frac{1}{1-S_{11}^2}\right) = 10 \log\left(\frac{1}{1-S_{22}^2}\right) = 10 \log\left(\frac{1}{1-R}\right) \quad (3)$$

$$SE_T(dB) = 10 \log\left(\frac{1}{S_{12}^2}\right) = 10 \log\left(\frac{1}{S_{21}^2}\right) = 10 \log\left(\frac{1}{T}\right) \quad (4)$$

The penetration depth of EM radiation into an electrically conductive material is limited by the skin effect, which is related to the surface thickness associated with charge current and polarization. The shielding effectiveness due to absorption is inversely proportional to the skin depth ( $\delta$ ), which represents the distance over which the electromagnetic field strength decreases to  $1/e$  of its incident value. Given a material thickness of  $t$  [20,21], the proportion between  $SE_A$  and skin depth is evaluated using Eq. 5 [22].

$$\delta = -8.68 \left[ \frac{t}{SE_A} \right] \quad (5)$$

Note that the negative sign of the value indicates the direction of propagation from the surface into the interior of the material.

### 3. Results and Discussion

Titanium/CF FML materials incorporating PI veils as interleaves may be expected to provide EMI shielding performance in addition to withstanding stress, and thermal fluctuations, making them ideal for safety-critical automotive components such as EV battery enclosures or ADAS housings. As the PI veils used in this study are not electrically conductive and are not doped with any electrically conductive particles it might initially be expected that their presence would decrease the EMI shielding effectiveness (SE) of the FMLs. Therefore, it is crucial to investigate whether the improvement in interlaminar properties—essential for vehicle crashworthiness—is achieved at the expense of EMI performance.

The SE results of the materials as a function of frequency are presented in Fig. 2. The average shielding performance of the samples was calculated across the measured frequency range. Specifically, the FML sample exhibited

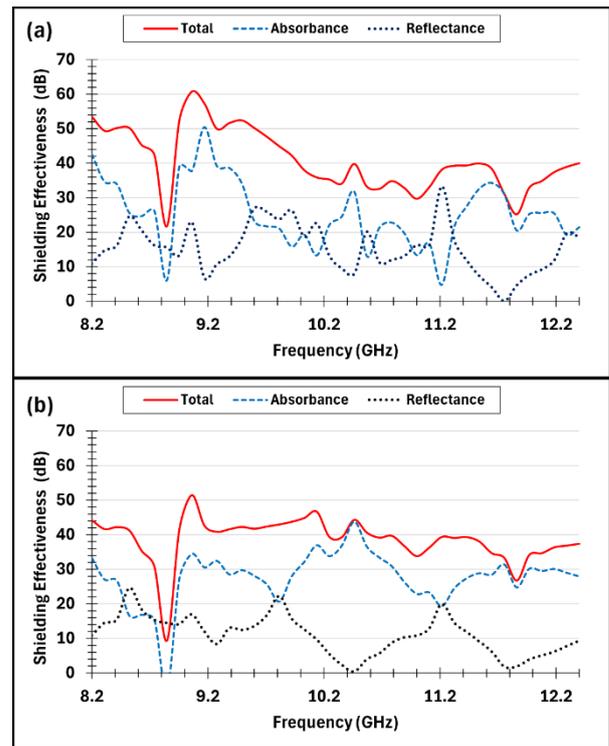


Fig. 2. EMI shielding effectiveness of (a) FML, (b) FML/veil

a mean total SE of 40.927 dB, consisting of a mean absorption (SEA) of 25.559 dB and a mean reflection (SER) of 15.368 dB. Similarly, the average SE values for the FML/veil samples were determined as 38.661 dB for total SE, with SEA and SER components of 27.661 dB and 11.000 dB, respectively. Note that multiple reflections were neglected because the total SE value exceeded 10 dB. The results indicate that the samples possess comparable shielding effectiveness and exceed the commercially required SE value of 30 dB [23,24]. Based on the data, both samples exhibit peak shielding effectiveness within the 9.0-9.2 GHz frequency range, demonstrating superior shielding performance at these frequencies. However, the shielding effectiveness of both materials decreases slightly prior to reaching this peak frequency. Specifically, the materials' response declines around 8.6-8.8 GHz. This reduction, primarily observed in the absorbance component of the shielding effectiveness for both materials, is attributed to frequency-dependent impedance mismatch [23]. However, both samples exhibit shielding characteristics dominated by absorbance. Based on the calculated average values, the FML achieves 62.4% of its total shielding effectiveness through absorbance,

while this value is 71.5% for the FML/veil. This difference is attributed to internal reflections within the gaps formed between the PI veil, carbon fiber, and titanium surface contact points in the FML/veil. The literature indicates that surface-enlarging features, such as intra-structure pores, enhance internal reflections, thereby promoting absorbance [20,21]. This increased internal reflectance leads to greater attenuation of the EM wave. Furthermore, at frequencies of 9.2, 10.4, and 11.2 GHz, the shielding mechanism shifts from absorbance to reflectance for both materials. The increased difference between absorbance and reflectance at these frequencies in the FML/veil samples suggests a change in shielding characteristics compared to the FML. The absorbance increases after 9.6 GHz for the FML/veil, while the reflection decreases.

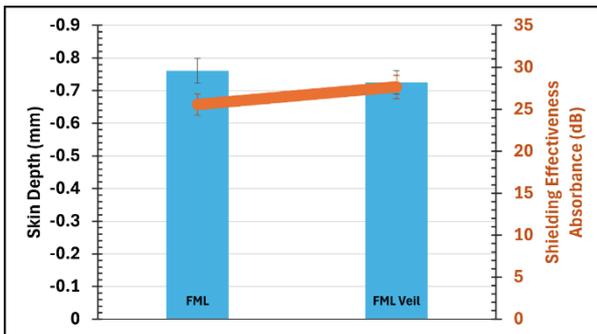


Fig. 3. Skin depth and shielding effectiveness absorbance of FML and FML/veil

Fig. 3 presents the calculated skin depth values for the FML and FML/veil. The skin depth of the FML was determined to be -0.693 mm. This value represents the required penetration depth for EM waves within the FML (titanium-carbon fiber-epoxy) during shielding. Given that the thickness of the titanium layer used in this study is 0.55 mm, the EM waves penetrate the initial titanium and carbon fiber layer and reach the inner layers.

Consequently, the FML attenuates EM waves due to its inherent electrical conductivity. The calculated skin depth for the FML/veil is -0.640 mm, indicating a slightly shallower penetration depth compared to the FML. However, because the EM waves penetrate the initial titanium-carbon-veil, which exhibits enhanced absorbance, the inner layers of the mesh-reinforced FML also contribute significantly to the overall SE. Therefore, the calculated skin depth suggests that EM

absorption occurs within a thinner region in the FML/veil, which is consistent with the observed increase in absorbance when comparing the FML with same reference thickness.

#### 4. Conclusion

This study establishes the multifunctional potential of neat thermoplastic polyimide (PI) veils as interleaves in Ti-6Al-4V/Carbon Fiber FMLs, specifically tailored for the rigorous demands of next-generation automotive engineering. The experimental results confirm that both the baseline FML and the PI-integrated hybrid laminates achieve a shielding effectiveness of 40.9 dB across the X-band. This performance significantly surpassing the 30 dB industrial threshold required for protecting sensitive autonomous driving sensors and high-speed processing units.

A pivotal finding of this research is the transition in the dominant shielding mechanism. While the introduction of a non-conductive PI veil was initially expected to reduce shielding performance, it instead optimized the electromagnetic interaction within the laminate. The integration of the veil increased the contribution of absorbance to the total shielding from 62.4% to 71.5%. In the context of densely packed electronic architectures in electric vehicles (EVs), this shift toward absorption is highly advantageous as it creates an "electromagnetically silent" structure. By minimizing secondary reflections, the laminate prevents electromagnetic crosstalk between internal sensors, thereby ensuring higher signal integrity for critical ADAS and V2X communication links.

Furthermore, the skin depth analysis revealed that the PI-interleaved FML attenuates EM waves within a shallower region (0.640 mm) compared to the baseline FML (0.693 mm). This increased shielding efficiency within a thinner cross-section supports the automotive industry's lightweighting objectives, allowing for the design of compact and thin-walled protective housings without compromising electromagnetic reliability. The internal reflections facilitated by the dielectric PI veil effectively "trap" and dissipate electromagnetic energy between the highly

conductive titanium and carbon fiber phases. In summary, the Ti/CF FMLs interleaved with neat PI veils emerge as a robust, dual-purpose solution for safety-critical automotive applications, such as EV battery enclosures, ADAS processing unit housings, a bio-protective barrier for occupants and structural firewalls. This work establishes a critical baseline for the development of smart, hybrid structural materials that prioritize both mechanical safety and electromagnetic reliability in the future of mobility.

### Conflict of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### CRedit Authorship Contribution Statement

V. Eskizeybek: Conceptualization, Methodology, F. Yıldırım: Investigation, Writing- original draft, Visualization, O. Demir: Writing- Review & Editing, Visualization

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