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To cite this article: Saravana Kumar P, Thanigaivelan V , Arun K & Arunkumar S (01 Jan 2026): Influence of aluminum foam core thickness on the mechanical and thermal properties of epoxy-carbon fiber mat sandwich composites, Mechanics of Advanced Materials and Structures, DOI: [10.1080/15376494.2025.2603422](https://doi.org/10.1080/15376494.2025.2603422)

To link to this article: <https://doi.org/10.1080/15376494.2025.2603422>



Published online: 01 Jan 2026.



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Influence of aluminum foam core thickness on the mechanical and thermal properties of epoxy-carbon fiber mat sandwich composites

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ABSTRACT

This study examines the influence of aluminum foam thickness on the mechanical and thermal characteristics of epoxy resin-based sandwich composites reinforced with carbon fiber matting. Four samples (S1–S4) were produced: S1 comprised one layer of pure carbon fiber mat, while S2–S4 consisted of three layers of carbon fiber mat mixed with two layers of aluminum foam at thicknesses of 0.5 mm (S2), 1 mm (S3) and 1.5 mm (S4). The results indicate that the use of aluminum foam significantly improves mechanical characteristics relative to the pure carbon fiber sample. Sample S3, with 1 mm thick aluminum foam, attained the maximum tensile strength (128.7 MPa) and impact strength (10.2 J/m²), exhibiting the best balanced mechanical performance. The flexural strength and hardness of the sandwich samples increased, with the maximum hardness observed in S3 (246 HV). Thermal conductivity diminished with increasing foam thickness, varying from 1.6 W/m•K in S1 to 0.9 W/m•K in S4. This situation signifies a compromise between mechanical strength and thermal conductivity. The findings indicate that employing aluminum foam of suitable thickness can markedly boost the performance of sandwich composites in applications necessitating lightweight materials with superior mechanical characteristics and regulated thermal behavior.

ARTICLE HISTORY

Received 27 September 2025
Accepted 15 October 2025

KEYWORDS

Aluminum foam; sandwich composites; carbon fiber mat; mechanical strength; thermal conductivity

1. Introduction

Over the past several years, metal foams have garnered a significant amount of interest due to the exceptional qualities that they possess. These qualities include a low density, high specific strength and stiffness, high energy-absorbing capabilities and many more [1,2]. Within the category of metal foams, the aluminum-based foam is the one that garners the most interest from individuals due to its higher technological capabilities and complete qualities [3].

Sandwich composites have considerable benefits compared to traditional composites, owing to their elevated strength-to-weight ratio, improved flexural and bending characteristics and exceptional energy absorption capabilities. The lightweight core distinguishes robust face sheets, enhancing rigidity while minimizing material consumption and expense. Moreover, sandwich structures offer superior thermal and acoustic insulation, enhanced buckling resistance and design versatility, rendering them optimal for aerospace, automotive, marine and construction applications that necessitate lightweight, high-performance materials [4].

The rough-surfaced aluminum foam and smooth-surfaced carbon fiber/epoxy composites are optimal for sandwich design in many structural applications, meeting almost all required structural criteria and enabling facile manufacturing through composite processing. The lasting structural integrity of a

carbon-fiber/aluminum foam sandwich is influenced by the potential for delamination between the carbon-fiber/epoxy composite facings and the aluminum foam core, which may occur due to localized surface contact, low-energy impacts, or unintentional excessive bending of the sandwich structure. Thus, the overall load capacity and functional applications of sandwich structures are often limited by the interfacial toughness and strength of the face/core rather than the stiffness or strength of the carbon-fiber face sheets [5,6]. Thus, interfacial toughness and toughening mechanisms are identified as essential components for aluminum foam core and carbon-fiber composite sandwich structures and consequently form the central focus of this study.

The skins frequently employ fiber-reinforced composite laminates, which predominantly withstand axial bending and in-plane shear forces, while the core materials manage shear loads in the thickness direction. The integration of fiber-reinforced skins (such as glass or carbon fiber) with an aluminum foam core in sandwich composites provides numerous substantial benefits, particularly in high-performance structural applications, including thermal insulation, acoustic attenuation, shock mitigation and energy absorption, making it one of the most prevalent core material configurations. Frequently utilized foam core materials comprise styrene acrylonitrile (SAN), polyethylene terephthalate (PET), polyvinyl chloride (PVC), epoxy

and polymethyl acrylamide (PMI), among others. SAN serves as a structural closed-cell thermoplastic core material, renowned for its high toughness and impact resistance, garnering increasing attention, while PVC foam exhibits superior stiffness and a favorable stiffness-to-weight ratio, epoxy offers exceptional adhesion between layers, thereby augmenting the mechanical strength of the composite. It provides exceptional chemical resistance and durability under environmental stress [7,8].

In the past few years, researchers have conducted extensive studies on the mechanical and thermal characteristics, as well as the failure processes, of composite sandwich structures. A plethora of scholars have focused on the low-velocity impact damage and ensuing compressive performance of composite laminates and sandwich panels. Chang Yan et al. [9] enhanced sandwich constructions made of aluminum foam reinforced with carbon fibers by incorporating short carbon fibers into the epoxy glue. Tests revealed mechanical interlocking through adhesive penetration into foam pores, higher adhesive contact from fiber clustering, and improved bonding as a result of fiber bridging.

The impact resistance of CFRP sandwich panels was examined by Bozkurt et al. [10] in relation to the core forms of egg box, lattice, and square. Lattice cores completely failed during drop weight testing, but square cores exhibited the highest resistance to impact. Peak force variations across core types and progressive damage are properly modeled by simulations with LS-DYNA matched experiments.

Selvamuthukumar et al. [11] examined sandwich composites made of aluminum reinforced with glass and carbon fiber for usage in automobiles. Tests indicate that augmented fiber reinforcement improves impact resistance. Variants of carbon fiber were better suited for lightweight structural applications because they were stronger and less likely to delaminating than glass fiber.

Limited research specifically investigates the systematic influence of aluminum foam core thickness in epoxy-carbon fiber mat systems; however, several studies have analyzed the mechanical and thermal properties of fiber-reinforced sandwich composites. Moreover, previous research inadequately evaluates the cumulative effects on mechanical properties (tensile, flexural, impact, and hardness) and thermal performance, including microstructural correlations *via* SEM, and often lacks a comprehensive comparative analysis across different foam thicknesses.

In order to determine how foam core thickness affects tensile strength, flexural strength, impact resistance, hardness and thermal conductivity, the study fabricates four epoxy-carbon fiber mat sandwich composites (S1 to S4) with different aluminum foam core thicknesses (0, 0.5, 1.0 and 1.5 cm). In order to determine the ideal foam core thickness that provides a compromise between mechanical strength and thermal performance for possible lightweight structural applications, scanning electron microscopy (SEM) will be used to examine failure mechanisms and interfacial bonding.

2. Experimental

2.1. Materials

The sandwich specimens were manufactured using epoxy, the hardener HY951, aluminum foam for the core, and carbon

fiber for the skin. In this experiment, epoxy resin grade LY556 was utilized. From The Brand Season Resin Art & Resin Raw Materials in Chennai, Tamil Nadu, India, epoxy resin and HY951 were purchased. Precipitation-hardened aluminum foam, or Al 6061, is of higher quality than other aluminum types. Aluminum foam cores acquired in thicknesses of 0.5, 1, and 1.5 mm from MVM FOAMS, situated in Egmore, Chennai, Tamil Nadu, India. The aluminum foam sandwich is composed of a carbon fiber mat. S M COMPOSITES: FIBRE GLASS RAW MATERIAL, Chennai, India, supplies carbon fiber mats (300 GSM and 20 mm).

2.2. Fabrication of hybrid sandwich composite

An aluminum foam core made by compression molding was positioned between the carbon fiber mats. For samples S1 through S4, two layers of aluminum foam with different foam thicknesses (0, 0.5, 1 and 1.5 mm) were used to create the sandwich composites. The volume percentage (vol%) of the reinforcement and matrix varied, with the epoxy matrix proportion falling and the aluminum foam weight gradually rising. The resulting samples were $300 \times 300 \times 8$ mm. The reinforced fibers used in this experiment are a carbon fiber mat, an epoxy resin matrix and a sandwich plate made of aluminum foam. Epoxy resin and hardener HY951 mixes are first poured into the mold. After the thinner was rolled out on the mold surface, carbon fibers were added to the resin mixture. Using rollers, 0.5 mm thick cores of aluminum foam were injected into the resin. Resins are usually impregnated using steel rollers. To improve impregnation, nip-rollers are used. Until the desired thickness is reached, the process is repeated. The hardener and glue mixture is then used to polish the surface of the carbon fiber. After that, the foam was put into the mold [12,13]. The next hardener and resin are polished on top of the aluminum foam. At this point, the carbon fiber is situated above the resin. The second layer of aluminum foam was applied using the same process. To enable the sandwich composite to cure completely over the course of a day, the mold was exposed to a prescribed weight of 1 kg and pressure of 40 psi. Additionally, sandwich composites made of aluminum foam with thicknesses of 1 and 1.5 mm were created. Table 1 lists the various sandwich composite designations for the four distinct thicknesses encased in carbon fiber epoxy laminates. Figure 1 illustrates the produced aluminum sandwich composite samples. The test specimens are made in compliance with ASTM guidelines and are generated in accordance with ASTM standards.

2.3. Specimen dimension and testing condition

2.3.1. Mechanical test

Tensile testing is conducted using universal testing equipment, functioning at a head speed of 0 to 5 mm/min. The experiment employed a single load type on the sandwich composite. Composite samples for the tensile test were meticulously cut to the specified dimensions in accordance with the ASTM D 638 standard. Utilize a three-point flexure test to demonstrate the failure associated with interlaminar shear phenomena. The primary method employed is the three-point static flexural test.

Table 1. Sandwich composite designations of two layers aluminum foam core with three different thicknesses.

S.No	Sample	Matrix	Reinforcement
1.	S1	Epoxy resin	Pure 1 layers of carbon fiber mat
2.	S2	Epoxy resin	2 layers aluminum foam (0.5 mm thickness) & 3 layers of carbon fiber mat
3.	S3	Epoxy resin	2 layers aluminum foam (1 mm thickness) & 3 layers of carbon fiber mat
4.	S4	Epoxy resin	2 layers aluminum foam (1.5 mm thickness) & 3 layers of carbon fiber mat

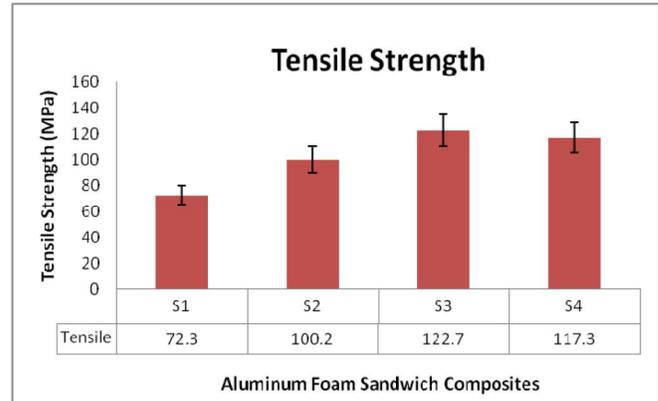
**Figure 1.** Aluminum sandwich composite samples.

The universal testing machine conducts this test at a head speed between 0 and 5 mm/min. The ASTM D 790 standard requires the performance of a bending test. The impact test is comprehensively outlined in ASTM D 256. The impact energy of the sandwich specimen was documented, and the energy of the composites was evaluated. The Rockwell 574 hardness machine RAB 250 SCNO: SN 7078 utilizes Shore A and Shore C durometers to evaluate the hardness of various materials. Increased numerical values on the scale indicate a denser and less ductile material. The standard for conducting the hardness test is ASTM D2240. The test employed a ball indenter with a diameter of 10 mm, applying a force of 100 N/mm to the specimen. Each sample was subjected to five tests to calculate an average for all measurements. Investigated tensile fracture spaceman's on sandwich composite surfaces using a JEOL JSM 5610 LV scanning electron microscope. To increase conductivity, the composites were thoroughly cleaned, allowed to air dry, and then covered with platinum. At 20 kV and 50 μ m magnification, scanning electron microscopy was detected. The thermal conductivity of aluminum foam sandwich composites was assessed at temperatures ranging from 50 to 200 °C utilizing a capillary rheometer barrel (Model 3211, Instron Corp., Canton, MA), which served as both a heating source and material container.

3. Result and discussion

3.1. Tensile strength

Figure 2 depicts the tensile strength of four aluminum foam sandwich composites (S1–S4), including different reinforcing arrangements, all utilizing epoxy resin as the matrix. S1, augmented with only one carbon fiber mat, exhibits the

**Figure 2.** Tensile strength of different thickness aluminum foam sandwich composites.

lowest tensile strength (72.3 MPa). The use of aluminum foam markedly enhances strength, with S2 (0.5 mm thickness foam) attaining 100.2 MPa and S3 (1.0 mm thickness foam) obtaining the maximum strength of 122.7 MPa. The maximum tensile strength results from several reinforcing techniques. The use of aluminum foam enhances load distribution by facilitating stress transmission between the epoxy matrix and the carbon fiber layers, while the foam's porous structure contributes to increased stiffness and mechanical interlocking, particularly at intermediate thicknesses [14–16]. Foam up to 1.0 mm efficiently contributes without substantially undermining the interlayer bonding, yielding optimal strength. Nonetheless, S4, with thicker 1.5 mm aluminum foam, exhibits a little reduction to 117.3 MPa. The tensile strength markedly increases with the increase in aluminum foam layer thickness. Conversely, S3 has an ideal foam thickness of 1.0 mm; beyond this, increasing the foam thickness, as in S4, might diminish mechanical performance. This decrease can be ascribed to many factors: The denser foam may generate additional voids or flaws, reduce the effective bonding surface with the matrix, and increase brittleness or the likelihood of delamination under tensile stress. Furthermore, excessive foam thickness may obscure the composite's structure, thereby reducing its overall tensile performance [17–19]. Consequently, an ideal foam thickness of 1.0 mm exists, which equilibrates strength, stiffness, and interfacial adhesion.

3.2. Flexural strength

Figure 3 illustrates that the flexural strength of aluminum foam sandwich composites rises with the incremental thickness of aluminum foam up to 1.0 mm, attributable to improved load distribution, higher stiffness and efficient stress transfer between the core and face sheets [20]. At a thickness of 1.0 mm (S3), the aluminum foam delivers ideal

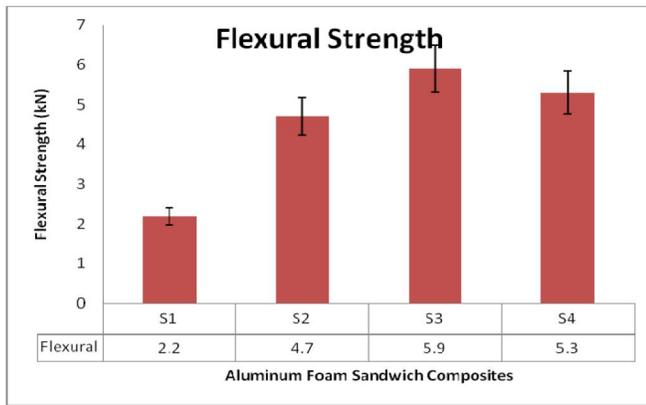


Figure 3. Flexural strength of different thickness aluminum foam sandwich composites.

structural support while maintaining the integrity of the link among the foam, epoxy resin and carbon fiber layers, yielding the maximum flexural strength of 5.9 kN. Nonetheless, increasing the foam thickness to 1.5 mm (S4) results in a marginal reduction in strength (5.3 kN), presumably attributable to diminished interfacial bonding, heightened susceptibility to delaminating and enhanced core deformability under bending loads. Increased foam thickness may potentially create more internal voids or stress concentrations, thus compromising the overall structural integrity under flexural loading [21–23]. An ideal thickness of aluminum foam, approximately 1.0 mm, exists for optimizing flexural performance in these composite constructions.

3.3. Impact strength

Figure 4 illustrates that the impact strength of aluminum foam sandwich composites rises with foam thickness up to 1.0 mm, mostly due to the foam's role as an effective energy absorber, which distributes and dissipates impact forces throughout its porous structure, thereby averting abrupt failure. The aluminum foam, with a thickness of 1.0 mm, had the volume and cell density to undergo plastic deformation upon impact, thereby absorbing kinetic energy and safeguarding the composite layers from fracture initiation and propagation, culminating in a peak impact strength of 10.2 J/m^2 (S3) [24]. As the foam thickness surpasses 1.5 mm in sample S4, energy absorption diminishes due to heightened structural stiffness and a transition from ductile to brittle behavior, thereby constraining the material's capacity to deform and absorb energy, resulting in a slight reduction of impact strength to 9.8 J/m^2 [25–27]. The 0.5 mm foam (S2) attained an impact resistance of 9.6 J/m^2 , whereas the baseline sample lacking foam (S1) exhibited the lowest resistance at 7.2 J/m^2 .

3.4. Hardness

The hardness of aluminum foam sandwich composites, displayed in Figure 5, exhibits a pattern that is comparable to that of tensile and flexural strength, with values rising up to a foam thickness of 1.0 mm and then marginally falling with increasing thickness. The hardness measurements for the

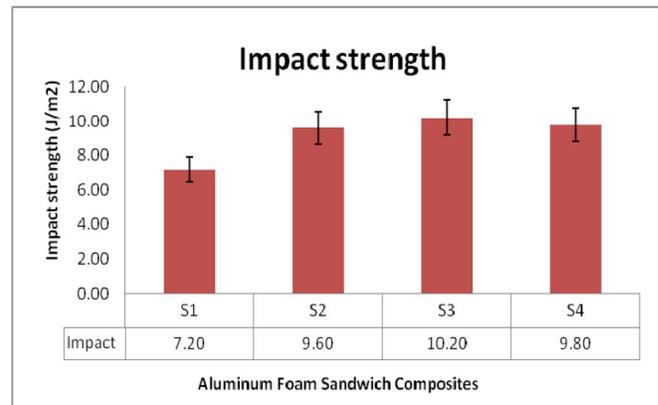


Figure 4. Impact strength of different thickness aluminum foam sandwich composites.

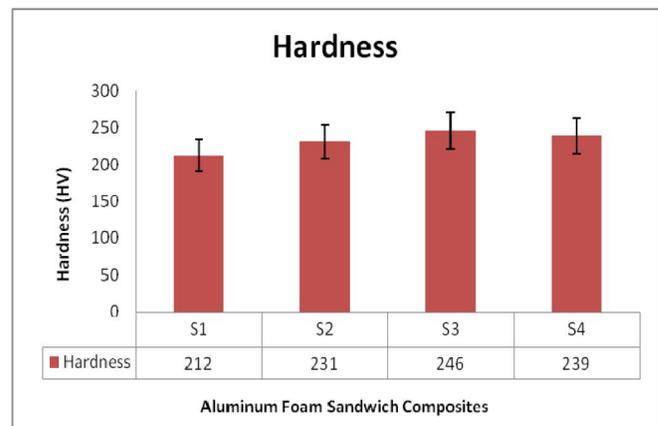


Figure 5. Hardness of different thickness aluminum foam sandwich composites.

samples are as follows: S1 – 212 HV, S2 – 231 HV, S3 – 246 HV and S4 – 239 HV. This tendency suggests that the use of aluminum foam augments hardness by facilitating enhanced stress transmission and bolstering resistance to localized deformation. At a thickness of 1.0 mm (S3), the foam structure achieves an ideal equilibrium between surface stiffness and interior support, hence enhancing the composite's resistance to indentation. However, increasing the foam thickness beyond 1.0 mm (as illustrated in S4) slightly reduces hardness, likely due to an increase in voids, elevated internal porosity, and weakened interfacial bonding between the foam and matrix, which collectively compromise the material's ability to endure localized pressure [28,29]. This behavior reflects the trend observed in tensile and flexural performance, where mechanical parameters reach their zenith at 1.0 mm foam thickness before diminishing due to analogous structural and interfacial constraints.

3.5. Thermal conductivity

Figure 6 illustrates that the thermal conductivity of aluminum foam sandwich composites diminishes progressively with an increase in foam thickness, as indicated by the values: S1 – $1.60 \text{ W/m}\cdot\text{K}$, S2 – $1.40 \text{ W/m}\cdot\text{K}$, S3 – $1.10 \text{ W/m}\cdot\text{K}$ and S4 – $0.90 \text{ W/m}\cdot\text{K}$. These phenomena result from the substantial quantity of closed cells containing air in

aluminum foam, which is a poor thermal conductor. As the thickness of the foam develops, the ratio of air-filled holes

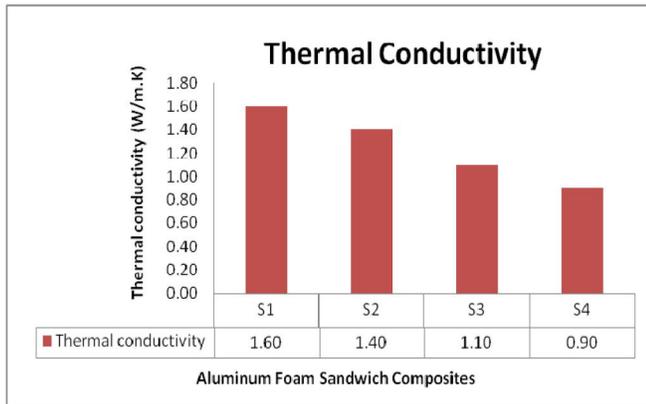


Figure 6. Thermal conductivity of different thickness aluminum foam sandwich composites.

inside the structure escalates, markedly impeding heat transport paths [30,31]. Foam with a thickness of up to 1.0 mm (S3) significantly reduces heat conductivity by obstructing continuous metallic pathways and improving insulation. Nevertheless, beyond this juncture, while conductivity persists in its decline (as observed in S4), the pace of reduction diminishes owing to the saturation of insulating pores and a possible escalation in thermal interface resistance between the foam and adjacent layers. In contrast to mechanical qualities like tensile or flexural strength, thermal conductivity is more influenced by porosity and the interior cellular structure than by load-bearing capacity.

3.6. Tensile fracture morphology of aluminum foam sandwich composites

The tensile fracture regions of the aluminum foam sandwich composites exhibit the distribution of carbon fiber mats and

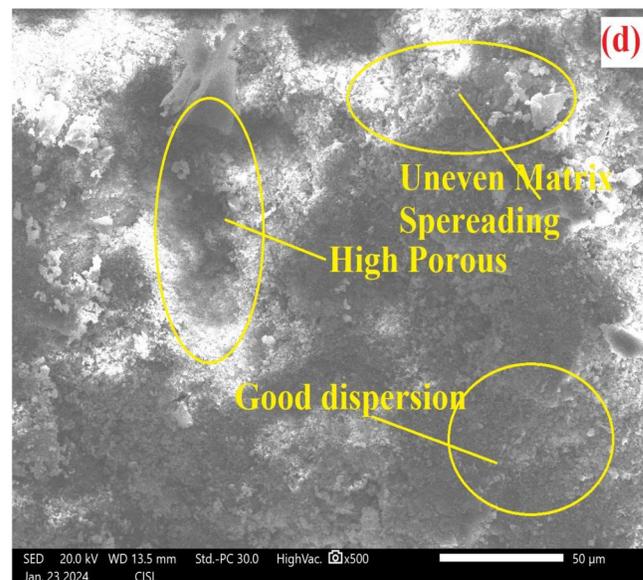
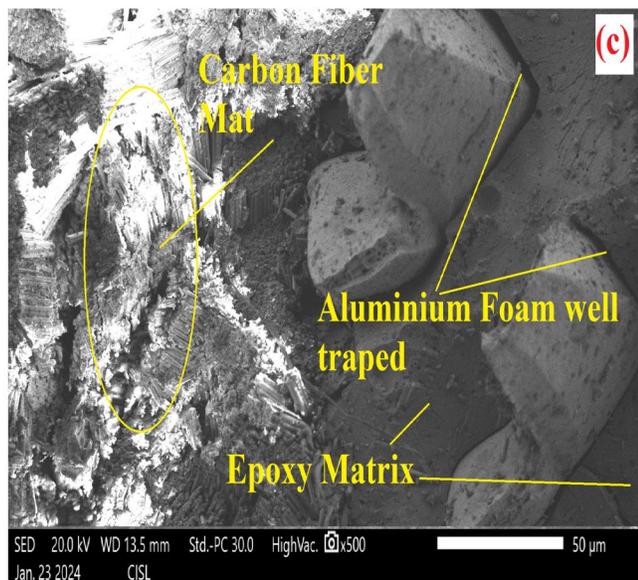
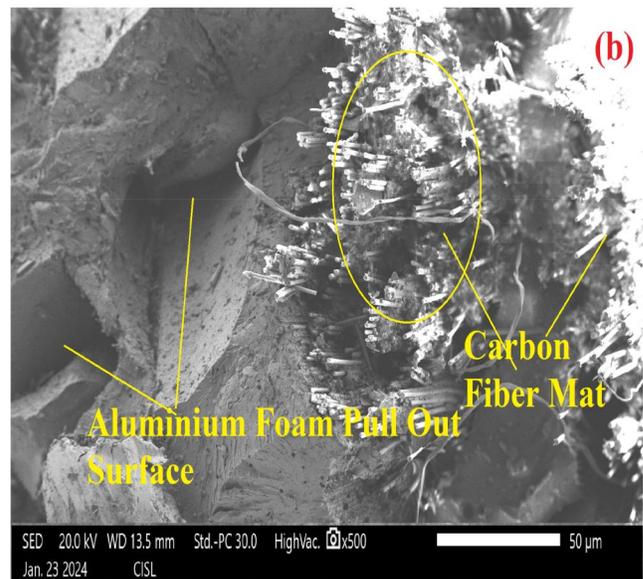
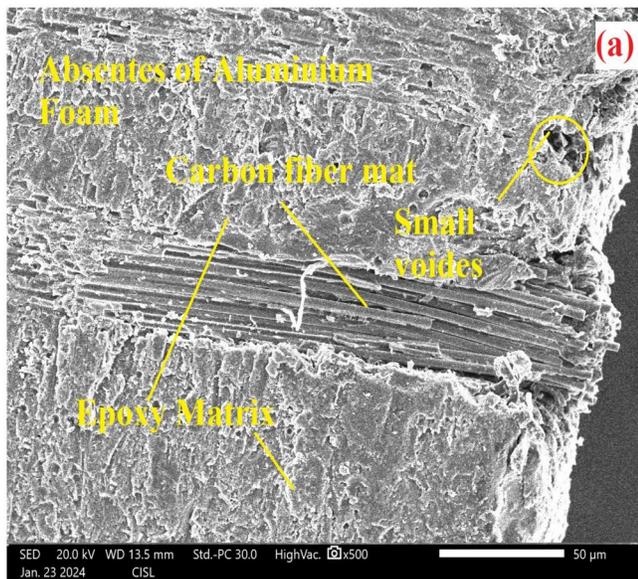


Figure 7. Photomicrographs of aluminum foam sandwich composite fracture surfaces of a sample subjected to tensile strength, for (a) one layer of carbon fiber, (b) 0.5 mm thickness aluminum foam, (c) 1 mm thickness aluminum foam and (d) 1.5 mm thickness aluminum foam.

aluminum foam inside the matrix, as seen in Figure 7 (a–d). Upon extraction of the carbon fibers and aluminum foam, the aluminum foam exhibited cracking within the matrix, voids, and pores, indicative of a brittle fracture. The lack of aluminum foam indicates the presence of a single-layer carbon fiber mat in Figure 7(a). Scanning electron micrographs reveal the presence of minute spaces. Minor voids inside the matrices are unbounded or contain air pockets. Premature failure and stress concentration arise from increased void content. The existence of gaps that allow air entrapment within the composite or on its surface indicates strong compatibility between the carbon fiber and the matrix. Micro voids indicate inadequate adhesion. The transfer of load from the face sheets to the core is diminished due to inadequate bonding. Delaminating at the interface diminishes impact resistance and fatigue life [32,33]. Figure 7(b) demonstrates that the carbon fiber mat increases the interfacial area of the composite, leading to enhanced ductility in fracture behavior and a little augmentation in tensile strength. The enhancement, albeit not substantial, demonstrates that a slender fiber interlayer (0.5 mm) can offer significant reinforcement by facilitating load transmission, fracture bridging and energy dissipation [34]. S3 sandwich composites consisting of 1 mm thick aluminum foam containing entrapped carbon fibers, exhibiting robust adhesion at the aluminum foam-matrix interface, absence of carbon fiber cohesion, and devoid of voids (Figure 7(c)). Consequently, 1 mm thick aluminum foam sandwich composites have superior tensile strength (122.7 MPa) compared to other thicknesses (0.5 & 1.5 mm) of sandwich composites [35]. Figure 7(d) illustrates the failure surface of sandwich composites made of aluminum foams that are 1.5 mm thick. The failure mechanism is defined by incompatibility between fiber and matrix, with the quality of matrix dispersion and bonding deteriorating when the thickness exceeds ideal values. In 1.5 mm aluminum foam sandwich composites, elevated porosity and irregular matrix distribution negate the advantages of increased material, leading to a reduction in tensile strength to 117.3 MPa compared to the 1 mm variation [36].

4. Conclusion

The four distinct combinations of aluminum sandwich composites were successfully fabricated using the compression method, which involved blending epoxy resin with two layers of three different thicknesses of aluminum foam (0, 0.5, 1 and 1.5 mm) and carbon fiber mats. They also conducted experiments to assess the mechanical, thermal and morphological properties of aluminum foam sandwich composites.

Tensile, flexural and impact strengths increase linearly with the incorporation of 0.5 and 1 mm thick foam reinforcement; however, strength values sharply decrease with the inclusion of 1.5 mm thick foam reinforcement. Investigated the mechanical properties of aluminum sandwich composites, including tensile, flexural, impact, and hardness strength, and identified the maximum values as 122.7 MPa, 5.9 kN, 10.2 kJ/m² and 246 HV10. The material

subjected to tensile testing has its fractured surface analyzed by scanning electron microscopy. The study's findings advocate for the utilization of aluminum foam sandwich composites in the production of automotive and aerospace components.

Disclosure statement

The authors declare that they have no conflict of interest.

Credit authorship contribution statement

P. Saravana Kumar – Conceptualization, Methodology & Writing-original draft

V. Thanigaivelan – Supervision & Formal analysis

K. Arun - Project administration, Demonstration & Validation

S. Arunkumar - Data curation & Visualization

Author contributions

CRedit: **Saravana Kumar P**: Conceptualization, Writing – original draft; **Thanigaivelan V**: Formal analysis, Supervision; **Arun K**: Writing – review & editing; **Arunkumar S**: Validation, Visualization.

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Data availability

All data generated and analyzed during this study are included in this published article.

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