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Advancements In Metal-Fiber Composites for Aerospace and Defense Applications: A Comprehensive Review

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Abstract

This paper provides a comprehensive review of fiber-reinforced composites, focusing specifically on the utilization of metal-fiber composites in aerospace such as metal surface preparation prior to bonding, resin selection, and detailed examination of mechanical testing and impact studies. The significance of metal surface preparation for establishing strong bonding, which is a crucial initial step in composite fabrication, is discussed. Additionally, the prevalent use of epoxy resins and their importance in bonding metal fibers is highlighted. The mechanical strength of these composites is thoroughly assessed through a combination of tensile and flexural tests, providing insight into their structural integrity. The paper also provides a concise overview of low and high-velocity impact studies conducted on metal-fiber composites, offering valuable insights into material response under various impact conditions and real-world performance. Furthermore, it briefly explores the application of metal-fiber composites in armor and aerospace, emphasizing their role in achieving weight reduction while significantly improving stiffness and impact strength. This research paper presents a detailed exploration of metal-fiber composites in aerospace and defense applications.

Keywords: Fibre-reinforced composites, metal-fiber composite, impact strength, sand blasting, tensile, flexural

INTRODUCTION

A composite material is created by combining two dissimilar constituent materials with contrasting mechanical, physical, and chemical properties, resulting in a new material with superior properties compared to its individual constituents. In the aerospace industry, composites are widely utilized to achieve weight reduction at the component level, owing to their low density, elevated stiffness, and strength. Incorporating composites in modern aircraft is estimated to reduce weight by 15 to 25% [1]. Fiber-reinforced composites, utilizing synthetic or natural fibers, have gained significant importance in aerospace applications in recent years. These composites offer exceptional resistance to corrosion, impact, wear, and heat, along with a high strength-to-weight ratio. Commonly used fibers include Carbon, Aramid, Glass, and Basalt, along with reinforcement alloys such as Titanium, Steel, and Aluminum. A resin serves as the bonding agent for the fibers, which are arranged in various orientations, stacked, layered, or used to bind fibers with metals. Critical mechanical properties, including tensile strength, flexural strength, and peel strength, are essential considerations for metal-fiber composites in aerospace applications. Impact resistance is particularly crucial for these composites to qualify as promising materials for aircraft components prone to unpredictable impacts. Parameters such as delamination and interphase strength play vital roles in developing composites

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for reliable aerospace structures. Additionally, understanding failure modes in metal-fiber laminates is crucial to ensure they provide sufficient strength, possess fatigue resistance, fracture toughness, and can withstand environmental degradation [2]. Composites used in defense include carbon fiber-reinforced polymers (CFRPs), glass fiber-reinforced polymers (GFRPs), and ceramic matrix composites (CMCs), often used in armor, missile systems, and aircraft.

MATERIALS AND METHODS

The use of fiber reinforced composites started occurring in Aerospace applications very early when they were looked as an alternative for metals. However, they possessed low fracture toughness, low impact strength and were highly susceptible to environmental conditions like moisture and salinity. Hence, the idea of adding one or two layers of thin metal emerged to nullify the disadvantages of fiber laminates. Thus, metal-fiber laminates improved mechanical properties so that they can be considered as an alternate in aerospace structures without compromising the structural stability. The different fibers used in the metal-fiber combinations are shown in Figure 1. Three types of fibers commonly used in aerospace composites are carbon fibers, glass fibers, and aramid (Kevlar) fibers.

Over these years, plenty of fibers from Aramid to carbon and glass fibers have been used in combination with metal alloys like Aluminum, Stainless steel, Titanium and Magnesium with an epoxy resin as a bonding agent to produce reinforced composite materials. As the cruise speeds increase and the mission requirements keep on increasing, the need for light-weight structurally-stable heat-resistive metal fiber composites is on a rise [3]. The different metal combinations used in the metal-fiber combinations are shown in Figure 2.

This paper provides a comprehensive review of the various works reported in the literature on Metal-Fiber composites mainly for aerospace applications. The literature review is categorized as below in Figure 3.

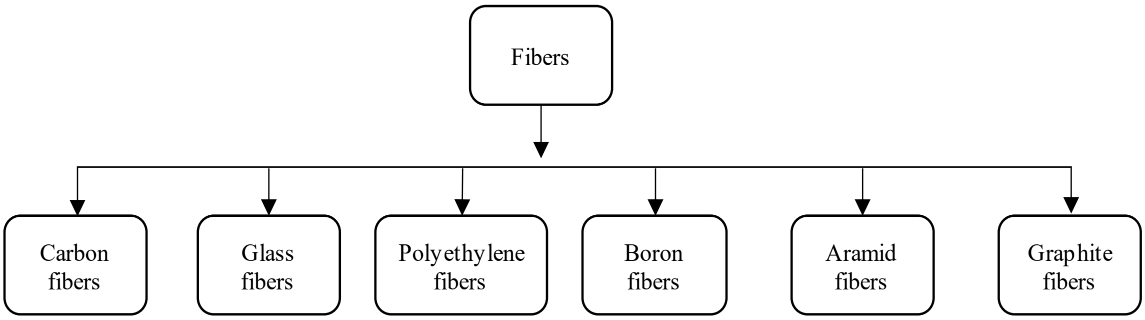

Figure 1. Fibers in reinforced composites

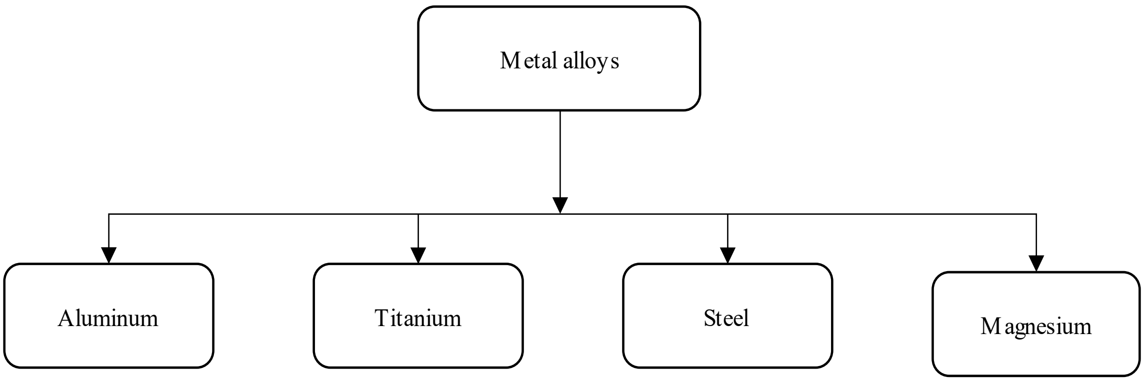

Figure 2. Metals used in the metal-fiber reinforced composites.

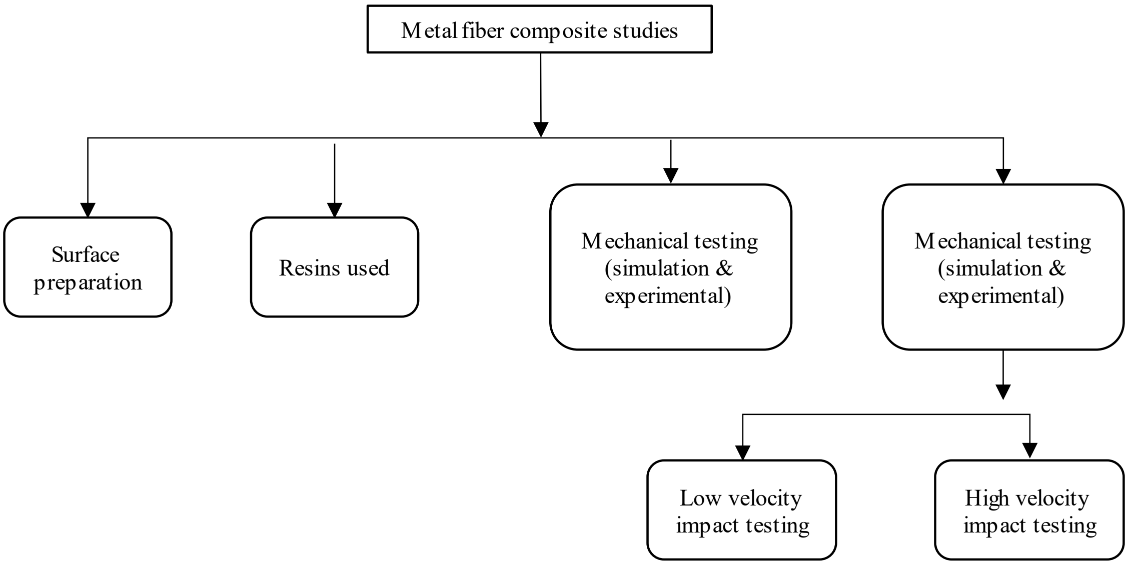

Figure 3. Review summary of metal-fiber reinforced composites.

METAL-FIBRE REINFORCED COMPOSITES

Metal-fiber composites play a crucial role in aerospace applications, particularly in the containment wall surrounding the engine casing. This barrier serves to prevent foreign objects from entering the engine, especially during blade-out events. Traditionally, the hard-wall containment approach employs containment rings made of heavy metals such as Titanium. These metals absorb foreign particles, minimizing damage to the structure. However, a newer method known as soft-wall containment utilizes a metal-fiber composite in the containment ring. In this approach, the impact is primarily absorbed by the fiber, protecting the metal structure from damage. Kevlar is a prominent fiber used in soft-wall containment, often in conjunction with Titanium. Additionally, Carbon fiber, along with Aluminum alloy, sees extensive use in various aircraft and spacecraft structures. On the other hand, Metal matrix composites (MMCs) in aerospace are materials composed of a metal matrix (like aluminum or titanium) reinforced with fibers or particles, offering improved strength, stiffness, and resistance to wear and heat. Also, Wood plastic composites (WPCs) are made from a blend of wood, polymers, and additives, and can be processed using methods like extrusion and additive manufacturing. While natural fibers in WPCs offer benefits, they also have limitations such as lower strength, moisture absorption, and thermal degradation [4]. This study reviews recent advances in raw materials, manufacturing processes, and applications of natural fiber composites (NFCs). Natural fibers are explored as alternatives to synthetic fibers like glass, aramid, and carbon in biocomposite applications. The review compares the physical and chemical properties of natural and synthetic fibers, highlighting the advantages and disadvantages of NFCs. Criteria for selecting and processing natural fibers in industries such as automotive and construction are discussed [5].

Surface Preparation of Metals

Studies have shown that bonding metals and fibers which are two different distinctive materials is really a challenge. Over the years, studies have also shown that, the metal surface and fibers can be bonded together to obtain satisfactory mechanical strength by preparing the metal surface before bonding. Most commonly used pre-treatments processes are degreasing, abrasion and chemical treatment. The choice of the right pre-treatment process is crucial in obtaining desired results from the metal-fiber composite. Some of the surface preparation methods used in the fabrication of metal-fiber composites is shown in Figure 4.

Some of the recent researches in the preparation of metal surface reported in the literature have been consolidated below.

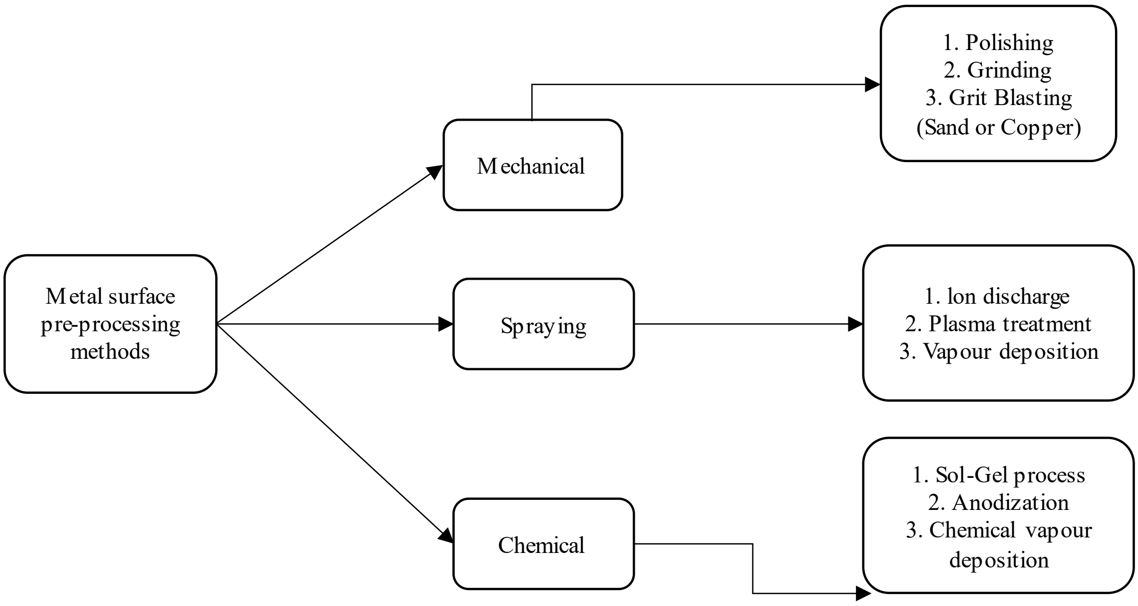

Figure 4. Surface preparation methods in metal-fiber composites.

Various studies have explored methods for modifying titanium surfaces to enhance their bonding properties with veneering composite resins. Ban Seiji and colleagues discovered that etching commercially pure titanium with 48% H_2SO_4 effectively alters the surface for improved resin bonding [6]. Another investigation by Gaurav Raj Singh compared the surface characteristics of smooth titanium disks with sand-blasted and acid-etched ones (Group SLA). Singh's findings indicated that the latter exhibited increased roughness and enhanced attachment of osteoblast cells, suggesting superior osseointegration potential [7]. Revankar examined the machining of titanium alloy using a polycrystalline diamond (PCD) tool under various coolant strategies. Results revealed that employing minimum quantity lubrication (MQL) with specific parameters minimized surface roughness, while dry machining maximized surface hardness. The study concluded that MQL lubrication combined with PCD inserts yielded superior surface finish and hardness in titanium alloy machining [8]. Balza analyzed the sandblasting process using alumina abrasive particles on Ti-6Al-4V surfaces. Optical microscopy revealed that the particle size decreased after sandblasting, resulting in a decrease in kinetic energy. As a result, the Ti-6Al-4V surfaces initially became rougher, but interestingly after 7 seconds a reverse process was initiated leading to a polishing effect on the alloy's surface [9]. Some research also discusses the problems in bonding polymer composites to titanium and the need for environmentally friendly surface treatment methods. Though it has been proved that surface treatments can improve bond strengths, many of these processes involve the use of hazardous chemicals that need to be phased out [10]. There are also studies reported on the use of sandblasting as a surface treatment method for titanium dental implants and the potential adverse effects of using alumina (Al_2O_3) grits. A study on the roughening effect and contamination of different grit materials including Al_2O_3, silica (SiO_2) glass, and aluminum (Al) on titanium implant surfaces shows that, while each material has its own advantages and disadvantages, Al_2O_3 is the most suitable grit material for sandblasting titanium implants [11]. A separate investigation by Aria Wira Yuda analyzed the impact of sandblasting parameters on the surface roughness of Ti-alloy implants, highlighting the significant influence of parameters like impact distance and sandblasting media type on surface characteristics [12]. Additionally, research by Jemat proposes acid etching and coating application as effective methods for achieving desirable surface roughness on commercial pure titanium [13]. Natural fiber-reinforced composites (NFRCs) have gained popularity as eco-friendly alternatives to traditional materials like glass fiber. Natural fibers such as abaca, jute, and flax offer advantages like lightness, biodegradability, and competitive mechanical properties, making them suitable for engineering applications [14]. Abaca is a strong contender among natural fibers for reinforcing polymer composites due to its durability, flexibility, and mechanical strength.

Treatments like alkali and silane enhance its properties, making abaca-based composites superior to some synthetic fibers. These composites find applications in industries such as automotive, packaging, and textiles [15].

Resins used in Metal-Fibre Composites

A number of reported literature are available on the resins used in meal-fiber composite fabrication. Normally, two types of resins (Polymers) such as thermosets and thermoplastics are used in various applications in Aerospace Engineering. In thermosets, resins like polyester resin, epoxy resin, vinyl esters, phenolic, polyurethane, polyester-based polyurethane resins and polyunsaturated resins are used. In thermoplastic resins, resins like Polyethylene, Polypropylene, Acrylic, High Density Poly Ethylene and Polystyrene are used [16]. In a review conducted by Kazemi and team on Fiber-Metal Laminates (FMLs), the different surface treatment methods like sandblasting, anodization, chemical etching, plasma treatment, Micro Arc Oxidation (MAO) and ozone formation process were compared. Also, the various fabrication methods like autoclave, VARI, VARTM, hand layup and stamp forming processes were discussed. The mechanical properties of the FMLs like fatigue properties, tensile and flexural properties, shear properties, Metal Composite Interface (MCI) properties and impact properties were analyzed. It is seen that, when compared to GLARE (aluminum-based FMLs), hybrid titanium composite laminates (HTCLs) expressed superior in-plane mechanical properties such as fatigue, tensile, compression and shear [17]. A study was conducted on three hybrid composites with E-glass fiber and Kevlar-49 and dissimilar ratios of epoxy resin and hardener by hand layup method. The results show that, the laminate with resin and hardener in the ratio 3:2 exhibited best mechanical properties in terms of hardness and tensile strength while the laminate with and 4:1 showed better inter-laminar properties and adhesion capabilities [18].

Mechanical Testing of Metal-Fibre Composites

The bending behavior of a carbon-fiber composite specimen was investigated through a three-point beam impact test using two different sets of gas gun apparatus [19]. The force of impact and beam deflection was measured using statically calibrated strain gauges. Damage observed in the specimen was attributed to the energy release caused by the difference in kinetic energy of the impactor and the potential energy of the beam. Gouda and colleagues explored the Mode-I fracture behavior of glass-carbon fiber reinforced hybrid polymer composites along two different directions using a computer-controlled universal testing machine [20]. The study revealed that the elastic modulus was predominant along the fiber orientation, and the stress intensity factor for Mode-I fracture was higher along the fiber orientation. Fracture surfaces exhibited brittle cleavage failure with some debonding between the fiber and matrix. Azzam investigated the three-point bending behavior of composite laminate structures with quasi-isotropic and unbalance stacking sequences [21]. The quasi-isotropic sequence demonstrated superior advantages and exhibited brittle behavior, while the unbalance sequence showed a non-linear curve due to compressive yielding. Rajesh studied the flexural behavior of Kevlar composites prepared by hand layup process [22]. The study reported that the Kevlar fiber composite broke at 226 kN with a maximum displacement of 6.7 mm at an ultimate stress of 5.56 N/mm2. Changing fiber orientation was found to affect the ultimate strength. Eksi analyzed the mechanical strength in epoxy composites comprising unidirectional fibers of glass and carbon, as well as woven fibers of glass, Aramid, and carbon [23]. The results indicated that unidirectional carbon fiber composites showcased superior mechanical properties compared to glass fiber composites. Among woven fibers, Aramid fiber composites demonstrated superior mechanical properties compared to both glass and carbon fiber composites. In a study on Kevlar Fiber reinforced Aluminium 6061 Sandwich composite, the material exhibited superior tensile, flexural, and impact properties, suggesting its potential as an advantageous alternative in aerospace applications [24]. A similar study comparing the mechanical characteristics of Kevlar fiber epoxy composites with aluminum revealed errors up to 18% when experimental results were compared to FEA results [25]. Belan evaluated the three-point bending fatigue loading on a TiAl6V4 titanium alloy and concluded that the width of lamellae significantly influences fatigue life [26]. Three-point bending was identified as more suitable for assessing complex fatigue life in advanced materials.

A recent study examined the impact of fiber orientation on the mechanical properties of flat plates and flat plates with circular holes made of woven Kevlar/Epoxy composite laminates [27]. Results showed maximum displacements in x and y directions at 0° and 90°, no displacement in the z direction, and higher stress at 0° and 90°. Flat plates with circular holes exhibited reduced strength due to material removal. Another investigation focused on the effect of modified Alumino Silicates (bentonite) on Kevlar/epoxy reinforced composites [28]. The study analyzed the mechanical and morphological characteristics of composites incorporating 1% and 3% modified bentonite, demonstrating enhancements in mechanical properties. Vasudevan investigated the mechanical properties of hybrid composite laminates with different orientations of Kevlar and glass fibers [29]. Tensile and flexural tests showed that the 0° Kevlar composite had the highest load carrying capacity, flexural modulus, and mechanical properties. Rayhan compared the elastic properties of unidirectional composite materials through analytical and experimental means [30]. The outcomes revealed that ANSYS Finite Element (FE) values were in agreement with the Bridging model, and the specialized Material Designer FE code yielded superior results compared to COMSOL FE. ANSYS Material Designer was identified as a potent and efficient tool for calculating the stiffness of unidirectional composites.

In summary, numerous studies have extensively investigated the mechanical behavior of diverse composite materials, exploring factors such as fiber orientation, stacking sequence, and the incorporation of additives. The research covered carbon-fiber composite bending behavior, Mode-I fracture in glass-carbon fiber reinforced hybrid polymer composites, and the three-point bending behavior of composite laminate structures with varying stacking sequences. Additionally, studies focused on the impact of fiber orientation on Kevlar/epoxy composite laminates, the assessment of mechanical properties in Kevlar composites, and the potential substitution of conventional aluminum with Kevlar fiber-reinforced aluminum 6061 sandwich composites in aerospace applications. Comparative analyses included investigations into Kevlar fiber epoxy composites versus aluminum, three-point bending fatigue loading on a titanium alloy, and the influence of modified alumina- silicates on Kevlar/epoxy composites. Hybrid composite laminates with different orientations and a comparison of elastic properties in unidirectional composite materials also contributed to the collective understanding of composite materials' mechanical behavior, providing valuable insights into applications and potential areas for improvement.

Low Velocity Impact Test

In a separate research endeavour, composite laminates featuring an epoxy matrix were meticulously crafted using the hand layup technique. The impact characteristics of these laminates were extensively investigated employing a drop weight impact tester at varying falling heights, including 600 mm, 700 mm, 800 mm, 900 mm, and 1000 mm. Notably, the study revealed that the unidirectional carbon/epoxy composite exhibited diminished energy absorption during impact, displaying deformation and rapid failure compared to other tested compositions. Furthermore, hybrid carbon + glass composites exhibited superior impact strength compared to carbon-only composites. At higher impact heights, all laminate specimens exhibited reduced time to reach maximum loads [31]. In a study conducted by Ruzuqi, laminate composites were fabricated using epoxy resin, glass fiber reinforcement, and various filler materials through the hand layup method. Impact strengths of the different material combinations were measured using Charpy and Izod impact tests. Results indicated that the E-glass laminate exhibited the highest impact strength of 17.82 kJ/m2 among other fiber-reinforced polymer composites. Additionally, hybrid polymer composites, particularly epoxy glass and sisal fiber with silicon carbide filler, displayed the maximum impact strength of 33.71 kJ/m2 among other hybrid polymer composites [32]. A low-velocity impact failure analysis on thin composite laminates using carbon fiber/epoxy demonstrated that the stacking sequence and impact energy level can influence the dynamic response of the laminates [33]. Furthermore, low-velocity impact tests on composite plates with compressive pre-loading of carbon fiber showed that the extent of intra-laminar damage for the pre-loaded model was slightly higher than the unloaded plate, resulting in increased deflection and energy absorption [34]. Sharma designed and fabricated glass fiber composite sandwich panels, conducting low-velocity impact tests with variable mass and height. Results indicated that the load absorbed versus time and absorbed energy versus time were higher in the top surface compared to the bottom surface [35]. Another study by Zike validated experimental and numerical results from low-velocity impact tests on unsaturated polyester/glass fiber composite laminates. The impact tests led to perforation in all samples, demonstrating a brittle response followed by matrix cracking and delamination. Importantly, there was a notable agreement between experimental findings and simulation results [36].

In another study on predicting the damage area of laminated composite plates following low-velocity impacts using ANSYS software the authors have developed models to anticipate the extent of damage sustained by these plates, aiding in the design and engineering of resilient composite materials. Their findings contribute to enhancing the durability and performance of laminated composites in various industrial applications [37]. In a study by Taraghi, Iman and team, it was observed that the inclusion of multi-walled carbon nanotubes (MWCNTs) led to notable enhancements in the low-velocity impact resistance of woven Kevlar/epoxy laminated composites with increased energy absorption and improved damage tolerance of the composite material. At both ambient and low temperatures, the specimens reinforced with MWCNTs exhibited reduced delamination and matrix cracking compared to the unreinforced counterparts. The findings suggest that the incorporation of MWCNTs holds promise for enhancing the mechanical performance of Kevlar/epoxy laminates under impact loading conditions, offering potential benefits for applications requiring lightweight yet robust materials in challenging environments [38]. Buang and Kashif focused on simulating low-velocity impact tests on carbon/epoxy composite plates to understand the behavior of these composite structures under impact loading conditions. Their simulation results revealed valuable insights into the damage mechanisms and deformation patterns experienced by the carbon/epoxy composite plates during low-velocity impacts. Specifically, they observed the formation of delamination, matrix cracking, and fiber breakage within the composite material, providing detailed information on the damage progression and severity [39]. Sansudin focused on the design and development of a drop weight impact test rig. This study detailed the specific components and features incorporated into the test rig to ensure accurate and reliable impact testing which is crucial for assessing the impact resistance of various materials and structures [40].

Jen, Chang, and Wu conducted numerical analysis and experimental verification of Ti/APC-2/Kevlar hybrid composite laminates subjected to low-velocity impact. Through computational simulations and physical experiments, they aimed to understand the impact response and damage mechanisms of these hybrid composite laminates. Their research provided valuable insights into the energy absorption, delamination, and damage propagation characteristics of the laminates under low-velocity impact conditions. The combination of numerical analysis and experimental validation offers a comprehensive understanding of the performance of Ti/APC-2/Kevlar hybrid composite laminates [41]. In a study investigating the impact of fiber orientation on the penetration resistance of aircraft composite material, it was found that plates with a cross-ply orientation exhibited the highest resistance to low-velocity impact loads. Conversely, plates with a quasi-isotropic lay-up were perforated by the impactor. Finite Element (FE) simulation results using LS-DYNA demonstrated favorable agreement with experimental data [42]. Another investigation focused on understanding the penetrating mechanics of composites through penetration tests on flat Kevlar-29/epoxy panels, revealed inner fractures induced through quasi-static indentation experiments [43].

In a dynamic effects examination resulting from impacts during low-velocity tests, inner fractures were induced through quasi-static indentation experiments. However, the study encountered limitations as dynamic effects caused by impacts could not be adequately explored using quasi-static experiments. It was noted that the thickness of the composite plate and the high velocity of stress waves in the through-the-thickness direction led to results that almost did not disclose any discernible dynamic influence in the thickness direction [44]. An experimental study with low-velocity impact tests on carbon fiber-reinforced composite plates was conducted aimed to determine the effect of temperature on impact strength. Results concluded that the impact strength changes as temperature drops, and impact energy behavior changes due to the alteration in orientation and the number of laminates [45]. In a study involving Twaron cloth, used in soft body armor, oblique low-velocity impacts were conducted using ANSYS-AUTODYN, and drop-weight impact tests were carried out with hemispherical, flat, and ogival heads to validate the model. The study indicated that energy absorption of Twaron fabric falls with an increase in obliquity, but under similar conditions, energy absorption grows with an increase in impact energy [46]. A study by Mahesh focused on determining energy absorption and damage mitigation in two different sandwich composites with rubber cores—carbon epoxy and Kevlar/epoxy. The sandwich made of carbon outperformed the Kevlar sandwich, with its absorption capability greater at 37.7%. The presence of rubber aided in minimizing damage to the bottom face sheet. The study established that Kevlar-based sandwich materials are lighter and less dense than those made of carbon [47].

High Velocity Impact Test

In a study on impact resistance, a thick glass/epoxy half-ring experienced local fiber shear fracture upon being impacted by a wedge-shaped titanium projectile at a velocity of 259 m/s. Delamination occurred extensively throughout the composite, prompting suggestions for potential improvement through the placement of a ceramic layer on the impact surface and reinforcement in the transverse direction to control delamination. Subsequent experiments involving small flat panels and cylindrical titanium projectiles indicated similar damage characteristics to the initial half-ring impact tests. Explicit finite-element tests demonstrated that small panel tests could be a cost-effective method for assessing local impact resistance [48]. The ballistic performance of protection panels made of woven Twaron and unidirectional non-woven Para-Aramid fabrics at different ply numbers was investigated. Results showed that unidirectional (K-Flex) fabric panels absorbed 12.5-16.5% more energy than woven (Twaron CT 710 type) fabric panels for the unit panel weight [49]. In a separate study, a Kevlar/epoxy composite plate was subjected to impact by a cylindrical flat-ended steel projectile. Ballistic limit velocity was determined to be 178 m/s, and damage mechanisms varied before and after reaching the ballistic limit. Factors such as incident impact velocity, projectile mass, and diameter were found to influence impact behavior [50]. For a composite laminate using Kevlar and ramie fibers reinforced by polyester resin, ballistic limit speeds at different target thicknesses were determined. Results showed an increase in ballistic limit with increasing relative humidity but a decrease with rising temperature. The damage size of the Kevlar composite at the rear face was smaller than that of the raw ramie composite [51]. In experiments with Kevlar-29 woven fabrics and epoxy resin, different laminate thicknesses and orientations were tested for impact behavior. Damage characteristics varied with crack formation, delamination, and matrix cracking. The layup orientation influenced energy-absorbing capacity, with thicker laminates generally exhibiting higher energy absorption [52]. High-velocity impact response of sandwich structures made of Kevlar-29/epoxy and aluminum plates showed excellent energy-absorbing characteristics, making them suitable for armour systems. The stacking sequence of the aluminum plates influenced impact resistance, with the Al-back stacking sequence offering high resistance to impact loading [53]. AA5083-H116 aluminum alloy plates coated with polyurea were tested for high-velocity projectile penetration. Results indicated reduced residual velocities with polyurea-coated plates, and thicker coatings positively contributed to reducing residual velocity and increasing energy absorption. Polyurea demonstrated higher energy absorption capacity per unit area density than aluminum [54].

Ballistic impact tests on laminated armor samples comprising Kevlar 29 fabric, steel, and fiber-cement layers demonstrated the capability to stop bullets with minimal deformation. Experimental and simulation results exhibited good agreement, validating the use of simulations in designing ballistic armors [55]. A ballistic impact test using a structural steel projectile on 2D woven Kevlar basalt composite revealed better impact resistance in Kevlar than basalt. The suggestion was made to weave basalt into warp and Kevlar into the weft for improved safety in armor wears [56]. Research on three-dimensional orthogonal woven composites made of carbon fibers and bismaleimide resin showed superior resistance to crack initiation and propagation under impact velocities ranging from 180 m/s to 280 m/s [57]. In a study on composite material samples, including Kevlar-Ballistic steel, Carbon fiber

Ballistic steel, and Kevlar/glass steel, increased plate thickness contributed to enhanced strength. Kevlar carbon fiber composites were particularly effective in resisting impact loads [58]. A study on a bi-metal fiber-metal laminate (FML) comprised of titanium and Kevlar-129 demonstrated energy dissipation mechanisms and ballistic velocity reduction during impact. Different thicknesses of titanium skins minimally influenced energy dissipation in Kevlar [59]. Experimental and numerical investigations on laminate failures using a 7g, 12 mm diameter impactor on woven carbon composite laminates revealed damage size and residual strength accurately. The orthotropic layup exhibited velocities ranging from 52.6 m/s to 211.5 m/s, while the quasi-isotropic layup ranged from 54.2 m/s to 209 m/s [60]. An examination of different aluminum alloy grades concluded that Al-2024 had the highest tensile strength. Hybrid composites with aluminum/Kevlar fiber exhibited better anti-ballistic properties [61]. Interface failure in metal/GFRP laminates using a hemispherical projectile was explored, suggesting that laminates without metal layers exhibited optimal performance for lower impact energy [62]. A study comparing two types of Fiber Metal Laminates (FMLs) revealed that a sandwiched Ti/HB50 system exhibited superior ballistic performance compared to a Ti/CFRP combination [63]. Experiments with hybridization using Kevlar/Glass/Carbon fiber showed no significant improvement, with Kevlar/Glass/Kevlar performing effectively. Layup orientations influenced damage size, delamination, and energy-absorbing capacity. An increase in thickness generally increased energy-absorbing capacity [64].

CONCLUSIONS

The comprehensive review presented in this paper offers a thorough examination of the fabrication and testing of metal-fiber composites, with a focus on mechanical and impact strength. The review encompasses a range of critical factors, including pre-treatment of metal surfaces, resin types, mechanical testing, and impact testing.

- One key observation highlighted in the review is the significance of enhancing the roughness of metal surfaces through mechanical or chemical processes, which contributes to increased bond strength in metal-fiber composites.
- The choice of resins, whether thermoset or thermoplastic, is also explored, with the selection being tailored to the specific metal-fiber combination.
- Simulation studies emerge as a valuable tool in the analysis of mechanical and impact strengths in metal-fiber composites. The review emphasizes the successful alignment of simulation results with experimental studies, underscoring the potential for utilizing simulation approaches to analyze composite strength. This not only enhances efficiency but also offers cost savings in the testing and analysis phases. Finite element analysis, particularly employing ANSYS and AUTODYN, is extensively used in the study of mechanical and impact strengths of metal-fiber composites. This analytical approach proves to be a robust method for assessing the performance of these composites, providing valuable insights into their stiffness, tensile properties, fatigue strength, and impact resistance.
- Studies showed that unidirectional carbon fiber composites exhibited superior mechanical properties compared to glass fiber composites, while Aramid fiber composites demonstrated advantages over both glass and carbon fibers
- Studies suggested that Kevlar fiber-reinforced aluminum sandwich composites could offer superior mechanical properties compared to conventional aluminum, especially in aerospace applications. Additionally, investigations into the impact of additives and fiber orientation provided valuable insights into potential enhancements and optimization strategies for composite materials.
- Studies have revealed that unidirectional carbon/epoxy composites tend to exhibit limited energy absorption and rapid failure upon impact, whereas hybrid carbon + glass composites show superior impact strength compared to carbon-only composites.
- Factors such as stacking sequence, impact energy level, and compressive pre-loading of carbon fiber significantly influence the dynamic response and intra-laminar damage in composite laminates.

- The impact strength of carbon fiber-reinforced composite plates varies with temperature changes, emphasizing the importance of considering environmental factors in composite design.

The overall importance of studying metal-fiber composites is underscored by their potential to offer enhanced mechanical properties and reduced weight. These composites show promise as suitable alternatives to traditional metal alloys, particularly in the context of future aircraft structures and defense applications. The amalgamation of superior stiffness, tensile strength, fatigue resistance, and impact strength positions metal-fiber composites as pivotal materials for advancing structural engineering in aerospace and defense sectors. The findings of this review contribute not only to the current understanding of these composites but also pave the way for continued exploration and application in cutting-edge technologies.

REFERENCES

1. Campbell FC. Structural composite materials. Materials Park, Ohio: Asm International; 2010.
2. Advanced Materials by Design. 1988.
3. Kazemi ME, Shanmugam L, Yang L, Yang J. A review on the hybrid titanium composite laminates (HTCLs) with focuses on surface treatments, fabrications, and mechanical properties. Composites Part A-applied Science and Manufacturing. 2020 Jan 1;128:105679–9.
4. Bhuvaneshwaran Mylsamy, Senthil Kumar Marudhamuthu Shanmugam, Karthik Aruchamy, Sivasubramanian Palanisamy, Rajini Nagarajan, Nadir Ayrilmis. A review on natural fiber composites: Polymer matrices, fiber surface treatments, fabrication methods, properties, and applications. Volume 64, Issue 6, 2345-2373.
5. Palanisamy, S., Murugesan, T. M., Palaniappan, M., Santulli, C., Ayrilmis, N., and Alavudeen, A. (2024). “Selection and processing of natural fibers and nanocellulose for biocomposite applications: A brief review,” BioResources 19(1), 1789-1813.
6. Ban S, Taniki T, Sato H, Kono H, Iwaya Y, Miyamoto M. Acid etching of titanium for bonding with veneering composite resins. Dental Materials Journal [Internet]. 2006 Jun 1 [cited 2024 Jul 30];25(2):382–90.
7. Singh R. A comparative analysis of sandblasted and acid etched and polished titanium surface on enhancement of osteogenic potential: An in vitro study. Journal of Dental Implants. 2012;2(1):15.
8. Revankar GD, Shetty R, Rao SS, Gaitonde VN. Analysis of surface roughness and hardness in titanium alloy machining with polycrystalline diamond tool under different lubricating modes. Materials Research-ibero-american Journal of Materials. 2014 Aug 15;17(4):1010–22.
9. Balza JC, Zujur D, Gil L, Subero R, E Gutiérrez Domínguez, Delvasto P, et al. Sandblasting as a surface modification technique on titanium alloys for biomedical applications: abrasive particle behavior. IOP conference series. 2013 Jun 7;45:012004–4.
10. Molitor P, Barron V, Young T. Surface treatment of titanium for adhesive bonding to polymer composites: a review. International Journal of Adhesion and Adhesives. 2001 Jan;21(2):129–36.
11. Cecilia Yan Guo, Jukka Pekka Matinlinna, James Kit-Hon Tsoi, Tin A. Residual Contaminations of Silicon-Based Glass, Alumina and Aluminum Grits on a Titanium Surface After Sandblasting. Silicon. 2015 Apr 3;11(5):2313–20.
12. Aria Wira Yuda, Sugeng Supriadi, Agung Shamsuddin Saragih. Surface modification of Ti-alloy based bone implant by sandblasting. AIP conference proceedings [Internet]. 2019 Jan 1 [cited 2024 Jul 30]; Available from: https://pubs.aip.org/aip/acp/article/2193/1/020015/889553/Surface-modification-of-Ti-alloy-based-bone
13. Jemat A, Ghazali MJ, Razali M, Otsuka Y. Surface Modifications and Their Effects on Titanium Dental Implants. BioMed Research International. 2015;2015:1–11.
14. Palanisamy S, Murugesan TM, Palaniappan M, Santulli C, Ayrilmis N. Fostering sustainability: The environmental advantages of natural fiber composite materials – a mini review. ERT. 2024;7(2):256-69.
15. Kurien, R.A., Selvaraj, D.P., Sekar, M. et al. A comprehensive review on the mechanical, physical, and thermal properties of abaca fibre for their introduction into structural polymer composites. Cellulose 30, 8643–8664 (2023). https://doi.org/10.1007/s10570-023-05441-z

16. Ramakrishnan T, Mohan Gift MD, Chitradevi S, Jegan R, Hency Jose PS, Nagaraja HN, et al. Study of Numerous Resins Used in Polymer Matrix Composite Materials. Advances in Materials Science and Engineering [Internet]. 2022 Mar 20;2022:e1088926. Available from: https://www.hindawi.com/journals/amse/2022/1088926/
17. Kazemi ME, Shanmugam L, Yang L, Yang J. A review on the hybrid titanium composite laminates (HTCLs) with focuses on surface treatments, fabrications, and mechanical properties. Composites Part A-applied Science and Manufacturing. 2020 Jan 1;128:105679–9.
18. Hussian Siyal S, Ali Jogi S, Muhammadi S, Ahmed Laghari Z, Ali Khichi S, Naseem K, et al. Mechanical Characteristics and Adhesion of Glass-Kevlar Hybrid Composites by Applying Different Ratios of Epoxy in Lamination. Coatings. 2021 Jan 15;11(1):94.
19. Hallett SR. Three-point beam impact tests on T300/914 carbon-fibre composites. Composites Science and Technology [Internet]. 2000 Jan 1 [cited 2024 Jul 30];60(1):115–24. Available from: https://www.sciencedirect.com/science/article/abs/pii/S0266353899000998
20. Gouda PSS, Kudari SK, Prabhuswamy S, Jawali D. Fracture Toughness of Glass-Carbon (0/90)s Fiber Reinforced Polymer Composite – An Experimental and Numerical Study. Journal of Minerals and Materials Characterization and Engineering [Internet]. 2011 Jun 27 [cited 2024 Jul 30];10(8):671–82. Available from: https://www.scirp.org/journal/paperinformation?paperid=20899
21. Azzam A, Li W. An experimental investigation on the three-point bending behavior of composite laminate. IOP Conference Series: Materials Science and Engineering. 2014 Aug 8;62:012016.
22. Rajesh S, Vijayaramnath B, Elanchezhian C, Vivek S, Prasadh MH, Kesavan M. Experimental Investigation of Tensile and Impact Behavior of Aramid-Natural Fiber Composite. Materials Today: Proceedings. 2019;16:699–705.
23. Genel K. Comparison of Mechanical Properties of Unidirectional and Woven Carbon, Glass and Aramid Fiber Reinforced Epoxy Composites. Acta Physica Polonica A [Internet]. 2017 Sep 1 [cited 2024 Jul 30]; Available from: https://www.academia.edu/117224965/Comparison_of_Mechanical_Properties_of_Unidirectional_and_Woven_Carbon_Glass_and_Aramid_Fiber_Reinforced_Epoxy_Composites.
24. Ramesh V, Anand P. Evaluation of mechanical properties on Kevlar/Basalt fiber reinforced hybrid composites. Materials Today: Proceedings. 2020 Jun;39(4): 1494-1496.
25. Suthan R, Jayakumar V, Madhu S. Evaluation of Mechanical Properties of Kevlar Fibre Epoxy Composites: An Experimental Study. International Journal of Vehicle Structures and Systems. 2018 Dec 31;10(6).
26. Belan J, Lenka Kuchariková, Tillová E, Mária Chalupová. Three-Point Bending Fatigue Test of TiAl6V4 Titanium Alloy at Room Temperature. Advances in Materials Science and Engineering. 2019 Sep 10;2019:1–11.
27. Mali M, Hussain AK, Muzafar MA, Zainol AFM, Mahmud J. Failure analysis of woven kevlar/epoxy composite laminates under compression due to variations in fiber orientation. Journal of Physics: Conference Series. 2019 Nov 1;1349(1):012050.
28. Oliwa R. The Mechanical Properties of Kevlar Fabric/Epoxy Composites Containing Aluminosilicates Modified with Quaternary Ammonium and Phosphonium Salts. Materials. 2020 Aug 23;13(17):3726.
29. Vasudevan A, Pandiyarajan R, Navin Kumar B, Vijayarangam J. Effect of Kevlar Ply Orientation on Mechanical Characterization of Kevlar-Glass Fiber Laminated Composites. IOP Conference Series: Materials Science and Engineering. 2020 Dec 16;988:012088.
30. Rayhan SB, Rahman MM. Modeling elastic properties of unidirectional composite materials using Ansys Material Designer. Procedia Structural Integrity. 2020;28:1892–900.
31. Ahmed PS, Fadhil BM, Mohamed AAK. Effect of Unidirectional and Woven Fibers on Impact Properties of Epoxy. Research Journal of Applied Sciences, Engineering and Technology [Internet]. 2016 [cited 2024 Jul 30];12(2):197–205. Available from: https://maxwellsci.com/jp/mspabstract.php?jid=RJASET&doi=rjaset.12.2321

32. Sheikh S. Impact Strength Analysis of Polymer Composite Materials (PCM) Fiber Reinforced in the Fiberboat Application – Material Science Research India [Internet]. [cited 2024 Jul 30]. Available from: https://www.materialsciencejournal.org/vol17no2/impact-strength-analysis-of-polymer-composite-materials-pcm-fiber-reinforced-in-the-fiberboat-application/
33. Tita V, de Carvalho J, Vandepitte D. Failure analysis of low velocity impact on thin composite laminates: Experimental and numerical approaches. Composite Structures. 2008 Jun;83(4):413–28.
34. Heimbs S, Heller S, Middendorf P. Simulation of Low Velocity Impact on Composite Plates with Compressive Preload. 2008 Jan 1;
35. Sharma RS. Design and Fabrication of Equipment for Low Velocity Impact Testing of Composite Sandwich Panels. wwwacademiaedu [Internet]. 2011 Jan 1
36. ZIKE S, KALNINS K, OZOLINS O, KNITE M. An Experimental and Numerical Study of Low Velocity Impact of Unsaturated Polyester/Glass Fibre Composite. Materials Science. 2011 Nov 24;17(4).
37. V. Balasubramani, S. Rajendra Boopathy. Damage area prediction of laminated composite plates after low velocity impact in ANSYS. 2013 Jan 1; 534-540.
38. Taraghi I, Fereidoon A, Taheri-Behrooz F. Low-velocity impact response of woven Kevlar/epoxy laminated composites reinforced with multi-walled carbon nanotubes at ambient and low temperatures. Materials & Design. 2014 Jan;53:152–8.
39. Buang ZB, Kashif SM. Simulation of Low Velocity Impact Test on Carbon/Epoxy Composite Plates. Advanced Materials Research. 2015 Jul;1115:523–6.
40. Habibah. N., Faizal. W.M., Iamie.M., Izatti.N., Hasni, N. THE DESIGN AND DEVELOPMENT DROP WEIGHT IMPACT TEST RIG PART 4. Second Integrated Design Project Conference (IDPC); December 2015. Universiti Malaysia Pahang 1-9.
41. Jen[1] MH, Cai DY, Chang CK, Hsu FC. Numerical Analysis and Experimental Verification of Ti/APC-2/Kevlar Hybrid Composite Laminates due to Low-Velocity Impact [Internet]. [cited 2024 Jul 30]. Available from: https://www.sci-en-tech.com/ICCM2018/PDFs/3117-11176-1-PB.pdf
42. Ahmad F, Abbassi F, Park MK, Hong JW. Numerical investigation to evaluate effect of fiber orientation on penetration-resistance of an aircraft composite material. Mechanics of Advanced Materials and Structures [Internet]. 2018 [cited 2024 Jul 30];26(19):1613.
43. Concli F, Gonzalez-Jimenez A, Manes A, Giglio M. Experimental testing and Numerical modelling of a Kevlar woven – epoxy matrix composite subjected to a punch test. Procedia Structural Integrity. 2019;24:3–10.
44. Wang R, Chen DD, Zhu M, Xing SL. Dynamic effects of low-velocity impact on composite plates. IOP Conference Series Materials Science and Engineering. 2019 Oct 1;657(1):012058–8.
45. Özdemir Z, Türkbas S, Yılmaz D. Low Velocity Impact Damage Response of Carbon Fiber Reinforced Composites at Low Temperatures. Dicle Üniversitesi Fen Bilimleri Enstitüsü Dergisi [Internet]. 2019 Dec 31 [cited 2024 Jul 30];8(3):35–60. Available from: https://dergipark.org.tr/en/pub/dufed/issue/50918/631485
46. Canyi H, Lina C, Hong X, Yiping Q, Qing-Qing N. A numerical study on the low-velocity impact behavior of the Twaron® fabric subjected to oblique impact. Reviews on Advanced Materials Science [Internet]. 2021 Dec 1 [cited 2024 Jul 30];60(1):980–94. Available from: https://doaj.org/article/206b76432acd4dfe95a64dcc79cfd21c
47. Mahesh V, Joladarashi S, Kulkarni SM. Comparative study on kevlar/carbon epoxy face sheets with rubber core sandwich composite for low velocity impact response: FE approach. Materials Today: Proceedings. 2021;44:1495–9.
48. Roberts GD, Revilock DM, Binienda WK, Nie WZ, Mackenzie SB, Todd KB. Impact Testing and Analysis of Composites for Aircraft Engine Fan Cases. Journal of Aerospace Engineering [Internet]. 2002 Jul;15(3):104–10. Available from: https://ntrs.nasa.gov/api/citations/20020061387/downloads/20020061387.pdf
49. Karahan M. Comparison of Ballistic Performance and Energy Absorption Capabilities of Woven and Unidirectional Aramid Fabrics. Textile Research Journal. 2008 Aug;78(8):718–30.

50. Kumar S, Durga Shankar Gupta, Singh I, Sharma A. Behavior of Kevlar/Epoxy Composite Plates Under Ballistic Impact. Journal of Reinforced Plastics and Composites. 2009 Sep 8;29(13):2048–64.
51. Ali A, Shaker ZR, Khalina A, Sapuan SM. Development of Anti-Ballistic Board from Ramie Fiber. Polymer-Plastics Technology and Engineering. 2011 Apr 13;50(6):622–34.
52. Sikarwar R, Velmurugan R, Madhu V. Experimental and analytical study of high velocity impact on Kevlar/Epoxy composite plates. Open Engineering. 2012 Jan 1;2(4).
53. Ramadhan AA, Abu Talib AR, Mohd Rafie AS, Zahari R. High velocity impact response of Kevlar-29/epoxy and 6061-T6 aluminum laminated panels. Materials & Design [Internet]. 2013 Jan 1;43:307–21. Available from: https://www.sciencedirect.com/science/article/pii/S0261306912004074
54. Kamel H, Harraz O, Yacoub M. Developing a Custom Anthropometric Test Device for Experimental Evaluation of Blast Mitigation Seats. International Journal of Automotive and Mechanical Engineering. 2021 Mar 2;18(1)
55. Soydan AM, Tunaboylu B, Elsabagh AG, Sarı AK, Akdeniz R. Simulation and Experimental Tests of Ballistic Impact on Composite Laminate Armor. Advances in Materials Science and Engineering. 2018 Aug 23;2018:1–12.
56. J. Jensin Joshua, Singh D, Y. Murali Krishna, P. Sivaprakasam, D. Raja Joseph, Venkatanarayanan PS. Estimation of Impact Strength of Kevlar/Basalt and Kevlar/Glass Interwoven Composite Laminate after High-Velocity Bullet Impact. Advances in Materials Science and Engineering. 2023 Nov 20;2023:1–8.
57. Hu Y, He Z, Xuan H. Impact Resistance Study of Three-Dimensional Orthogonal Carbon Fibers/BMI Resin Woven Composites. Materials. 2020 Oct 1;13(19):4376.
58. Narendiranath BT, Singh AP, Reddy NS, Murpani D. SIMULATION OF BALLISTIC IMPACT ON DIFFERENT COMPOSITE SAMPLES OF BULLET PROOF VEST. IOP Conference Series: Materials Science and Engineering. 2021 Apr 1;1123(1):012030.
59. Zhu Z, Li X, Yang R, Xie W, Zhang D. The energy dissipation mechanism of bi-metal Kevlar\titanium fiber metal laminate under high-velocity impact. European Journal of Mechanics - A/Solids. 2023 Jul 1;100:104956–6.
60. Giannopoulos IK, Mehdi Yasaee, Nikolaos Maropakis. Ballistic Impact and Virtual Testing of Woven FRP Laminates. Journal of composites science. 2021 Apr 22;5(5):115–5.
61. Madika B, Syahrial AZ. Study of aluminum/kevlar fiber composite laminate with and without TiC nanoparticle impregnation and aluminum/carbon fiber composite laminate for anti-ballistic materials. International Journal of Lightweight Materials and Manufacture [Internet]. 2024 Jan 1 [cited 2024 Feb 28];7(1):62–71.
62. Patterson BA, Busch CE, Bratcher M, Cline J, Harris DE, Masser KA, et al. Influence of temperature dependent matrix properties on the high-rate impact performance of thin glass fiber reinforced composites. Composites Part B: Engineering. 2020 Jul 1;192:108009–9.
63. Li X, Zhang X, Guo Y, Shim VPW, Yang J, Chai GB. Influence of fiber type on the impact response of titanium-based fiber-metal laminates. International Journal of Impact Engineering. 2018 Apr;114:32–42.
64. Stephen C, Mourad Abdel-HamidI, Shivamurthy B, Selvam R. Energy absorption and damage assessment of non-hybrid and hybrid fabric epoxy composite laminates: experimental and numerical study. Journal of Materials Research and Technology. 2021 Sep;14:3080–91.

