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Hybrid Laminates: Advancements in Multi-Material Machining Processes for Fiber Metal Laminates (FML) - A Comprehensive Review

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***Abstract* :**Hybrid laminates, particularly Fiber Metal Laminates (FML), have gained significant attention in recent years due to their unique combination of structural strength, lightweight properties, and durability. This comprehensive review explores the advancements in multi-material machining processes specific to FML, shedding light on the evolving landscape of hybrid laminates used in automobile, aircraft, and structural engineering applications. The study encompasses an in-depth analysis of the state-of-the-art technologies, methodologies, and materials utilized in the fabrication of FML, emphasizing the importance of integrating diverse materials for enhanced mechanical and thermal performance. The review spans from traditional machining techniques to cutting-edge technologies such as additive manufacturing and laser processing, providing insights into the challenges and opportunities associated with each method. Furthermore, the review addresses the implications of hybrid laminates in optimizing the design, manufacturing, and performance of complex structures. By synthesizing information from recent research, this review contributes to a holistic understanding of the advancements in FML machining processes, paving the way for future innovations in the field of multi-material laminates.

Keywords: FML, Multi-Material Machining Processes, fiber, hybrid laminates, strength, composite material

Introduction

Hybrid laminates, as a class of composite materials, have emerged as a promising avenue in the realm of structural engineering due to their unique combination of diverse fiber reinforcements[1]. These laminates, composed of different types of fibers and matrix materials, demonstrate better mechanical qualities than their single-material counterparts. Among the essential mechanical characteristics, tensile properties play a pivotal function in establishing the content's suitability for various engineering applications. Tensile strength, modulus, and elongation are critical parameters that influence the overall performance and reliability of hybrid laminates in real-world scenarios[2]. The development of composite materials has reached new heights with the advent and refinement of hybrid laminates. Hybrid laminates represent a sophisticated evolution in composite technology, combining multiple types of fibers and matrices to create materials with tailored and synergistic properties[3]. This innovative approach aims to harness the strengths of individual components while mitigating their respective weaknesses, offering enhanced performance and versatility[4]. The design and manufacturing of hybrid laminates involve meticulous considerations of fiber types, orientations, and matrix materials[5]. By carefully selecting and combining different components, engineers can tailor the mechanical, thermal, and chemical properties of the composite to meet specific performance requirements[6]. For instance, the incorporation of high-strength fibers with high-impact resistance fibers can result in laminates that exhibit a balanced combination of strength and toughness[7].

1.1. materials

Because of their better qualities over other material families, composite materials have attracted substantial attention in the last several decades, especially in the aerospace sector, but there is also major interest in the automobile industry. This trend began with military application advances after World War II, whereby materials with improved fatigue and corrosion resistance were also able to decrease structural weight[8],[9].

Fiber-reinforced polymers, sometimes referred to as CFRPs, being heterogeneous composite materials made of glass, carbon, and aramid, which are lightweight, stiff, along with brittle reinforcing fibres. These fibres are joined by a polymeric matrix, which may be thermoset or thermoplastic[9]. The fibres, or phase of reinforcement, help to improve the The matrix influences the apparatus characteristics concerning reinforced composites material. shifts the weight to the interior fibres while also protecting protecting them from outside harm and contributing to the high fracture toughness of the composite material [10].

Composite laminates with an epoxy matrix strengthened by two different kinds of reinforcement (glass and carbon) were the materials employed in this investigation[11]. These components are supplied by Boeing and meant for use in aviation applications; their excellent performance supports their selection for this job[12]. The carbon reinforcements (Figs. 1) are made of glass and plain fabric, respectively, with corresponding areal weights of 106 g/m2 and 193 g/m2. Figs. 1 show Micrographs by SEM of the interlacing thread type between the weave and warp. In accordance with the supplier's guidelines, the matrix Epocast 50-A1/946 (BMS 8-201) is formulated through a 15% hardener-to-epocast mixture.[13]. Three systems were created using hand lay-up: G/E (glass/epoxy) and C/E (carbon/epoxy), and C/G/E (glass/carbon/epoxy). (Figs. 1). It involves laying each of the reinforcing fabrics separately in an open mould and impregnating them using resin in order to overlay the plies. After the stack is carefully covered, a vacuum pump is utilised to drain the excess resin and eliminate air bubbles before the curing process is completed in room temperature air. Plates with a regulated quantity of resin and a lower porosity rate can be produced using this procedure. The orientation of the laminates is parallel with their loading axis and in the exact same direction (0°). Fig. 1 is an example of the stacking procedure for hybrid laminates made up of eight plies.

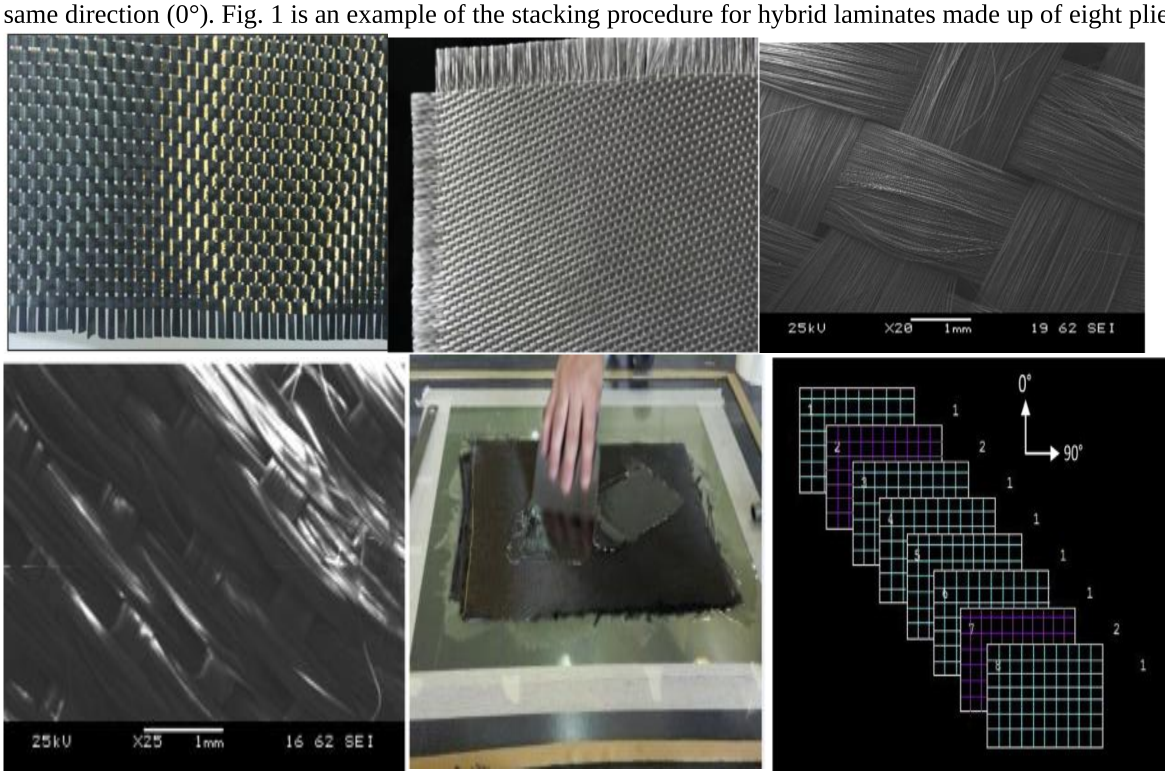

Fig 1. Fabric Materials

Source: [14]

Materials used in the iinclude readily accessible DOW Airstone epoxy resin (760E/766H). Carbon fibre, glass fibre rovings, and a commercially available carbon/glass composite fabric are utilised as reinforcing elements. Raw material resources consist of Young's modulus-compliant glass fibre and carbon fibre rovings from Zoltek Panex 35 (50K tow) segments from PPG Hybon 2026 (2400 tex). in tension of 82.7 GPa and 242 GPa, respectively, and blended textiles sourced via Devold AMT AS - Norway. The proportion of total fibre volume in the composites was about 50%[15].

Because of their superior features, including Composite materials are renowned for their remarkable dynamic real estate, high strength-to-weight ratios, and corrosion resistance. major significance in engineering applications[16]. For fiber-reinforced composites, damping is crucial since it prolongs the structures' service life while lowering noise and vibration levels. Enhancing the damping properties of lightweight structural material composites is especially important in order to make better use of them in the development of outstanding durability machineries and structures[17]. The damping behaviour of fibre-reinforced hybrid along with non-hybrid composite materials has drawn the attention of several researchers. presented an overview of the literature upon damping in fibre-reinforced composite components and frameworks, gathering key research on enhanced laminate damping, better thick laminate damping models, and optimised resonance in structures and composites made with fibres [18]. They came to the conclusion that laminated composites' dynamic performance might be enhanced by structural optimisation through dampening. Furthermore, the damping mechanism of composite materials is subject to many damping processes, including the viscoelastic nature of the transition dampness, matrices and/or fibres supplies, or damage-induced damping[19]. investigated the turbulence and stable mechanics of the densely mixed, irregularly oriented short Bonded banana/sisal mixed fibre structures. [20]. The Modulus of dynamic properties (storage) during dampening action) and structural features (tension, flexible, and impact capabilities) were described as functions of the total strand volume portion and the relative volume portions.[21]. They provided evidence that it is feasible to manufacture composites that are both cost-effective and manageable. with the ideal degree of elasticity and absorption qualities by hybridising banana and sisal fibres. [22]. The primary contribution of this study is the incorporation of hybridization effects into the analysis of the tensile and damping behaviour of Kevlar/S-glass/epoxy hybrid composites.. In order to illustrate the effects by hybridization based on fibre composition, from complete Kevlar is laminated to glass/epoxy. laminates, the proportion of Kevlar fibres in the laminate was enhanced. alone.[23]. The purpose of this attempt is to minimise the cost of entire Kevlar/epoxy compounds while simultaneously increasing the shear along with vibration damping properties of S-glass fibres via the combination of Kevlar fibres. The tension and acoustic traits of hybrid composite laminates were ascertained through experimental measurements and comparisons with non-hybrid laminated material. The logarithmic decay technique was utilised to ascertain the distribution of the samples' vibration damping capabilities in each case.[24].

FML

Despite this, the advancement of metal-fiber laminates allowed for the further improvement of these materials' characteristics in order to make them more resilient to the more extreme environments encountered in aircraft[25]. By definition, These are hybrid constructions that alternating FRP phases in the form of layers with tiny metal composition layers, often titanium (FRP/Ti) or aluminium (FRP/Al)[26],[27].

For most industrial and structural applications, the three most essential factors in Specific material selection criteria include cost, weight, and resilience. FML (fiber-metal laminate) is a hybrid composite material. construction composed of plastic layers reinforced with fibres sandwiched between metal layers. Currently, the metals utilised include aluminium, magnesium, and titanium, cemented laminate with fibres of carbon, glass fibre, or aramid fibres - comprising the fiber-reinforced layer. As depicted in the figure below, Fiber-Metal Laminates (FMLs) consist of metal and fiber-reinforced composite layers that alternate.. Owing to the hybrid nature of the two components (metal and fibre), FMLs offer superior mechanical properties over standard composite lamina, including outstanding corrosion resistance and a remarkable strength-to-weight ratio.[28]. The first fibre metal laminates (FMLs), also known as Reinforced aluminium laminates with aramid (ARALL), were produced in the 1980s at the Delft University of Technology. Aluminium laminates reinforced with carbon fibre and glass fibre are being developed to enhance the mechanical qualities of FMLs. These laminates comprise of alternating unidirectional composite prepregs to fuse together thin, Strong strips of aluminium alloy (usually 0.3–0.5 mm thick). Glass, carbon, or aramid fibres combined with epoxy resin are used to form composites called prepregs.[29].

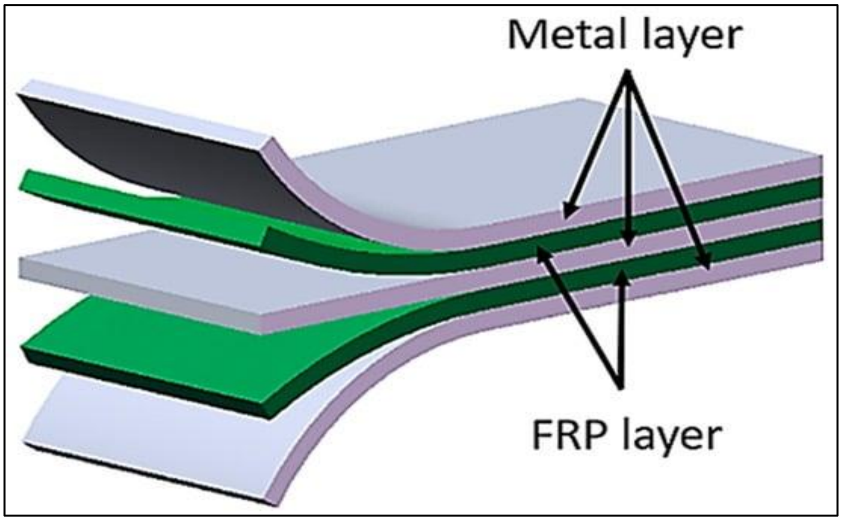

Fig. 1 Typical Fiber Metal laminates[30]

Fig. 2 determines the FML categorization according to metal plies. The two most widely used FMLs on the market are GLARE1, which is founded on fibres of glass with great strength, and ARALL1, which is based on aramid fibres.

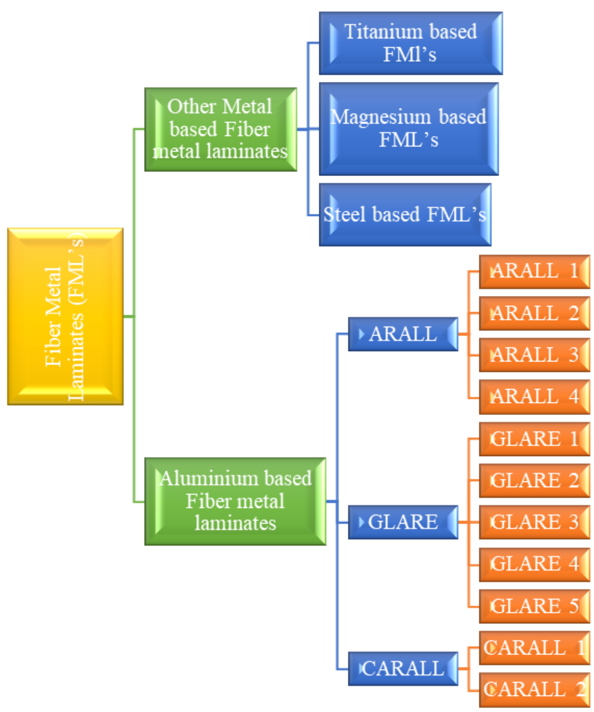

Fig 2: Typical Classes of FML's

Source:[31]

FMLs combine the remarkable particular qualities, fatigue in addition to fracture resistance, and simplicity of manufacture of metal alloys with the strength as well as durability of high-performance composite materials[32],[33]. In addition, metals are weak in fatigue strength along with resistant to corrosion, while composites are weak in impact along with bearing strength in addition to the serviceability problem[34]. Consequently, the two elements work together to overcome their own shortcomings. The end product is a portable, extremely strong metal with outstanding mechanical, both tribological and thermal characteristics [35].

Literature Review

The process of manufacturing Using many materials is challenging. since the materials to be coupled have different characteristics and relatively poor adhesion[36],[37],[38],[39]. Additionally, surface treatments may be used to enhance adhesion along the metal-composite interface[40],[41],[42],[43]. For the composite laminates to form a strong mechanical along with adhesive contact with metal surfaces, the metallic layer must be properly surface treated. This treatment can be chemical, where an acidic solution is used to remove undesirable oxide layers from the substrate and form a macro-roughened surface; or electrochemical in nature, where a dry surface or coupling agent is utilised, such in plasma-sprayed coating or ion-beam accelerated deposition[43]. Metal sheets may be annealed after treatment to reduce heat and mechanical stresses, which promotes adhesion[44].

The most popular technique for achieving the required configuration is chemical bonding, or fusion—the joining of two materials together using structural glue[45],[46],[47], mechanical along with physical joining, such riveting or screwing [39], and connecting procedures based on friction [48]. A few of the processing methods used to create Carbon Fibre Reinforced Metal Matrix Composites are shown in the picture below.

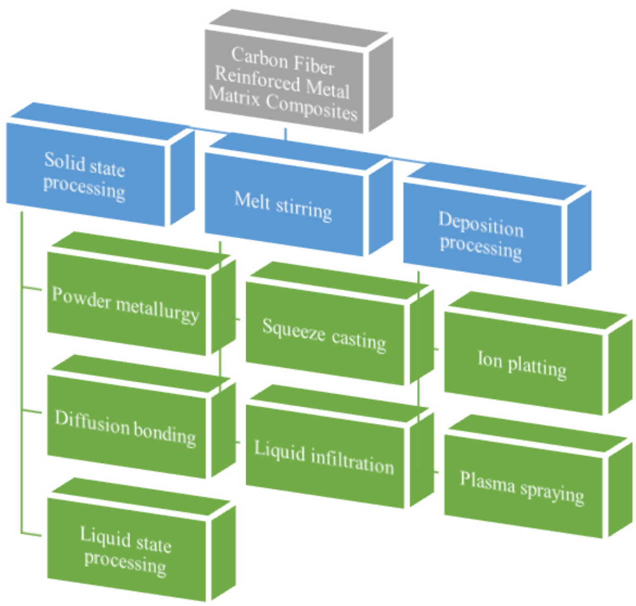

Figure 3. Processing methods for fabrication of CF/MMCs

Source: [35]

The methods shown may differ in kind. Composites are produced in solid-state processing as a result of mutual diffusing in solid states at elevated conditions of pressure and temperature, which bonds the carbon fibre to the metallic matrix. Among the liquid-based metallurgical processes are casting, gravity, along with vacuum infiltration. Fast processing times, a high fibre content, along with a low cost are the benefits of this technique; nevertheless, because of the significant density differences, the carbon fibres were prone to break and float on the top. Lastly, the deposition process comprises consolidating the final product after using various techniques to deposit the matrix on the fibres[35].

Forming procedures are among the additional manufacturing processes[49],[50], utilising a mix of optimised inside glass fibre patches along with non-cured FMLs, in which the metal levels are plastically bent by deep drawing and the cured fibre along with resin matrix levels are elasticity deformed[51],[52], along with vacuum infusion, which does not need a press or autoclave [53],[54].

The metal surfaces of CFRP/Al as well as CFRP/Ti stacks are prepared beforehand to provide adequate adhesion of the alloy as well as epoxy resin. After that, they are heated to a high temperature in a hot press to achieve their ultimate form, in which the metallic layers and adhesive-impregnated fibre prepress effectively fuse[8].

Due to its better qualities, which allow it to outperform other material families in certain applications, the multi-material is essential to the production of aeroplanes[55]. Critical structural components of aircraft, including floor beams, frames panels, together with a large percentage of the tail parts, are made of CFRP composites[56]. Moreover, composites make up 25% of the Airbus A380 aircraft, of which 22% are polymers reinforced with carbon or glass fibre and 3% are GLARE[57]. When GLARE was used in place of aluminium panels alone inside the higher fuselage shell for the Airbus A380, weight savings of 15–30% were achieved, along with notable improvements in fatigue characteristics[58]. Think about the commercial Boeing aircraft: 30% of the Boeing 767's outer structure is built of composites, whereas almost 57% of the Boeing B-787's primary structure is constructed completely of composite materials, providing it its vast range of flexibility. Similarly, CFRP is utilised to make The compressor cooling section's rotors as well as fan casings, such are often found in aircraft engines. This reduces the whole assembly weight about 180 kg as well as operational costs by 20%[59],[60]. Moreover, CARALL is used to cushion shocks in aeroplane seats along with helicopter struts. This FML offers outstanding Because of their exceptional impact qualities, CARALL layers have a high durability and rigidity. perfect for use in space applications. pressure intensity, energy absorption capacity, and resistance to fatigue fracture formation[61]. CARALL laminates benefit from their high rigidity and strength, as well as their superior impact properties, making them ideal for space applications[8].

The usage of these materials benefits not only the aeronautic industry, but also the car sector[62],[63]. Future automobile generations' lower CO_2 emissions and reduced fuel use are the main causes of this. Using CFRP prepregs with compounds of strong metal within the FML offers a possible way to make lightweight automobile chassis with a high stiffness-to-weight ratio[51]. In an automobile chassis, for instance, CFRP is useful if the chassis must be made of light, rigid aluminium with controlled deformation[64]. Additionally, metal-fiber composite hybrid components may be used to improve automobile parts' NVH (noise, vibration, and harshness) efficiency, which will improve driving, due to FRP's strong damping along with vibration resistance[65].

Table 1. Advantage of fiber metal laminates

Key Parameters	Ref.	Details
High strength	[66]	FMLs are composite structures composed of fiber-reinforced polymeric materials and thin metal alloy sheets.. FMLs with high strength and stiffness are made from metal and fibre reinforced composites.
Low density	[25]	It has a low density because it has thin layers of metal and composite piles. So, as compared to other structural materials, FMLs are lighter.
Excellent corrosion resistance	[67]	Because of their polymer base, FMLs offer excellent resistance to moisture along with exceptional resistance to corrosion.
Excellent	[68]	Even under very harsh conditions, the absorption of moisture

moisture resistance		FML composites exhibit reduced speed in comparison to polymer composites on account of the presence of metal layers. over the exterior surface. Pregreg layers inside the FMLs may also serve as moisture barriers amongst the various aluminium layers.
High fatigue resistance	[66]	Because the unbroken bridging fibres following the break limit the opening of the crack, it offers good fatigue resistance. FMLs offer superior fatigue properties over traditional metals and composites.
High energy absorbing capacity	[25]	According to inquiry results, FMLs absorb substantial energy via localised fibre breakage and metal ply shear failure.
High impact resistance	[68]	When opposed to composites, impact deformation is really one of the main advantages of FMLs.

The above features of FMLs are widely used in aerospace and automotive applications. The majority of businesses are now looking at aluminium components composed of FML composites. The aircraft manufacturing sector now uses laminates called ARALL along with GLARE as structural materials. The Airbus A380 is one aircraft that successfully uses fibre metal laminates[66].

2.1 Manufacturing of Fiber Meta Laminates (FML):

As with polymeric composite materials, the most typical process for producing FMLs involves autoclaves methodology. The whole creation of FML's composite involves the following main phases[69],[70],[8].

- In order to enhance the adhesion between the metal surface and the adhesive system, this process involves pre-treating the metal layer's surface with a corrosive solution such as phosphoric or chromic acid.
- Consistently apply resin utilising hand layup to metal plates as well as reinforced materials such as carbon fibre or glass. providing constant pressure with a hoover bag or an inflatable moulding machine.
- Following that, the cure phase starts, including the bind between both fiber/metal layers, chemical curing reactions, as well as the flow-consolidation process.
- Inspection is the next stage, which is often carried out with the use of mechanical testing, optical methods, X-rays, and ultrasound. Usually, the object is bagged during the cure preparation stage, and other supplementary ingredients are used.

Below figure depicts the usual cure preparation configurations, which include the component, tool, and bagging.

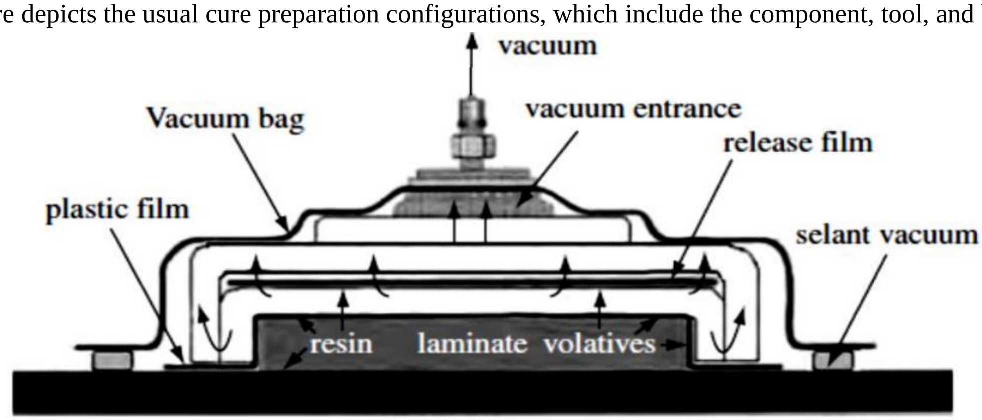

Fig 3. Schematic Representation of Vacuum bag system[28]

2.1.1 Multi-Material Process Preparation

FMLs are produced by an autoclave procedure, much as polymer composites. To create an FML, you need to follow six steps: Prepare the surface of sheet metal (i), deposit material (ii) (prepreg and metal layers), clean the mould and prepare the hoover bag (iii), cure (iv), stretch (v) and inspect (vi), usually using imaging methods and mechanical testing[8].

A FML with exceptional mechanical quality requires careful execution of each of these steps, which is reliant on the appropriate Selecting and implementing material preparation techniques. A major problem in composite constructions is the possibility of a delamination process due to a poor interfacial connection among the prepreg along with the metal. Thus, to increase the strength of the bonds between the materials., the proper surface treatment is required[65].

Adhesive bonding techniques, including dry, linking an agent, biological, and electrical, along with mechanical surface treatments, may be used alone or in combination to create an FML. The surface topography, surface roughness, and the bonding site and metal interaction are all changed by various surface treatments[39].

A single technique was used to apply certain surface treatments. Kwon et al. implemented a combination of three distinct varieties of abrasive. varied sanding durations in their single mechanical surface treatment method. They discovered that longer sanding times enhanced mechanical adherence of the composite to the metal while increasing surface energy. Drozdziel-Jurkiewicz et al. investigated Aqueous surface preparations for titanium and aluminium that produced high adhesion over the metal-composite interface by using mechanical, chemical, along with electrochemical techniques. These surface treatments provide excellent adhesion across the FML interface, strengthen the connection, and raise the interfacial fracture resistance of the FML[40]. According to the study, Anodization with chromic acid remains the most efficient method. way to increase anticipated bond strength. The first method, mechanical abrasion, was used by Thirukumaran et al. to remove an unwanted oxide layer and create a roughened macro-surface. The chemical process, often referred to as acid etching, was next examined using potassium dichromate along with ferric sulphate, two distinct solutions[65]. Greater tensile strength readings indicate that the ferrous sulphate treatment, which contains SO42e ions, improved performance by advocating for pitting, which improved the condition of roughness and promoted strong adhesion amongst The outer layers of substrates.

In the production of FML, aluminium sheets are subjected to surface treatment that includes laser and plasma procedures. Dieckhof et al. discovered that both treatments produced an ordered anodic oxide layer on AA2024 and AA5028 sheets, which enhanced interfacial adhesion and corrosion resistance.[71]**. Park et al.** Mechanical abrasion was utilised to prepare the metal surface prior to employing Techniques for phosphorus anodizing and alkali etching with acids. [72]. Additionally, they found that in order to increase the strength of binding at the point of the metal sheet-prepreg interaction, rough substrates were necessary. They also found that use different autoclave pressures might have an impact on the FML's quality by reducing void content and delaying early failure. Moreover, Cheng and colleagues optimized the pore-forming process with an aluminium substrate. Three distinct electrolytes were used to chemically treat the metal surfaces; these electrolytes comprised SO42e ions together with oxalic acid along with ferrous sulphate. For interfacial bridging along with ultimate bond strength, they used CNTs, which improved the composite's adherence to the metal sheet. They discovered that at the bonded junction, a A substrate surface with a coarser texture may facilitate enhanced moisture, contact area, and overall dynamic occlusion. [73].

The optimum approach to achieve excellent surface preparation, according to an analysis of the surface treatment procedure for aluminium alloy documented in the literature, is to combine mechanical and electrochemical techniques. great mechanical interlock and great interfacial adhesion are the results of appropriate surface preparation, as all of the examined publications showed. This ensures that the FML is of a high enough grade to be machined instead of delamination operations.

2.1.2 Numerical Simulation Applied to FML Machining

It is numerical simulation. a cost-effective option for product or process development. Since the The use of numerical simulations accounts for acquisition, maintenance, along with man-hours per machine, the cost of equipment along with man-hours is less than that of lubrication operations, finishing, and final product certification. If numerical simulation is performed in advance of experimental testing, it may help save costs by reducing the number of tests while also improving the accuracy of parameter selection. Additionally, by predicting the effects of temperature and cutting forces, numerical simulation could be used to get a deeper understanding of the mechanism behind the machining process.

Adequate processing parameter design is necessary for the FML machining procedure in the aviation industry in order to limit defects caused by the process temperature change and avoid the development of various challenges that might compromise the strength of the components. These factors, which include matrix burning, fibre extraction, in addition delamination, become increasingly significant during dry machining.

Reference	Code or Software	Type of metal and Fiber	Key aspects/features
[74]	ANSYS	ARALL and GLARE	examined the flexural and tensile strengths of GLARE and ARALL
[75]	The ABIAS/ANSYS	Carbon, Al, and Mg; natural jute fibre	In Laminate made of carbon reinforced aluminium, jute, a natural fibre, takes the place of some carbon fibre (CAJRALL). Additionally, an effort is made in CAJRALL to switch out aluminium with magnesium metal.
[76]	The ABAQUS	Al/GFRP	Subroutine VUMAT was used to create a comprehensive 3D stress-based Hashin failure criterion, accounting for the damage phenomena of composite materials, and the Johnson cook damages equation for metal layers.
[77]	The ABAQUS	Titanium/GFRP hybrid	Examine the adhesive layer using an explicit numerical model situated among the metal along with composite layers. Additionally, each metal face's consequences of internal and exterior damage were assessed.
[78]	The ABAQUS	Al 2024-T3/Glass and Mg AZ31B-H24 /Glass	talks about FMLs' impact resistance. Two factors, namely the kind of metal along with its thickness throughout a laminate, have been researched in relation to the impact behaviour of these materials.
[79]	The ABAQUS	2024-O Al alloy /woven glass fiber prepreg	A numerical analysis was conducted to examine the impact position, impactor size, and target size. Some of the crucial factors in this simulation include contact among the stacked layers, surface-to-surface interaction involving the impactor including the target, tensile including shear failure criteria over metal layers, along with 2D Hashin failure

			criteria over composite layers.
[80]	LSDYNA	Al/GFRP	Shell components were used to represent glass-based multilayered FML, and adequate damage criteria were used to specify intra- along with inter-laminar failure. Study conducted in order to measure the extent along with severity of the damage
[81]	The ABAQUS	Al/ Carbon fiber	A numerical analysis was conducted using the 2-D stress-based Hashin damaged model for composites layer to illustrate the influence of various impact energy on carbon based FML.
[82]	The ABAQUS	Al/GFRP	Emphasise the value of solid components over continuum shell elements. Numerical simulation was used to highlight the considerable influence of the 3D Hashin failure criterion over its 2D counterpart at low velocities.
[52]	The ABAQUS	Al alloy/(PP)fiber	It was possible to recreate thermoplastic-based FML using elastic-plastic metal layers including an isotropic composite layer.

Machining Al/GFRP dry (GLARE) along with Al/CFRP (CARALL), Parodo et al. kept an eye on the tool's and the workpiece's temperature. Investigations were conducted on how cutting speed affected temperature patterns. In order to study the in addition to developing the temperature development procedure during drilling, a numerical model was produced. Furthermore, it was illustrated through numerical simulation that Temperature fields consist of influenced through the temperature characteristics of carbon dioxide composite glass filaments. The Temperature characteristics in the CARALL exhibited a more uniform appearance in comparison to those in the GLARE.[83]. Analytical modelling and experimental techniques were utilised by Giasin et al. to investigate the mechanical properties of GLARE laminates. The parameters selected What were the impact of spindle speed and feed rate on cutting forces and hole quality?.[58]. Additionally, a 3D FE model was developed to aid comprehension of the GLARE drilling operation. By comparing the torque and thrust force data that were gathered in order to assess the effectiveness of the numerical model, it was demonstrated that the finite element drilling simulation is capable of forecasting cutting forces with reasonable accuracy. It was the inaugural inclusion in the simulation of the FML drilling procedure. Using experimental data and numerical models, The impact of tool geometry and machining parameters on cutting actions, hole quality, and the CFRP/Al contact was investigated by Zitoune et al..[84]. The tool-enhanced form produced less thrust force compared the standard one, according to the experimental study. The plastic behaviour of aluminium under isotropic hardening and Linear fracture (LAB) mechanics of CFRP served as the foundation for the numerical analysis. The results showed that the critical force of thrust as a consequence of aluminium thickness was responsible for the final layer's delamination, whereas the highest shear force being a measure of aluminium thickness was predicted to be responsible for the CFRP/Al interface's separation.

Kim et al. presented a technique for determining the optimal input direction and predicting cutting force simulations. In this investigation, a CFRP with six distinct absolute fibre orientation angles was utilised. It is feasible to modify the fibre cutting angle by adjusting the input direction, a factor that significantly impacts the cutting properties of the material. By making a straightforward modification to the feed direction angle, this technique successfully diminishes the cutting force employed during material milling. Furthermore, by employing a predictive force of cutting model, it becomes feasible to determine the optimal feed direction for diverse cutting scenarios with limited experimental effort.[59].

In the form of numerical simulation pertaining to the process of excavating procedure is a comparatively recent area of research within the machining process, further investigation is warranted. The impact of an instrument shape with regard to reducing forces and material delamination in the process has been investigated by a number of authors. However, limited attention is given by authors to the impact of temperature fluctuations in profiles on the properties of the material, the functionality of the instrument, and the potential for harnessing them in the investigation of innovative, eco-friendly lubricants.

2.1.3 Multi-Material Machining Processes

On composites, typical machining operations including turning, milling, and piercing, along with water jet cutting may be used, provided that the right tool design and operation conditions are followed. Because of its highly abrasive components, anisotropic characteristics, and non-uniform structure, an FML is challenging to machine. Degradation of laminates due to these processes often results in fibre Splitting, breaking down, and structural fracture, fibre failure or pullout, including excessive wear on the cutting tools[85],[86].

The FML is employed in the aerospace sector because it is lightweight and stable at high temperatures. Numerous cut-outs and holes must be constructed in these composite structures. As previously stated, FMLs are made up of a metal, aluminium, or titanium sheet reinforced with composite, carbon, or glass fibres, in addition to a thermoplastic or thermoset matrix. Drilling aluminium calls for a balance between speed and feed, whereas drilling composites needs high speed while requiring little feed. Drilling titanium calls for low speed as well as high feed. According to the materials' constituent qualities, which vary according on the ambient conditions, choosing the right parameters and methods is thus the most challenging part of drilling the FML.

Kumar et al. investigated The versatility of aluminium stack wood laminates that are hybrid titan/carbon fiber-reinforced polymer/titanium drilling force in a single stroke under cryogenic and arid conditions. The findings illustrate that elevated thrust force is accompanied by diminished hole quality due to the hardening of the Sheets of Metal at cold temperatures.[87]. Azwan et al. examined how the strength of composite components was affected by a number of drilling settings on FMLs, including drilling speed, rate of feed, as well as thickness. They discovered that drilling using a higher speed along with the identical feed rate requires less effort than drilling using a lower spindle speed along with feed rate. The higher effort associated with the thicker FML is in contrast to the narrower one[88]. Zitoune et al. investigated the impact of different cutting parameters on the quality, thrust, torque, and fragment production during the drilling process of a CFRP/Al stack. In comparison to CFRP drilling at a low feed rate, they discovered that thrust force and torque generated during Al drilling are double. As feed rate increases, both surface irregularity and hole circularity increase. The aluminium layer has a more refined appearance than the CFRP layer.[89].

Another common machining technique for creating holes in aeroplane components is milling. Rotary cutters are used utilising a cutter to eliminate material from a workpiece during the milling procedure. Helical milling, a process that creates holes by rotating a milling tool in a helical pattern, is the inspiration for this technique, which is employed in lieu of conventional twist drills to pierce these connections.[90] Further investigation has been conducted on helical milling as a means to generate perforations in FMLs. It offers a multitude of advantages, such as reduced cutting forces, diminished heat generation, and uncomplicated chip evacuation.. [91]. Drilling, as opposed to helical milling, defines the hole through a The intersection of the width of the instrument as well as its curved path, thereby providing increased circumference elasticity of the opening. Conversely, the diameter of the cavity in drilling is exclusively determined by the diameter of the instrument.[92].

Because titanium sheets are strong and CFRP has abrasive qualities, two compounds utilised in the aerospace industry that are challenging to process are unidirectional CFRP and Ti6Al4V. They found variations in diameter, which might be related in regard to the various Young's moduli of CFRP including titanium, and variations in surface unevenness resulting from crystal formation processes particular to the materials[90]. Hemant et alexamined the GLARE laminates' helical hole milling procedure[93]. Despite the fact that the dimensions and materials were different from those used in [90], Similar process variations were observed for surface roughness, production of discontinuous powdery chips, along with hole diameter alterations based on the material layer. The settings of the milling process must be adjusted to provide holes with constant diameters Persisting in their entirety, cracks in the metal zone, minimal surface roughness, and a composite layer free of delamination in order to create a finished product of exceptional quality.

- **Comparison of Drilling and Milling Processes Parameters**

The diverse characteristics of the components found in FMLs complicate the process of creating holes. Weak numerical quality, weak quality of the surface, inaccurate dimensions, or a full element failure may result irrespective of the method and process parameters.[94].

But there are a number of interconnected aspects. Ingredients, shaping power, and tool design, Analysis of Coverings, or, crystal construction, instrument fatigue, and hole metrics including hole size along with circularity error, surface roughness, along with burr formation are the most significant factors affecting material the ability to be machine[95]. Bolar et al. contrasted the two methods of creating holes in CARALL, which are milling and drilling. In their research, they assessed the two hole-making methods using a range of performance indicators, such as burr size, Thrust, radial force, surface irregularity, chip morphology, and hole diameter precision [94]. After In contrast, the results, the scientists discovered several advantages regarding the Circular cutting of holes procedure with regard to diminished propulsion and radial force. Simple chip evacuation, heat dissipation, and intermittent cutting all helped to reduce the temperature and avoid material damage. The helical milling procedure produced discontinuous aluminium chips that were beneficial because the holes had a greater surface polish. But in helical milling, over-axial feed led to tool clatter and distortion, which degraded surface quality. Microscopic examination of the machining surface demonstrated that the use of conventional drilling caused the delamination process. Conversely, the hole that was helically machined was devoid of these imperfections and displayed no breakdown indicators.. Additionally, they discovered that the production of sizable holes following the hole drilling procedure was really noteworthy. Finally, since helical milling produced less force and heat effect, the exit burr height was much lower. After taking into account all of the previously mentioned aspects, it makes sense to determine that helical milling provides a suitable technique for creating holes in FMLs.

Barman et al. conducted a comparison study between milling and drilling. They assessed the two-hole machining procedure on Ti6Al4V titanium alloy material[92]. Machining trials were performed with consideration given to thrust force, opening diameter, surface imperfection, and machining temperature. Burr formation and the morphology of the fragments produced were also examined. During the milling process, the cutting temperature and force components (radial and thrust) were reduced, leading to a consistent flow of powdered fragments that easily dissipated without causing any damage to the surface of the machined cavity. Helicoidal milling produces holes devoid of burrs, exhibiting enhanced hole quality and diameter in comparison to drilling. Prior to this study, Iyer et al. utilised tool drilling and helical milling to process AISI D2 tool steel.[96]. In comparison to drilling, they discovered that helical milling produced holes of H7 grade and exceptional surface roughness. Another comparison investigation was conducted by Wang et al. about the helical milling of a CFRP/Ti stack with a higher thickness and its individual layers[26]. The findings of their experiments indicated that the cutting pressures increased with the amount of holes due to material type and tool wear. In fact, the cutting force increased due to the CFRP's abrasive nature. The hole surface quality of the titanium alloy is good throughout the machining process, along with tool delamination is noted at the tool entry and exit locations in the material, suggesting that CFRP milling is the cause of any hole quality problems. The holes were inversely proportional in size when compared a single layer to a stack. Large CFRP holes along with underdeveloped Holes in the alloy of titanium are detected during helical milling layers.

As a consequence, when comparing drilling as well as milling processes, the literature is unanimous. Irrespective of the substance employed (Ti metal alloy, Al/CRFP layers, CRFP, or steel),), all results were equal, showing that the helical milling procedure is the most effective and results in the least amount of material damage.

- **Lubrication Processes during Machining**

The machining procedure has the potential to generate significant cutting and friction heat as a result of the abrasive nature of the substrate and tool attrition, both of which contribute to the rapid increase in temperature. Temperature is one of the most significant determinants of the quality of machined openings, particularly in CFRPs. CFRP drilling may cause the carbon filaments to catch fire, the matrices to fuse, the structural matrices to thermoset bonize, and the matrix resin to deteriorate.[97]. Moreover, the precision of the machined openings may be impacted by thermal effects. Nonetheless, a portion of the heat produced can be mitigated through the direct or indirect application of coolants to the interface between the dicing instrument and the workpiece. However, the use of coolants increases disposal and handling expenses and has an adverse effect on the environment.[98].

A frequently employed coolant Water-oil emulsion is utilised in machining operations. It consists of a solution incorporating oil from minerals and flexible oil for cutting lubricant.[99], The utilisation of micro-lubrication, or the use of CO2 cryogenic coolants with minimal ,[100], Cryogenic CO2 coolants [101] as well as liquid nitrogen (LN2)[102][103], air conditioning [91], as including vegetable oil [104], include others.

In their investigation, Shyha et al. assessed the integrity and quality of apertures drilled into stacks composed of titanium, CFRRP, and aluminium. To achieve this, they utilised a spray mist composed containing mineral-based lubricating and soluble oil cutting fluid as well as a water/oil emulsion for the flood cutting fluid. The machining procedure underwent significant enhancements. In many instances, the burr height was reduced to below 500 μm, with particular emphasis on the utilisation of the aerosol mist. The aluminium and titanium layers effectively supported the CFRP laminates, thereby reducing delamination. Particularly on the aluminium component, the surface irregularity was substantially diminished when through-spindle cutting fluid was utilised as opposed to spray mist. Spiral-shaped continuous aluminium chips were prevalent; however, when cutting titanium under damp conditions, helical chips produced by both short and long burrs were observed. Conversely, the CFRP layers exhibited no indications of delamination.[99].

Kumar and Gururaja investigated the impact of cryogenic refrigeration on Ti/CFRP/Ti stack drilling. The impact of employing liquid nitrogen (LN2) as an industrial coolant was investigated through the analysis of various parameters, including burr height, torque, delamination, thrust, and surface roughness. In contrast to dry drilling of Ti/CFRP/Ti stacks, the findings indicate that operations conducted in a cryogenic environment reduced exit burr height, torque, the top layer of the Fabricated brass junction, and surface irregularity. However, LN2 refrigeration increases thrust force and damages the bottom surface of the metal-composite contact.[105]. Biermann and Hartmann investigated the effects of cryogenic chilling on Ti/CFRP/Ti stack drilling. The impact of employing liquid nitrogen (LN2) as an industrial coolant was investigated through the analysis of various parameters, including burr height, torque, delamination, thrust, and surface roughness. In contrast to dry drilling of Ti/CFRP/Ti stacks, the findings indicate that operations conducted in a cryogenic environment reduced exit burr height, torque, the top layer of the metal composite interface, and surface irregularity. However, LN2 refrigeration increases thrust force and damages the bottom surface of the metal-composite contact.[101]. Giasin et al. discovered that, in comparison to dry drilling, the use of MQL with Cooling with cryogenic nitrogen gas increased the power of cutting. while lowering adhesion, built-up edge growth on the cutting tool, and surface roughness of machined holes. Using both coolants was found to enhance the microhardness about the top and bottom aluminium sheets surrounding the hole edges following machining[106]. Pereira et al. identified several advantages associated with the utilisation of air conditioning. It was utilised to increase cutting forces and temperatures by removing particles and chilling the cutting point. 30% less heat was applied to the cutting surface during helical milling. During CFRP drilling, the rotational speed is increased to reduce the cutting temperature. During the dicing of CFRP composite plates, pulverised pieces decrease cutting temperatures by absorbing heat. However, the powder-like crystal causes equipment component corrosion and attrition, which is detrimental to the machining centre.[91].

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Because the modulus of elasticity of metal and composite materials differs, machining deformations during drilling might occur, therefore coolants and lubricants are crucial to preventing delamination damage within the material, especially in FMLs. The main issues found after machining are covered in the section below.

- **Machined FML Defects and Analysis Techniques**

When the drill passes through both CRFP and FML, it might harm the material. Numerous faults may arise during drilling operations, affecting the hole's entrance and exit. These include surface roughness, dimensional drilling, and problems with the hole wall's surface integrity. The machining process may result in a number of defects, such as fibre pull-out, debonding, matrix cracking, as well as fibre fracture. Around 60 percent of all wasted components have poor hole quality.[107]. Since drilling is often the last step in the machining process, any damage sustained at this stage might result in large financial losses if almost finished products need to be destroyed. Comprehending and identifying the kind, dimensions, and positioning of imperfections that could emerge during drilling operations is crucial for cost-effective and long-lasting process enhancement[108]. The areas surrounding the hole always have a combination of this damage.

The biggest challenge in FML drilling operations involves hole quality: several flaws arise throughout the procedure, mostly on the hole's entrance and exit sides, as well as issues with the hole wall's size and surface roughness. It's challenging to identify these flaws, particularly when using non-destructive techniques. A number of techniques have been implemented to assess the integrity of cavities, including X-ray tomography and computed tomography (CT) examinations. [108],[109],[110], C-Scan[111], energy dispersive spectral analysis, stereo microscopy using light, and scanner electron microscopy are examples. [112]. Nguyen-Dinh et al. implemented x-ray imaging. to conduct an immediate surface strength analysis of composites after the pruning process. [113]. When compared to surface approaches such as surface roughness along with Optic topography in 3D, the X-ray methodology enables for the calculation of crater volume. During the cutting operation, they found many damaged zones containing craters across the material surface, suggesting material pull-out.

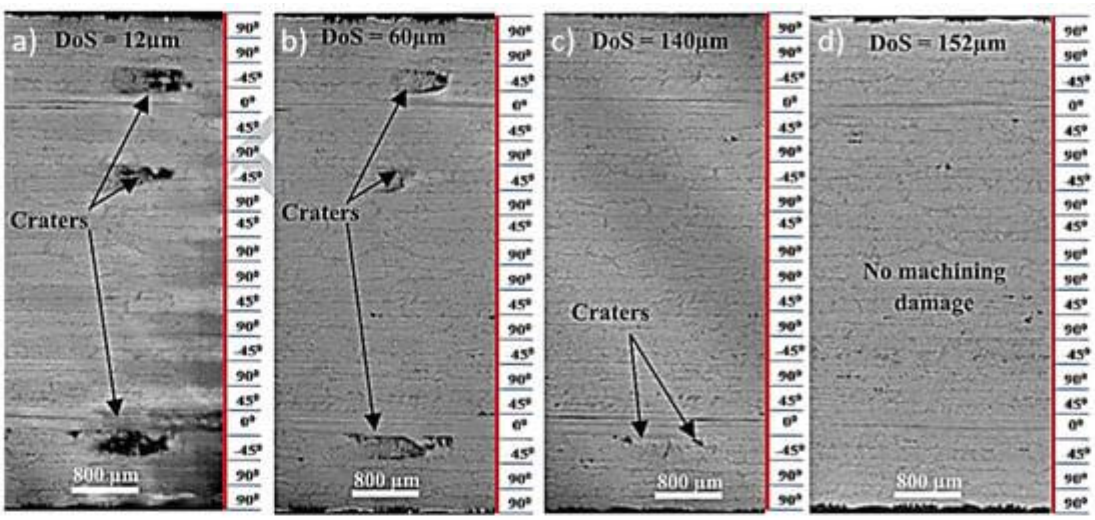


Fig: X-ray tomography pictures with a feed speed of 500 mm/min and a cutting distance of 1.68 m demonstrate machining damage at various scanning depths of (a) 12 μm, (b) 60 μm, (c) 140 μm, and (d) 152 μm[113].

By means of X-ray computed tomography, Pejryd et al. identified flaws produced by drilling perforations in a CFRP. Flaws and characteristics of the surface, such as surface texture and fibre deboning, can be readily assessed. Example of a surface image produced by reconstructing a bored cavity X-ray data is shown in Figure 8a. One method for highlighting the glass fibre material is shown in Figure 8b. This technique makes it possible to identify extra components by colour. In this instance, red is used to set it out from the surrounding content[108].

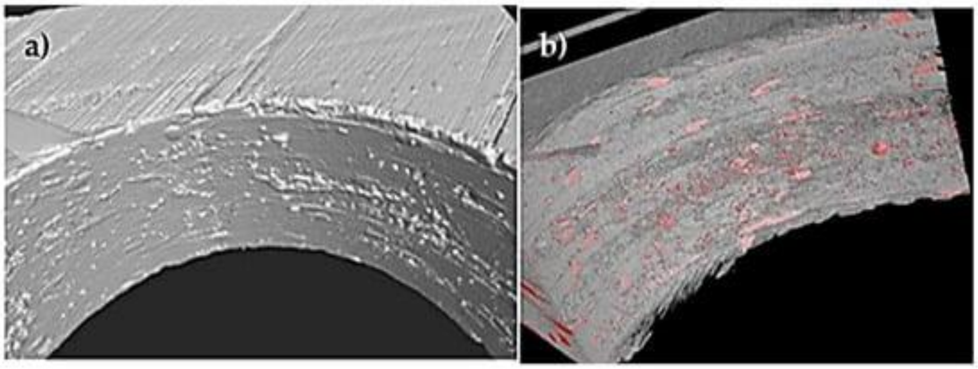


Fig: (a) A 3D model built from a CT scan of the drilled hole's outer surface. The hole's nominal diameter is 9.5 mm. (b) A CT scan of the hole's inner wall shows the glass fibre material, which is highlighted in red[108]

The perforation quality of CFRP/Al and CFRP/Ti-6Al-4V was compared by Wang et al. A two-step helical milling procedure was suggested and contrasted to conventional drilling in an effort to reduce injury.. Following the initial milling of the composite piece, the metal section was subsequently machined. They found that when the tool input for the composite begins component during the standard drilling procedure, there is more damage and more visible uncut fibres. The damage caused by the very first step is eliminated by the second step's cutting action, although fibre pull-out is visible on the surface around the hole. The images demonstrated that the helical milling procedure caused negligible injury to both stages[114].

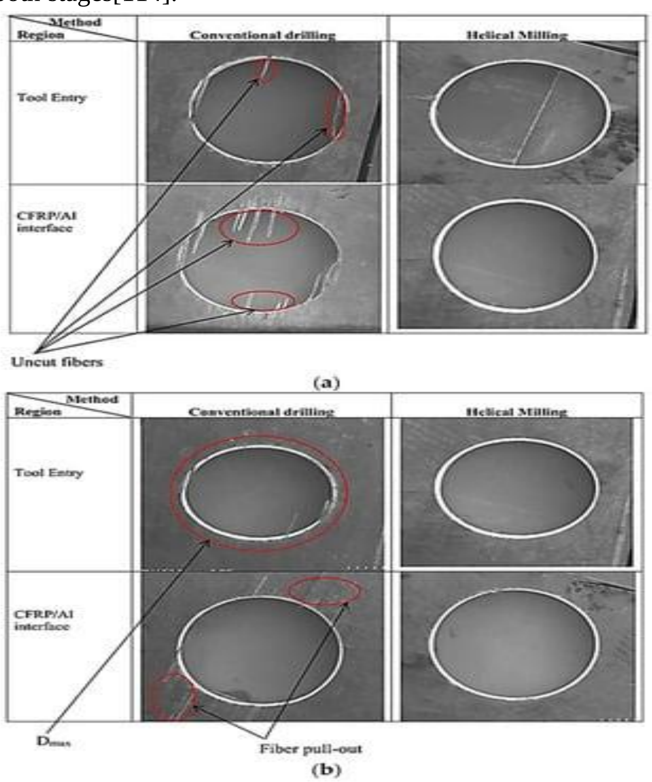


Fig: displays images from a scanning electron microscope comparing the hole quality produced by helical and conventional milling techniques (steps 1 (a) and 2 (b)).[114]

The Reducing The presence in terms of delamination injury critical as it dictates the approval status of composite components. In their investigation, Bertolini et al. compared the entry point quality of an Al/CFRP stack manufactured via cryogenic (CD) and ultrasonic (UD) drilling methods to that of conventional dry drilling. Feed rates of 0.05 mm/rev, 0.1 mm/rev, and 0.15 mm/rev were implemented. The FML comprised two distinct layers.: a CFRP sheet made up the exit face and an aluminium alloy 5 mm thick on the entering face. Since the entrance seemed to be defect-free, they were only assessed at the exit[102].

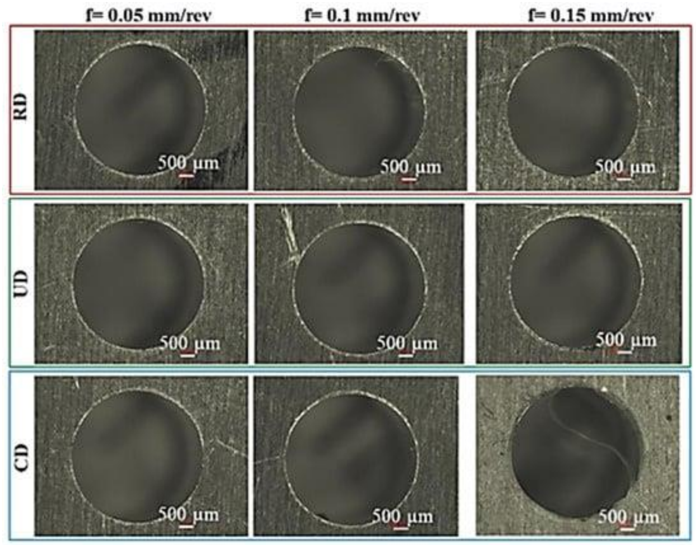


Fig: illustrates entry delamination utilising several feed and drilling techniques on an aluminium sheet[102].

The degree of delamination on the exit face varied according on the different feeding and drilling techniques used. Only when drilling trials were conducted under CD, irrespective of diet, did severe exit delamination occur. This phenomenon might be explained by a rise in thrust force brought on by the liquid nitrogen application hardening the material. Given that the last play of the FML deflects across a larger zone, It is widely recognised that as propulsion power increases, exit delamination also increases.

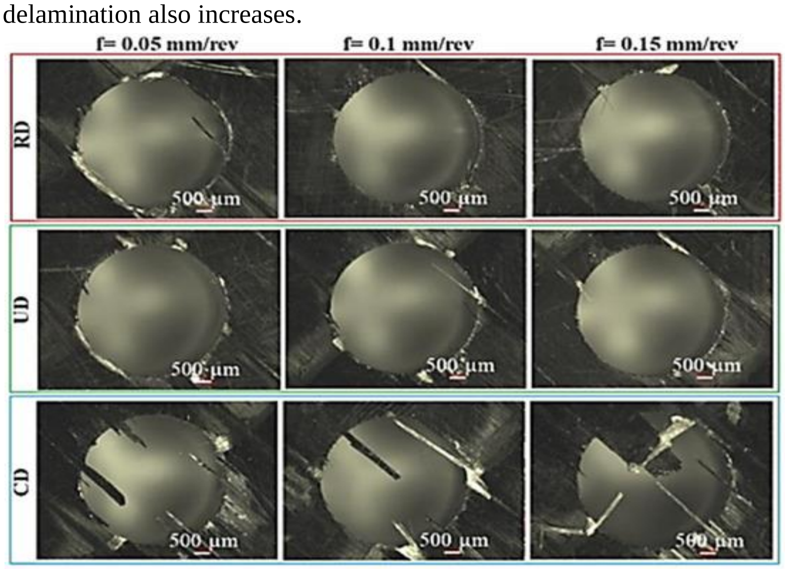


Fig: shows the CFRP sheet's exit delamination under different feed and drilling techniques[102].

Combining these methods with the various additional image analysis techniques discussed here not only increases the precision of the analysis by completing the picture and serving as a basis for process parameter adjustments, but it also guarantees the examination of the damage that results from the machining process.

To avoid damage through During the machining process, tool selection and attrition are critical. Consequently, It is advisable to furnish a comprehensive amount of information concerning the diverse tools and tool attrition employed in multi-material machining., Section 4 tackles this issue.

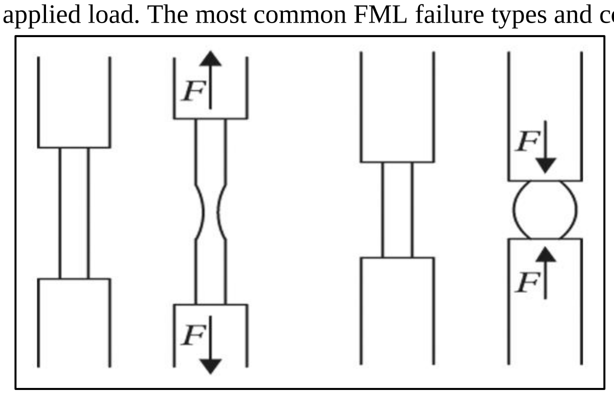
Table 2. Historical development in manufacturing of fiber metal laminates:

Ref.	Fiber Material and metal	Manufacturing techniques and its key details
[115]	Carbon/Glass fiber with Al 6061	Compression moulding is used to create aluminium alloy 6061 sheet and carbon/glass fibre at room temperature. by taking mass, specific gravity, and density into account. The weight percentage of the fibre was also established.
[116]	Carbon fiber reinforced polymer (CFRP) with Stainless steel SUS316 plate.	The CFRP sheet was made using a heated process using prepregs made of woven cloth. The fibre prepregs were first plated on stainless steel plates, then they were kept in the mould for two hours at a steady temperature of 130°C using a clamping press. After that, they were cured for a further two hours at room temperature. As a result, the CFRP as well as stainless plate were securely bonded by the hot process.
[117]	FM94/S2 glass fibre UD and M21/T700GC carbon fibre UD with AISI 304L stainless steel	Autoclave-prepared AISI 304L stainless steel FML with carbon fibre UD and FM94/S2 glass fibre UD.
[118]	Hardener (HY 917), glass/carbon fibres, Al alloy 6061 with epoxy resin (LY 556)	FML panels were made by hand using layup processes, then heated to 150 degrees Celsius and pressed to cure.
[75]	Carbon and jute fibers reinforced with aluminium 2024 T3	The final FML is created by applying thermoset after they were cured at room temperature as well as crushed in the compression moulding machine for ten minutes at a temperature of 700C and a pressure of 70 kg cm2.
[119], [120]	Polypropylene fiberreinforced polypropylene composite with 2024-0 aluminum alloy	The process used to create FMLs included stacking metal plies, composite, and interlayer material within a picture frame mould. In a pneumatic press, the stack was heated to 165oC under 7 bars of pressure. After that, it cooled gradually to room temperature at a pace of around 5oC per minute.
[70]	Thermoplastic reinforced with glass fibre and aluminium alloy 2024-T0	Along with the maleic acid hydride-modified polypropylene, a layer was deposited at the interface between the composite and metal. aluminium alloy was coated with chromate to promote adhesion between the composite as well as the metal. The laminates were then stamped in a cold press after being heated to 185°C in an air-circulating oven.

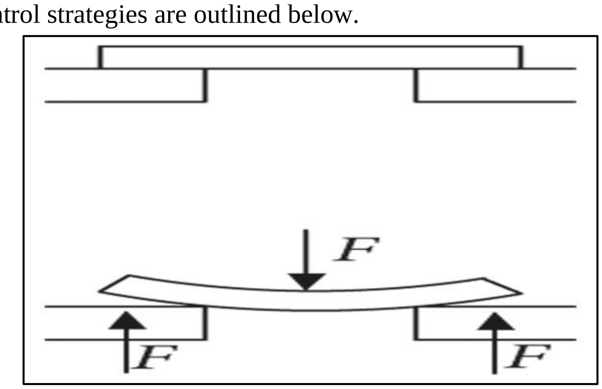
Metal surfaces need to be created through mechanical, chemical, as well as dry surface treatments in order to provide adequate bonding between metal as well as fibre reinforcement. Mechanical abrasion is the first step in mechanical treatment. It is used to remove an unwanted oxide layer along with provide a macro-level textured surface with varying degrees of surface texture roughness[121]. Sandpaper must frequently be used to severely scour the substrate surface in order to complete such an operation. Physicochemical changes would be induced by the mechanical treatment, leading to the formation of a damp table surface and a macro-roughed exterior topography. Mechanical treatments also involve the application of a variety of micro particle bombardments. substances, including silica dust, glass particles, or alumina, to alter the topography by generating a "peak-and-valley" morphology."[122],[8]. The chemical process, also referred to as "acid etching," is applying an acidic solution—mostly one that utilises a chromic-surface sulphuric etch—to the substrate's surface[123],[124]. The substrate is submerged in a potassium dichromate and sulfuric acid solution throughout this process. Acid etching, also referred to as chemical treatment, is frequently used as a transitional procedure spanning electrochemical treatment, alkaline cleaning, along with degreasing[121]. The metallic surfaces were altered using three standard acid-etching solutions: Laboratory for Forest Products [72], chromic-sulphuric acid [125], and sulfuric acid (P2) etches. The etches that use a combination of hydrofluoric as well as chromic acids generally the most effective[8]. In lieu of the chemicals wet treatment procedure, a number of dry treatments have been established for metal alloy surfaces. According to Ref.[121], An aluminium substrate's morphology and microstructure were altered by laser texturing, increasing the bond's durability and strength. Ion beam enhanced deposition (IBED) has become a technique that uses vacuum to sputter high-energy argon ions, cleaning and changing the surface. Grit blasting, or surface activation, is necessary before ion beam-enhanced deposition. When compared with per acetic acid (PAA), good initial bonding strengths were formed and wedge durability improved[8].

2.2 Main Failure Mode and Control Method of FMLS

Accumulation of damage is the leading cause of FML malfunctions. Delamination between metal and fibre layers, failure of metal fractures, deboning of fibres within the resin matrix, fracture of fibres, and propagation of fissures in the resin base are the primary failure processes.. [126]. Automobile and aircraft components frequently encounter intricate stress conditions, encompassing axial, bending, shear, and impact forces. FMLs are frequently subjected to compressive or longitudinal stress, such as when temperature fluctuations substantially or extrusion occurs between the components. When an automobile or aeroplane sustains substantial damage, its structure is frequently subjected to extreme warping and shear stresses. In situations involving tool deliveries or bird assaults, the aircraft structure must be capable of withstanding severe high-velocity contact stress.[8],[127]. The image below depicts a number of typical conflicts. The The FML's primary failure modes manifest in a more intricate manner. way with respect to the applied load. The most common FML failure types and control strategies are outlined below.



(a)



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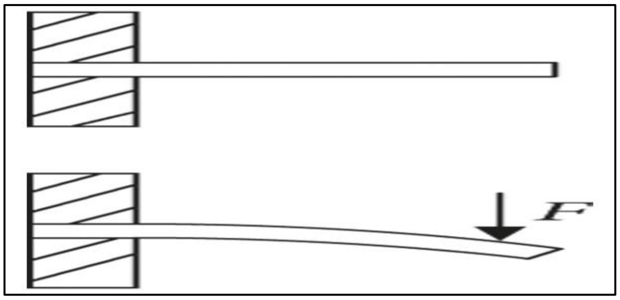

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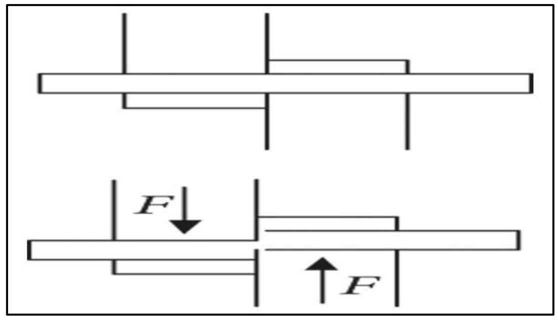

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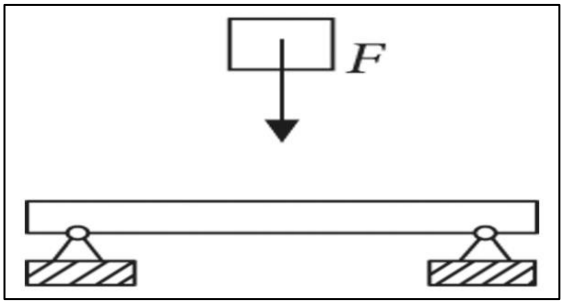

(e)

Fig: Five common stress diagrams. (a) Tensile stress, (b) compressive stress, (c) bending stress, (d) shear stress, and (e) impact stress.

2.2.1. Failure and Control Method under Shear Stress

Interlaminar shear strength denotes the force in FML. of the link connecting the fibres as well as the matrix resin [128]. The interlaminar bonding performance of materials is directly correlated with the interlaminar strength during shear of composite[129],[130]. When the shear stress exceeds at or above the maximal Under the influence of interlaminar shear stress, the composite material will fracture or be compromised. [130],[131].

Shear stress is especially prone to the FML interface, and debonding delamination is one of the most frequent ways t hat laminar composites fail. Whenever When the ratio of span to thickness exceeded 10, failures in bending occurred . occurred[132],[133].

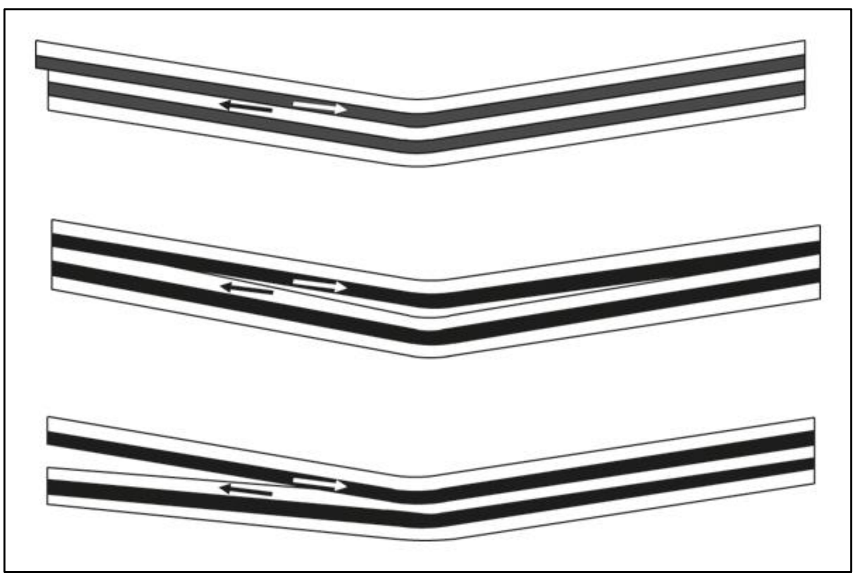

Fig: Failure of FMLs under pure shear stress[134]

Metal surface treatment and layer design modifications may effectively boost the intensity of interlaminar shear in the FML. A prepreg composed of CF/PMR polyimide, the superhybrid laminate Ti/CF/PMR polyimide is resistant to high temperatures. Due to the proximity concerning fiber/resin and metal/resin interfaces, exceptional adhesion resulted from the contact between the resin and the metal that has been treated on its surface. He and colleagues observed that the specimens undergoing anodizing, annealing, and priming exhibited superior performance in terms of specific elongation and shear strength compared to the initial specimens.[135]. In addition to electrochemical preparation, Goushegir et al. assessed aluminum-based laminates that had undergone various surface treatments, including mechanical grinding, sandblasting, acid pickling, and conversion coating. The findings indicated which interlaminar shear strength is present in FMLs was improved by all surface pretreatments, with the highest improvement seen in phosphoric acid anodizing-primer specimens[136].

2.2.2 Failure and Control Method under Bending Stress

The laminate's bending property may indicate its damage process and bending failure behaviour under load. The laminate receives both shear and normal stress under bending tension. Because of this, the failure mode becomes more complicated, and changes to the structural and layer designs will affect how the material fails[118],[129].

As shown in the picture below, the FML failure when subjected to bending stress is mainly manifested such as interlaminar shear failure, mixed collapse in the presence of shear stress and normal stress, and metal-fibre layer failure Amidst typical tension conditions.. Shear stress along with bend The tension in the diagonal region of GLARE laminate merged bending-induced deformation, as noted by Yurgartis and Sternstein, leading to the existence of both shear stress along with normal stress[137].

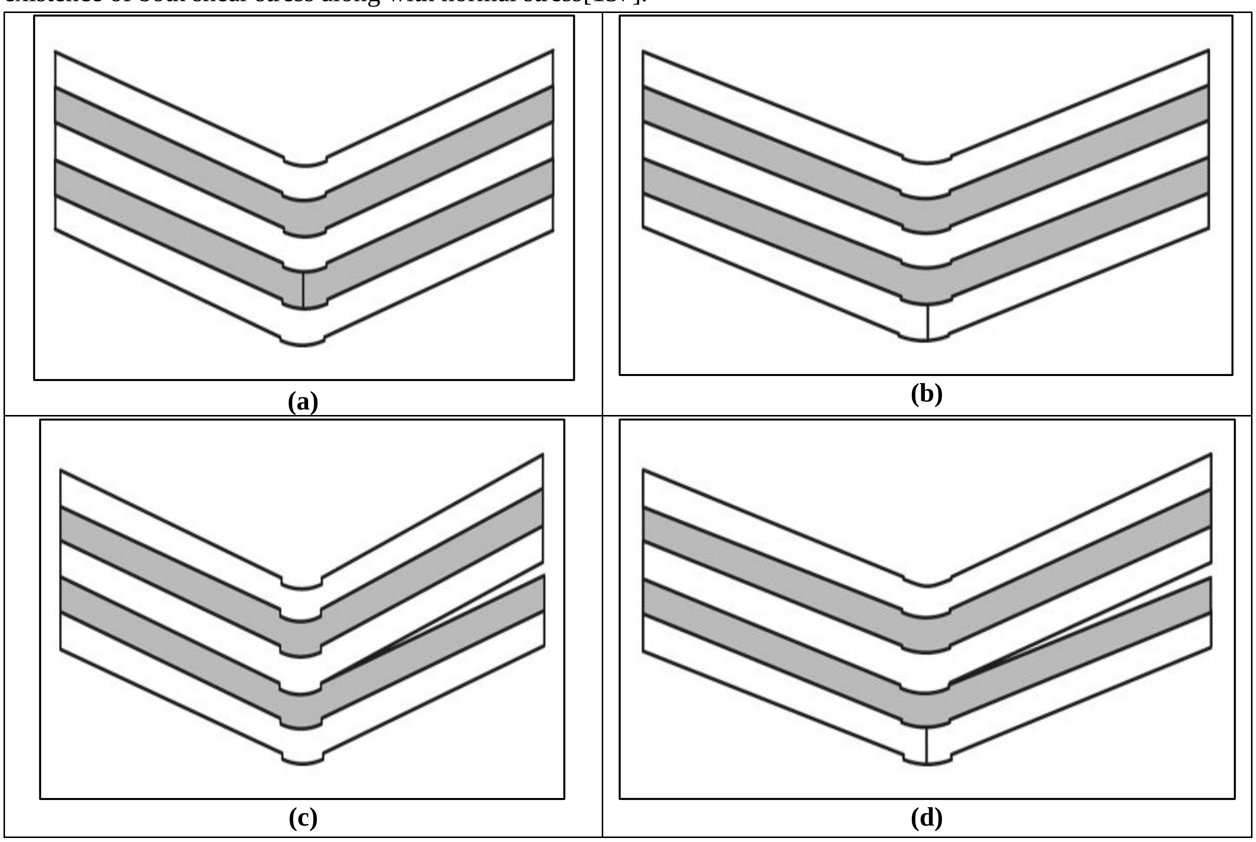

Fig: FML failure when bent under stress: (a) failure of the fibre layer; (b) failure of the metal layer; (c) failure of interlaminar shear; (d) combined damage [134].

Interlaminar failure occurred. behaviour of FMLs was strongly influenced by the ply angle. FMLs' horizontal fibres increase their bending strength as well as stiffness. [138]. Unidirectional FMLs may be used to control bending failure issues. Hu came to the conclusion that the flexural strength of the laminates will be impacted by the number of layers used based on bending test curves. According to the metal volume percentage idea,[139], Because of the metal layer, the The Ti/CF/PMR superhybrid polyimide laminate exhibited a reduced flexural strength in comparison to the unidirectional laminate. A comparative analysis of the the flexural rigidity of superhybrid Laminated polyimide Ti/CF/PMR at various ply angles, this was discovered that FMLs with uniform ply angles exhibited higher flexural strength throughout the fibre direction[140].

Moreover, strong interlaminar bonding may enhance failure behaviour when subjected to bending forces. Xu et al. discovered two techniques to strengthen the connection among layers of fibre and metals. In order to clear debris along with release the exterior oxide deposit, the first plan of action was to surface treat the metal prior to preparation, which improved surface roughness[141]. The use of adhesive was the second choice[142],[100], [143] to strengthen the prepreg's and metal's binding. Hu et al. discovered that the anodic oxidation process significantly improved the bending characteristics of PMR polyimide FMLs reinforced with carbon fibre [144].

According to Khalili et al.'s study, basalt FMLs' tensile and bending strengths were greatly increased by the addition of steel layers. [145].

2.2.3. Failure and Control Method under Axial Stress

Tensile stress along with compressive stress are two more categories for axial tension. In between the two unique pressures, FML will show various failure behaviours. Failure behaviours of the laminate under longitudinal tensile stress included fibre breaking, fiber/resin contact breaking down, resin matrix separating, along with so on.[146],[147]. Sharma et al. created FML and assessed its tensile response by adding metal layers at different thicknesses. The failure mechanisms of unidirectional laminates were discovered to involve necking, metal breakage, along with fibre breakage. Mixed failures, including fibre layer delamination, fibre breaking, along with metal breakage, may happen to orthogonal laminates[148].

FMLs buckled under compressive strain, according to the test results. Initially, the whole layer of metal bucked in the exact same direction. The metal/fiber layer contact delaminated as a result of the resin's subsequent distortion from shear stress[149],. As shown in the image below, local deformation brought on by buckling would result in matrix interlaminar along with several forms of intracellular failing, including debonding, which matrix failing, fibre failing, and breakdown.

(a)

(b)

(c)

Fig: The degradation of fibre metal components subjected to compressed axial strain may be attributed to thr ee main factors: skin bending, extended breaking, and general unsteadiness of the siding [134].

The different characteristics of the fibres at different angles lead to anisotropy. FMLs have different mechanical characteristics depending on which way the fibres are anisotropic[148],[150]. Consequently, the use of two-way reinforcement may enhance the tensile characteristics of the FML. In their investigation into the tensile characteristics of the GLARE laminate, a group of scientists discovered that The force differential that exists between fibre and iron in both horizontal and lateral orientations would lead to a deterioration in the tensile property in both directions. Tensile failure would be made worse by a reduction in tension property. However, the GLARE laminate's tensile capability increased in both directions. when glass fibre was used for bidirectional reinforcement, and the amount of fibre employed determined how much of an improvement there was. [151],[152].

The boost in the laminate's modulus of flexibility is due to the proportion of metal content, whilst the tangent modulus decreases. As the amount of metal rises, A decline occurs in the tensile strength of the substance.. As a consequence, good control over tensile flaws is possible by altering the metal's volume %[153].

The tensile strength of FMLs could be enhanced by thermal cycling. The impact of heat cycling on the tensile characteristics of FML was examined by Khalili et al. They discovered that the tensile strength could be increased regardless of whether the material underwent cycling at high or low temperatures. [154]. Their results showed that compared to less-layered FML, multi-layered FML were more susceptible to heat cycles.

2.4. Failure and Control Method under Impact Stress

FMLs need to be very strong and stiff, but they also need to be very resistant to impacts. Damage caused by impacts is a significant sort of failure in the structural parts of automobiles and aeroplane. Impacts of two different velocities make up this phenomenon.

Because they are often brittle, composite materials can only hold energy through elastic deformation. if a result, in th e absence of Plastic stretching and destruction at low speeds caused by impact is hidden, but if the damage increases, it might lead to the structural parts' total collapse[155]. Some of the failure mechanisms of FMLs under low velocity impacting stress include interfacial debonding, metal layer cracking, and fibre layer fracture[156],[25]. Interfacial de bonding under contact stress often includes debonding between different fibre layers as well as the connection betwe en the fibre layer along with the metal layer, as the picture below illustrates.

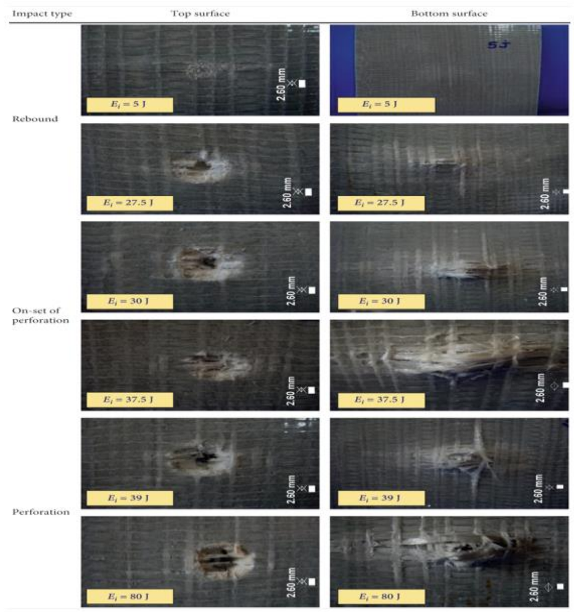

Fig: Damage perspective of one-way composites exposed to impact stress [157].

Extreme velocity at a contact may result in both penetration and the FML's complete failure[158],[159]. Chen et al. discovered that when magnitude of the impact's force rose, the extent of harm inside the GLARE laminate climbed gradually. GLARE laminates discharge absorbed impact energy mostly by debonding, plastic deformation, metals cracking, and fibre breaking under ballistic impact. The bullet's initial velocity affects the metal breaking, brittle fibre fracture, and damaged areas that occur in GLARE laminates. When impact load is applied to GLARE laminates, constraints greatly affect how they fail. For instance, it was discovered that the GLARE laminates' ballistic limit velocity, when touched at the plate's corner, was much lower than when impacted in the plate's middle[160].

The thickness, fibre diameter, along with ply angle of the laminate all affect the FML's ability to withstand impact. In a In their exhaustive study of the response of GLARE laminates to low-velocity impacts, Morinière et al. observed that as the number of levels increased, the individual absorption of the laminates exhibited a gradual increase, while the metal volume percent demonstrated a steady decrease.[161]. It demonstrates that the fibre layer is essential for increasing the laminate's specific absorption energy. Nevertheless, arbitrary modifications to the thickness level are not possible owing to the laminate's multifaceted structures. Due to this, adjusting the ply angle remains the primary method for mitigating impact failure defects.[162],[163].

The substance's resistance to impact is enhanced. by treating the metal surface. Prashantha Kumar discovered that the material laminates' impact resistance had greatly increased after the metal composite's surface treatment[164]. Additionally, Mehr's team discovered that the low velocities impacts behaviour of FML was enhanced when sulfuric acid anodizing or forest product laboratory etching were combined with sandblasting [127].

The impact of tiny clay particles with a tweaked base on the mechanics properties of composites made of basalt fibre, epoxy resin, and aluminium laminate was examined by Bahari-Sambran et al. They discovered that FMLs had great impact strength when clay was added. This might be because to the enhanced interlaminar characteristics[138].

Despite significant strides, notable research gaps persist in the FML landscape. The absence of standardized manufacturing processes and material specifications poses challenges, urging future studies to establish industry-wide standards for FML production. A deeper exploration of failure modes, especially under dynamic loading conditions and extreme environments, is warranted to refine control strategies. The integration of multi-scale modeling approaches to predict FML behavior at various scales remains an unexplored research avenue, crucial for improving accuracy and reliability. Assessing the environmental impact of FML manufacturing processes and conducting life cycle assessments are necessary to quantify sustainability aspects. Lastly, there is a gap in the exploration of emerging technologies, such as nanotechnology and additive manufacturing, with future research opportunities lying in their scalability and practical implementation in FML production. Bridging these gaps will not only advance the understanding of hybrid laminates but also propel the field towards innovative and sustainable solutions.

Conclusion

In conclusion, this comprehensive review has delved into critical aspects of Fiber Metal Laminates (FML), exploring both the manufacturing processes and the main failure modes, along with their corresponding control methods. The intricate relationship between the manufacturing methods and the resulting structural performance has been thoroughly examined, shedding light on the advancements and challenges within the realm of multi-material machining. The discussion surrounding the manufacturing of FML highlighted the significance of multi-material process preparation, numerical simulations applied to FML machining, and various multi-material machining processes. Notably, the research carefully compared the characteristics of the drilling and milling operations, highlighting how crucial it is to comprehend the subtleties of each method in order to get the best outcomes. The examination of machined FML defects and analysis techniques provided valuable insights into quality control and improvement methodologies.

The review examined the primary failure modes of FML in conjunction with the production processes, classifying them under axial, bending, and shear stress. Each failure mode was scrutinized, and control methods were proposed to mitigate the associated risks. This detailed analysis is paramount for engineers and researchers involved in the design and optimization of FML structures, providing a roadmap for enhanced structural integrity and durability. The synthesized knowledge presented in this review contributes to a comprehensive understanding of FML, from its manufacturing intricacies to the control of main failure modes. By bridging the gap between theory and practical application, this review facilitates the advancement of hybrid laminates in aerospace, automotive, and structural engineering applications. The interdisciplinary nature of the review, incorporating aspects of materials science, manufacturing engineering, and structural analysis, positions it as a valuable resource for researchers, engineers, and practitioners seeking to harness the full potential of FML in diverse engineering contexts. As the field continues to evolve, this review serves as a guiding reference for future research and development endeavors aimed at optimizing the performance and reliability in Metal Fibre Vinyl laminates.

Concerning Fibre Metal Laminates (FML), several promising avenues beckon future research and development. Firstly, a focus on advanced manufacturing techniques, including 3D printing, automated assembly, and robotics, could revolutionize the production processes, making them more efficient and cost-effective. Integration of optimization algorithms, leveraging artificial intelligence and machine learning, presents an exciting opportunity for enhancing the design and manufacturing parameters of FML structures. Sustainable materials represent another frontier, with research potential in exploring recycled or bio-based materials to align FML production with global sustainability goals. Additionally, the integration of advanced structural health monitoring (SHM) systems within FML structures, enabling real-time monitoring and early detection of potential failures, could enhance safety and reliability. Exploring multifunctional capabilities beyond structural strength, such as self-healing properties or thermal regulation, could further expand the application scope of FML in diverse industries.

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