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Review Article

Fatigue life of hybrid metal composite materials: A review

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Abstract

Hybrid metal composite materials, combining diverse metal components, have emerged as promising alternatives in engineering applications, offering a unique synergy of mechanical properties. This review comprehensively examines the fatigue life of hybrid metal composites, delving into the intricate interplay of materials, manufacturing processes, and environmental factors. Drawing from a rich array of literature, the review explores the evolution of hybridization strategies, emphasizing their impact on fatigue resistance. Key factors influencing fatigue behavior, including material selection, manufacturing techniques, and environmental conditions, are systematically analyzed. The article highlights the significance of strategic hybridization in enhancing fatigue characteristics, reducing costs, and optimizing the overall performance of metal composites. The insights presented contribute to advancing the understanding of fatigue mechanisms in hybrid metal composite materials, offering valuable guidance for future research and engineering applications. Hybrid metal composite materials, characterized by the combination of diverse metal components, have garnered significant attention in engineering applications due to their potential to provide a unique synergy of mechanical properties. This comprehensive review delves into the intricate aspects of the fatigue life of hybrid metal composites, offering a thorough analysis of the interplay between materials, manufacturing processes, and environmental factors.

Keywords: *Hybrid Metal Composites, Fatigue Life, Mechanical Performance.*

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1. Introduction

For almost 60 years, FRP composites have been used in aircraft, marine, civil engineering, sports, wind energy, autos, medical equipment, and electronics. These composites, comprised of synthetic materials such as glass, carbon, and Kevlar bonded with polymeric resins, offer superior stiffness, material strength and fatigue life comparable to steel and concrete [1], [2], [3], [4]. The fundamental concept involves combining a strong substance (fiber) with a softer one (resin/matrix) to create a composite material with tailored properties. This strategy does, however, have some inherent drawbacks, such as a linear response up until peak load and then an abrupt, brittle failure without warning. Addressing the drawbacks of conventional fiber-reinforced composites, the late 1970s saw the emergence of "composite composites," integrating multiple fiber types within a single resin [5], [6], [7], [8], [9]. This hybridization approach, often involving two types of fibers, leads to synergistic benefits, including enhanced strength, stiffness, and toughness with optimized designs. The cost-effectiveness of composites with expensive reinforcements is improved through the incorporation of cheaper, lower-quality fibers without compromising overall properties—a phenomenon known as the "hybrid effect" [7], [9], [10].

Hybrid designs strategically insert high-quality fibers to enhance composite qualities without significantly impacting costs, offering a versatile approach for diverse applications [9]. Various combinations of reinforcing fibers, such as high- and low-strength carbon fibers or dissimilar materials like glass and carbon fibers, showcase the adaptability of hybrid composites [9], [11] Notably, in large-scale structures like modern wind turbine rotor blades exceeding 100 meters and 50 tons, hybrid composites, combining carbon and glass fibers, contribute to minimizing weight and construction costs [12]. Additionally, incorporating Kevlar fibers with carbon fibers enhances toughness and damage tolerance in specific applications. The integration of nanomaterials at the micro and nano levels represents a recent advancement in hybridization [13], [14].

Interlayer composites containing micro/nano veils or matting improve interlaminar fracture toughness, a crucial factor for delamination resistance [7], [10], [15], [16] Despite being subjected to numerous fatigue cycles in most applications, hybrid composites have received inconsistent attention in fatigue studies since the early 1970s. While early research aimed to determine if hybrid composites exhibited superior fatigue behavior compared to linear blends of basic materials, the focus gradually shifted to the intricate architecture and design of materials. Careful design may result in hybrid composites with improved fatigue characteristics. Hybrid composites' fatigue response has received little research, focusing instead on compositefatigue stiffness, adhesively bonded composite joints, structural adhesives, and hysteresis loop area.

In order to provide a structured and intensive discovery of the region, the current review addresses the following main themes:

- The theoretical background of historical development and fatigue in composites.
- Their effects on hybridization strategies and fatigue properties.
- Mechanical fatigue behavior under various load mode.
- Fatigue damage mechanisms such as cracks, delay and loss of severity.
- Effect of material selection, fiber type, orientation and stacking sequence.

2. Literature Review

It is possible to observe the breakdown procedures of both pure and hybrid composites in Figure 1. The blue solid line 'b' represents homo-ductile hybrid composites. From the initial modulus (Ei) until the pseudo yield point (b1), this line transfers the load from LSF to HSF. After LSF fragmentation and stable LSF delamination from HSFs, a second rising area (b3) occurs in situations with higher strain rate loading. b4 failure is caused by the removal of LSF. The distance between the starting slope at b1 and the final failure strain at b4 is called the pseudo-ductile strain (εpd) [12].

Composite hybrids provide pseudo-ductility, unlike CFRP. A significant load decrease occurs after LSF fragmentation [17]. Thin-ply hybrid composites with comparable fibers but varying diameters or modulus may protect high modulus (HM) fiber fragmentation and delamination. Stress rises before failure, pseudo-yield stress rises like metals, and this design's stress-strain curve plateaus.[17].

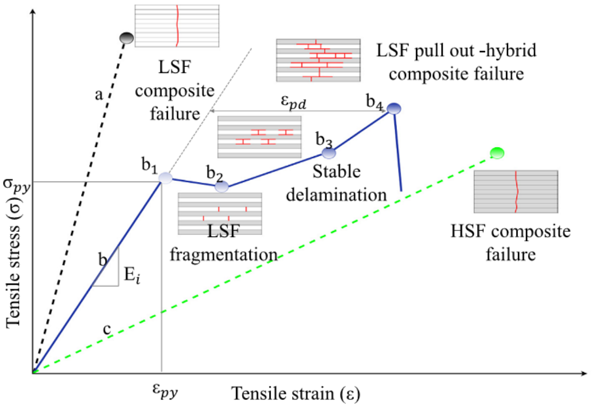

Figure 1. The usual tensile properties of polymeric composites reinforced with pure or mixed fibers.[18]

After uniaxial tensile stress, pseudo-ductile all-carbon/epoxy unidirectional hybrid composites fragmented and delaminated inner HM carbon plies from outer high-strength carbon plies, according to [9], [19]. Even though the initial modulus (Ei) went up from 12% to 71%, the pseudo-strain went down from 0.83% to 0.4% and the pseudo-stress went down from 990 MPa to 1400 MPa. Angle-thin ply hybrid CFRP composites after low velocity impact and indentation testing, [20] showed that local pseudo-ductility may be preserved under tensile loading.

Early in the twentieth century, scientists began to recognize fatigue as a crucial loading pattern [21], [22]. In 1841, Jean-Victor Poncelet wrote a book that likely contains the first mention of fatigue. He stated in it that a spring subjected to push-pull stress will eventually snap under a force significantly lower than its static breaking point.[23] performed the first long-term fatigue experiment with metals (wagon axles) subjected to bending, tensile, and torsional stresses from 1852 to 1870. Without any mathematical link to explain this pattern, the first S-N curve was generated by plotting the fatigue strength (S) against the number of life cycles (N). In 1910, [24] put up a power law equation to establish the S-N curve, which correlates the maximum stress (σmax) with the applied stress (σ0), cycle number (N) and curve slope (1/k), as seen in Eq. 1

$$\boldsymbol{\sigma_{max} = \sigma_0 N^{\frac{1}{k}}} \qquad \ldots 1$$

Composites still fatigue, but they do it less frequently than metals. The mechanisms of fatigue damage in composites, whether hybrid or not, differ according on the static loading conditions. Extensive studies on fatigue degradation mechanisms in non-hybrid composites have already been conducted. [25], [26]. As hybrid composites use two or more fiber types, their failure process changes [9], [27]. The S-N slope of a glass/carbon hybrid material is lower than GFRP and CFRP at various fatigue stress levels. [28]. As HSF delayed LSF fractures, hybrid composites had a longer fatigue lifespan than HSF composites, reducing the chance of additional HSF failure. To improve the tensile fatigue resistance of hybrid composites, optimal dispersion and adhesion between LSF and HSF fibers may be achieved by surface treatments. In Figure 2, Carbon/glass hybrid composite laminate fatigue damage and stiffness deterioration are observed. [9].

In the first stage of damaging events, a small number of cracks split and fragment the LSF layer. The next stage involves fragmentation and localized delamination. Eventually, the hybrid composite fails due to extended fragmentation and delamination. In the early stages of weariness, before delamination happened, the loss of stiffness was more apparent. Stiffness lessened to a lesser extent as fatigue set in. In many cases, metal fatigue starts with a single crack and progresses to catastrophic failure gradually, with little to no warning. Damage at multiple locations, rather than a single small crack, is the usual cause of composite material failure. Composites exhibit damage accumulation mechanisms such as fiber fracture, matrix cracking, debonding, transverse ply cracking, and delamination.

Based on material characteristics and loading circumstances, these processes may occur independently or concurrently [29]. Specifically, fatigue stress causes fractures in FML metal layers. Due to fatigue cracks, the fibers stay intact, delaminating composite and metal layers. Applied field stress creates bridging stress in intact composite layers. This bridging g mechanism is crucial for FML fracture development resistance during fatigue loading [30], [31] The quantity and length of fracture wake fibers determine crack growth reduction. The delamination type and gap between unbroken fibers and metal layers determine the effective fiber length.

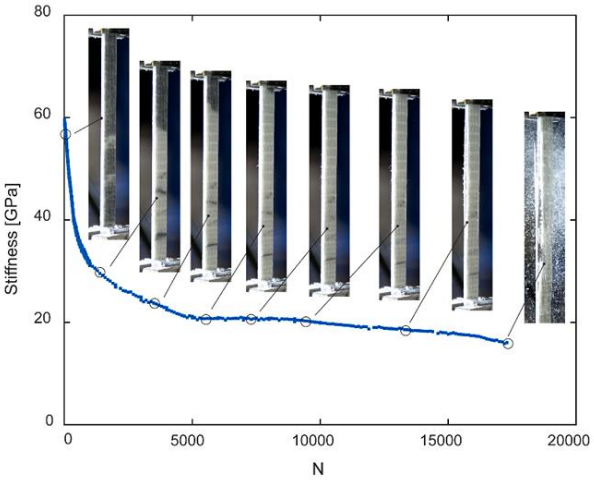

Figure 2. Fatigue test damage and stiffness deterioration at lowest maximum stress[32]

When contrasted with composites reinforced entirely with glass fibers, carbon/glass hybrids demonstrated an improvement in tensile fatigue strength that was directly proportionate to the amount of carbon fibers used [10]. In contrast to non-hybrids, unidirectional carbon-glass hybrids showed a positive divergence from the mixing rule in terms of fatigue stress and fatigue ratio [28], according to another pertinent investigation. Contrarily, [33] found no benefit to replacing 30% of the glass in glass fiber reinforced polyesters with carbon fibers. In contrast, [34] conducted a study comparing hybrid, pure glass, and pure carbon composites.

The results showed that, regardless of the load ratio, the pure carbon fibers exhibited the greatest rigidity and the longest tensile fatigue lifetime. However, there was a significantly larger scattering of results for tension-compression loading. The fatigue life of hybrid composites was shown to be greater than that of glass fiber composites, with a considerable increase observed in the carbon fiber percentage, as stated in [35]. Although [35] Both pure glass and pure carbon fiber composites exhibited typical fatigue behavior. The glass/epoxy composite showed a smooth, decreasing curved S-N curve, whereas the carbon/epoxy composite showed a consistently uniform response up to 5 million cycles, the hybrid UD composites displayed a combination of the two types of behavior, with the best performance achieved with a carbon-to-glass ratio of 2:1. Surprisingly, the 2:1 performance outperformed 1:1 and 3:1 and was almost on par with the pure graphite/epoxy performance. According to [35], this is likely due to the laminate's homogenous distribution of carbon and glass plies and the careful stacking sequencing of the two materials, so that the contacts between the plies experience less shear transfer resistance.

However, the tested quasi-isotropic glass/carbon hybrids laminates were the only ones that exhibit the hybrid effect. If so, the hybrid composites outperformed a pure carbon/epoxy material in fatigue. Beyond carbon/glass hybrid composites, a number of articles explored the fatigue behavior of other synthetic fiber reinforced composites. According to [36], the modulus of the used fibers primarily affected the tensile-tensile fatigue behavior of carbon/aramid fiber hybrid composites. On the other hand, Marom et al. [37] discovered that composites reinforced with aramid and carbon fibers in a sandwich configuration exhibited improved fatigue behavior due to the hybrid effect.

An analysis by found that aramid/carbon/aramid hybrids had better fatigue performance than carbon/aramid/carbon composites and aramid parent composites. [38]. Because the compressive and tensile characteristics (basically strength) of the parent carbon and aramid composites vary on distinct rates, the authors concluded that this is the cause of the discrepancy in fatigue performance between the two configurations. Despite having high specific strength/stiffness and long-term fatigue resistance, carbon fiber reinforced composites nevertheless encounter the problem of being brittle. To make composites with carbon fiber reinforcement less fragile, hybridization with HP-PE fibers is one option.

The traditional method can be used to understand the tensile behavior of HP-PE/carbon hybrids when subjected to monotonic and fatigue loading. "Constant strain model" hybrid composites, according to [39], Researchers studied the fatigue and quasi-static behavior of HP-PE fiber/carbon fiber hybrid composites. There were found deviations from the constant strain model, which are referred to as hybrid effects. The findings showed that the presence of hybrid or synergistic effects is determined by the hybrid design as well as the strength of the interfacial connection between the HP-PE fibers. The authors state that it is clear that when HP-PE fibers are not evenly distributed throughout the carbon fiber composite, the chances of crack arrest, which prevents the fast propagation of cracks from first failed fibers, decrease.

When subjected to fatigue loading, the mixed hybrids containing treated PE fibers demonstrated additive properties., meaning they deviated positively from this constant strain model's predicted fatigue behaviors. Furthermore, when evaluated using ultrasonic C-scan and acoustic emission, these hybrids exhibited the least amount of fatigue damage. Hybrid composites outperformed pure glass fiber composites in terms of fatigue lifespan, according to a study that modelled the causes of fatigue degradation in glass/carbon hybrid composites [40]. Moving from lower strain carbon fibers to higher strain glass fibers decreased crack spread, improving the system (as built experimentally for additional hybrid systems including glass and carbon in [9]. As shown in the modelling study, more fiber dispersion may boost the hybrid's fatigue resistance. [40].

Variations in processing, fiber orientation, volume/fraction, and location According to research by [41], the interplay carbon/glass hybrid composite's tension-tension fatigue life was shown to grow in a linear fashion as the volume ratio of carbon fibers increased. [40] found that fatigue lifespan under tension-tension cyclic loading is improved with greater carbon fiber percentages in carbon/glass fiber hybrid composites, which supports this result. Under compression-compression loads, higher carbon fiber percent may reduce fatigue lifespan, with multiple consequences during tension-compression cycling loading, according to further tests conducted under various loading circumstances. While fiber misalignment may increase the hybrid composites' fracture toughness, it also increases fiber damage and reduces fatigue life, as shown in [40]. The hybrid epoxy matrix composite with interplay biaxial glass-carbon laminae, biaxial glass laminae, and biaxial carbon laminae was studied for its tension-tension bending fatigue behavior by [42].

Frustration loadings ranging from zero to eighty-five percent of the ultimate flexural strength of the material were applied to the specimens. Deterioration of material stiffness due to cycling was seen after a few hundred loading cycles, indicating early deterioration. It was found that the specimen's stiffness was reduced in direct proportion to the size of the fatigue loading. After studying the tension-tension fatigue behavior of a hybrid composite laminate made of glass and ultrahigh modulus carbon UD, [9] observed similar results. At high stress levels, fatigue stiffness differed less with fatigue cycles; at low stress, when damage was widely dispersed across the specimen volume, the fluctuation was noticeable. Previous research also looked at how the fiber orientation and stacking sequence affected the results. [35] determined that sandwich hybrids were inferior than interplay hybridization with alternating carbon-glass plies in 1978 when they evaluated the effects of stacking sequences of carbon-glass hybrid laminates (0°), (±45°), and (0°,±45°). Only the quasi-isotropic (0/90/45) configuration showed an apparent hybrid effect, as shown in the preceding paragraph. Using compression molding, [43] studied the effects of stacking sequence on composites made of hemp and polyester reinforced with glass. As compared to composites with an inner layer of hemp fibers and two outer layers of glass fibers, The fatigue strength of materials improved when tested with a combination of hemp fibers on the outside and glass fibers on the inside. At high fatigue loading levels, [44] crossed-ply laminates were more damaged than angle-ply laminates. Additional study on bi-axial interplay C/G hybrid composites supported this concept. [42].

Numerical research on the effect of fiber mixing on fatigue behavior revealed a significant influence [40], suggesting that interlayer hybrids have the most effective fatigue behavior of all hybrid composites. A study conducted by [36] thoroughly examined how the fiber direction affected the fatigue life of hybrid composites made of interplay carbon, Kevlar fabric, and epoxy. The study's authors concluded that, in comparison to carbon loading, the degradation of fatigue correlation lines was slower when applied to Kevlar.. Both the fatigue performance and the quality of the hybrid composites are impacted by the processing procedures. Case in point: C/G hybrid composites were created by [45] using RTM and manual lay-up processes. RTM specimens performed worse than hand lay-up specimens throughout fatigue and post-fatigue, irrespective of the fiber orientation. This is because the resin-rich regions served as places where cracks may initiate.

A variety of studies have examined the effects of moisture on adhesive fatigue behavior., composites, and joints. Take [46] as an example. They discovered that fatigue modulus values based on nonwoven flax epoxy composites drop sequentially when exposed to moisture. Additionally, an overview of studies on the impact of the environment on the fatigue degradation of adhesive joints conducted over the last few decades was provided by [47]. With the goal of gauging the GFRP & G/C hybrid composites' environmental cyclicity, [41] used a 75 °C distilled water bath. Wet conditions reduced the fatigue life of both composites; however, GFRP with a high enough amount of carbon fibers retained fatigue life better than GFRP without the fibers [41], [48] In comparison to interplay hybrid composites, intra-ply hybrids seem to have superior fatigue life when subjected to environmental loading conditions. A single layer of interplay composites may mix fibers, which helps to minimize fiber mismatches. Interplay composites, on the other hand, are laminated with separate layers of fibers, which may cause diverse fatigue behaviors in each layer. According to [49], the impact of temperature on fatigue response is independent of whether the water is fresh or salty, even though environmental variables like moisture and temperature often degrade fatigue performance [50], [51].

Stitching, z-anchoring, z-pinning, and weaving can reduce delamination, a critical fatigue failure process in hybrid composites. [52] Delamination of 3D diagonal C/G hybrid composites reinforcing the z-axis occurs at a slower rate than that of C/G composites. Reducing interface stress concentrations switched rupture of fibers due to delamination, increasing fatigue life. This 3D textile self-healing composite resists mode I and mode II interlaminar fatigue cracking and repairs fatigue-induced delamination cracks in-situ. [53]. The carbon-based composite (0.35%) and poly [ethylene-co-methacrylic acid] (EMAA) (1.6%) z-binders rose by 800% and 2000% in modes I and II, respectively, for fatigue cracking thresholds.

The fatigue lifespan and fracture formation resistance of polymeric composites can be improved by adding thermoplastic layers or PA66 fibers to their interfaces. Adding 40 μm thick PA66 micro fiber (520 ± 100 nm) to the CFRP contact reduced fracture rate by 30 times. Fissures reverberated between the carbon fibers and the toughened PA66 nano-modified layer, spreading in different directions with different widths and thicknesses, necessitating greater energy for propagation [54]. Similarly, Shivakumar et al. [55] underwent fatigue loading on specimens treated with PA66 and discovered a notable postponement of delamination initiation. Interleaving carbon nano-fibers may extend axial fatigue life by 150-670% due to higher interface density and damage shielding [56].

There are a number of advantages to using natural fibers rather than synthetic ones. These include a lower carbon footprint, better mechanical properties, and environmental benefits including sustainability. [57]. Composites made from bamboo & glass fibers may have a longer fatigue life if they are hybridized, as suggested by [58], who developed composites made of glass and bamboo fibers and reinforced with polymers. When contrasted with 100% basalt fiber laminates, the hybrid composites demonstrated superior normalized fatigue resistance., as shown by [59], who demonstrated that basalt laminates may benefit from the addition of flux to them. Based on their research on fatigue life span in tension-tension mode using composites reinforced with hemp and glass fiber, [60] advise utilizing hemp fiber in place of glass fiber during fatigue loading to reduce fatigue sensitivity. The addition of jute fibers to hybrid composites may reduce their fatigue sensitivity, according to another study. [61].

When it comes to production setups, [62] looked into how different types of kenaf fibers—woven, UD, and non-woven—affect fatigue life. When using non-woven fibers in hybrid composites, the fatigue degradation coefficient rose by 7.9%, woven and UD kenaf fibers had an increase of 6.2% and 6.4%, respectively. Because fibers bear most of the stress, hybrid composite failure surfaces have fiber pull-out and breaking. [43]. As a result of fiber waviness, inherent manufacturing faults, low moisture resistance, and fiber orientation randomness, natural hybrid composites could not be justified for fatigue applications.

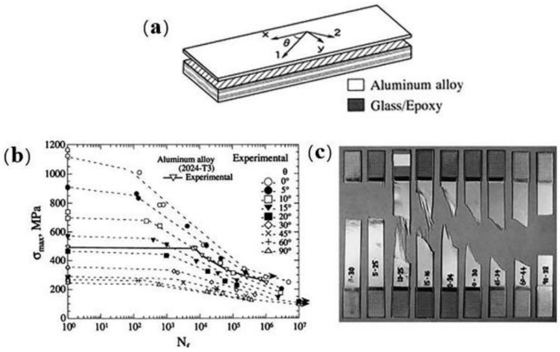

Figure 3. fatigue performance of GLARE: (a) sample configuration, (b) maximum stress versus number of fatigue cycles response and (c) failure images of tested samples[63]

Figure 3 Macroscopic failure in fractures outside the axis stretched under continuous dimensional conditions refers to morphology. This indicates that the fatigue of samples with these off-axis angles is controlled by fracture of fiberglass in LIFE GFRP layers.[63]
Figure 4 Shows the addition of hybrid ceramic reinforcements to aluminium matrices leads to reduced material loss and improved tribological performance.[64]

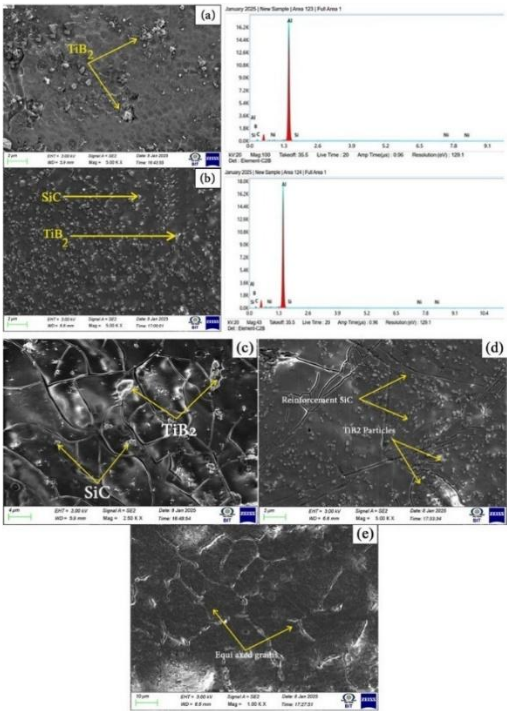

Figure 4. Microstructural observations of Stir casted AA8011 with: (a) 2% TiB2 and 1% SiC, (b) 2% TiB2 and 3% SiC (c) 2% iB2 and 5% SiC (d) 2% TiB2 and 7% SiC (e) un-reinforcement.[64]

3.Applications

Hybrid metal matrix composite (HMMC) has found different and impressive uses in different engineering fields due to its better fatigue resistance, high strength-to-weight ratio, and tailored mechanical properties. In the aviation industry, they are widely used in aircraft structures - for example, upper body panels and rotor blades - where carbon/fiberglass hybrid hybrids lose and lose weight as and lose weight and weight [63].

In addition, these composites are used for sports equipment, medical equipment and electronics, where fatigue resistance, mild design and analog thermal properties are important.[65]

Authors	Objective	Method/Model Used/ Dataset	Output and Accuracy	Weakness or Improvement
Zuo et al., 2021	Investigate pseudo-ductility in hybrid composites	Experimental testing, analysis of stress-strain curve	Identification of pseudo-ductile strain (εpd)	Further exploration is needed for optimization of pseudo-ductile behavior.
Fuller & Wisnom, 2015	Examine load decrease after LSF fragmentation in hybrid composites	Analytical and experimental approaches	Identification of stress-strain curve plateaus	Investigation required for optimizing load decrease characteristics and understanding implications for different applications.
Czél et al., 2017; Ribeiro et, 2021	Explore behavior of carbon/epoxy hybrid composites under tension	Experimental testing, analysis of stress-strain curve	Changes in initial modulus, pseudo-strain, and pseudo-stress	Optimization needed for achieving desired balance between pseudo-ductility and other mechanical characteristics.
Prato et al., 2019	Investigate preservation of local pseudo-ductility under tensile loading	Experimental testing, impact and indentation testing	Maintenance of local pseudo-ductility	Further research needed to understand and optimize local pseudo-ductility under various loading conditions.
Vassilopoulos, 2019; 2020	Recognize fatigue as a crucial loading pattern	Historical analysis, literature review	Establishment of fatigue as a crucial pattern	Continuous research needed to explore evolving aspects of fatigue and its implications in different materials.
Wöhler (Collins, 1993)	Conduct first long-term fatigue experiment with metals	Experimental testing, development of S-N curve	Generation of the S-N curve	Subsequent refinement of fatigue testing methods and understanding of fatigue phenomena.

Basquin, 1910	Develop power law equation for S-N curve	Mathematical modeling based on fatigue strength and life cycles	Equation for S-N curve	Continuous validation and improvement of the equation with diverse materials and loading conditions.
Friedrich, 2012; X. Zhao et a, 2019	Explore fatigue degradation mechanisms in non-hybrid composites	Experimental testing, analysis of fatigue damage mechanisms	Understanding of fatigue damage mechanisms	Further investigation needed to adapt knowledge to hybrid composites and explore hybrid-specific fatigue degradation.
Ribeiro et al., 2021	Investigate fatigue mechanisms in hybrid composites	Experimental testing, analysis of fatigue behavior in glass/carbon hybrid composites	Study of fatigue lifespan and mechanisms	Exploration of optimal dispersion and adhesion between fibers to enhance tensile fatigue resistance in hybrid composites.
Fernando et al., 1988	Study fatigue behavior of glass/carbon hybrid material	Comparative analysis of S-N slope in glass/carbon hybrid material	Comparison of S-N slope in hybrid material	Further investigation needed to understand the impact of hybridization on S-N slope and fatigue lifespan.
Hashim et al., 2019	Assess tensile-tensile fatigue behavior of carbon/aramid fiber hybrid composites	Experimental testing, analysis of tensile-tensile fatigue behavior	Understanding of factors affecting fatigue behavior	Continuous research needed to explore and optimize the influence of fiber types and configurations on tensile-tensile fatigue behavior in hybrid composites.
Marom et al., 1989	Investigate fatigue behavior of composites reinforced with aramid and carbon fibers in a sandwich configuration	Experimental testing, analysis of fatigue behavior	Improved fatigue behavior in hybrid composites	Further exploration needed to understand the specific benefits of sandwich configurations in hybrid composites.
Dai & Mishnaevsky, 2014	Study fatigue degradation in glass/carbon hybrid composites	Modeling study, analysis of fatigue damage and stiffness deterioration	Insight into fatigue degradation mechanisms	Continuous research needed to validate and refine modeling predictions, exploring various hybrid configurations.
Shan & Liao, 2002	Analyze tension-tension fatigue life in interply carbon/glass hybrid composite	Experimental testing, analysis of fatigue life	Linear relationship with volume ratio of carbon fibers	Further research required to optimize the volume ratio for enhanced fatigue life under tension-tension cyclic loading.
Belingardi et al., 2006	Study fatigue behavior of hybrid epoxy matrix composite with intraply biaxial glass-carbon laminae	Experimental testing, analysis of fatigue behavior	Impact of fatigue loading on stiffness reduction	Exploration of factors influencing stiffness reduction and strategies for minimizing deterioration under fatigue loading.
Habibi et al., 2019	Investigate the impact of moisture on fatigue modulus in nonwoven flax epoxy composites	Experimental testing, analysis of fatigue modulus in moist conditions	Sequential drop in fatigue modulus values	Further study needed to optimize material composition and explore ways to mitigate the impact of moisture on fatigue properties.
Shan & Liao, 2002	Evaluate GFRP & G/C hybrid composites' fatigue life under wet conditions	Experimental testing, exposure to moist conditions	Reduction in fatigue life under wet conditions	Research on strategies to enhance resistance to environmental cyclic loading and maintain fatigue life in hybrid composites.
Fan et al., 2019	Analyze the impact of 3D diagonal structure on delamination in C/G hybrid composites	Experimental testing, analysis of delamination behavior	Slower rate of delamination in 3D diagonal structure	Exploration of the applicability of 3D diagonal structures for enhanced fatigue resistance and delamination prevention.
Ladani et al., 2019	Investigate self-healing properties of 3D textile composite with z-binders	Experimental testing, analysis of fatigue lifespan and fracture resistance	Improved fatigue lifespan and fracture formation resistance	Further exploration needed to optimize the z-binder composition and distribution for enhanced self-healing and fatigue performance.
Brugo et al., 2017	Assess the impact of PA66 microfibers on fatigue resistance in CFRP	Experimental testing, analysis of fatigue performance with PA66 microfibers	30 times reduction in fracture rate	Investigation of optimal thickness and distribution of PA66 microfibers for fatigue resistance and damage tolerance.
Alawar et al., 2005	Study the influence of interleaving carbon nano-fibers on axial fatigue life	Experimental testing, analysis of axial fatigue life with carbon nano-fibers	150-670% increase in axial fatigue life	Further research required to optimize the integration of carbon nano-fibers for improved fatigue resistance.
Fotouh et al., 2014	Explore advantages of using natural fibers over synthetic ones	Comparative analysis of carbon footprint, mechanical properties, and environmental benefits	Lower carbon footprint, better mechanical properties, and environmental benefits	Continuous exploration of natural fibers in hybrid composites for sustainable and high-performance applications.

Thwe & Liao, 2003	Investigate fatigue life of hybrid composites made from glass and bamboo fibers	Experimental testing, analysis of fatigue life	Superior normalized fatigue resistance in hybrid composites	Further optimization needed to understand the specific benefits and ideal compositions of glass and bamboo fiber hybridization.
Seghini et al., 2020	Examine the impact of flux addition on fatigue resistance in basalt laminates	Experimental testing, analysis of fatigue resistance with flux addition	Improved fatigue resistance in basalt laminates	Exploration of optimal flux types and concentrations for enhancing fatigue resistance in basalt laminates.
Shahzad & Isaac, 2008	Investigate the impact of hemp fiber reinforcement on fatigue sensitivity	Experimental testing, analysis of fatigue life with hemp fiber reinforcement	Reduction in fatigue sensitivity with hemp fibers	Further study needed to optimize hemp fiber content and configurations for reduced fatigue sensitivity in hybrid composites.
Mostafa, 2019	Assess the reduction of fatigue sensitivity with the addition of jute fibers	Experimental testing, analysis of fatigue sensitivity with jute fiber addition	Reduction in fatigue sensitivity with jute fibers	Exploration of optimal jute fiber content and configurations for mitigating fatigue sensitivity in hybrid composites.
Sharba et al., 2016	Investigate the impact of different types of kenaf fibers on fatigue life	Experimental testing, analysis of fatigue life with woven, UD, and non-woven kenaf fibers	Variation in fatigue degradation coefficient	Further study required to understand the influence of kenaf fiber types on fatigue life and identify optimal configurations.

4. Conclusion

This paper examines hybrid metal composite materials reinforced with different fibers' failure processes, fatigue resistance, and fatigue damage mechanisms. The study delves into the behavior of these materials under various loading conditions, including tension-tension, compression-compression, and tension-compression cycles. The authors investigate the impact of factors such as fiber orientation, volume/fraction, and processing methods on the fatigue life of the composites.

The study discusses the performance of hybrid composites in comparison to non-hybrid composites and highlights the benefits of using hybrid materials in terms of fatigue resistance. We look at different kinds of hybrid composites, like carbon/glass, carbon/aramid, and carbon/high-performance polyethylene (HP-PE) hybrids, focusing on how they behave under fatigue and how they work together. Additionally, the authors explore the influence of environmental factors, such as moisture and temperature, on the fatigue degradation of hybrid composites. The study suggests that some hybrid designs, like mixed hybrids with treated PE fibers, have better fatigue resistance when loaded in the environment.

The paragraphs also discuss strategies for mitigating fatigue failure mechanisms, such as delamination, through techniques like stitching, z-anchoring, z-pinning, or weaving. The inclusion of 3D reinforcements and self-healing mechanisms is explored to enhance fatigue resistance. The authors provide insights into the fatigue behavior of hybrid composites reinforced with natural fibers, such as bamboo and jute, emphasizing their advantages in terms of low density, good technical qualities, and benefits for the environment. However, challenges such as fiber waviness, manufacturing faults, and low moisture resistance are acknowledged for natural hybrid composites. In summary, the paragraphs cover a wide range of topics related to the mechanical behavior and fatigue resistance of hybrid metal composite materials, offering a comprehensive overview of the research findings in this field.

Hybrid composite shows better fatigue resistance than traditional materials, but the material-specific weaknesses and environmental challenges are whole potential hinges. Future work will focus on aviation, car and renewable energy fields to unlock the next generation applications, focus on the devices, advanced reinforcement and strong future tools from Table 1 Hybridization (e.g., glass/carbon, aramid/carbon) improves fatigue resistance (Fernando et al., 1988; Marom et al., 1989), but fiber dispersion, adhesion, and volume ratios (Shan & Liao, 2002) critically influence performance.

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