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Advances in Mechanical Joining Techniques for Metal–Composite Hybrid Structures—A Mini Review

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Abstract

The integration of fiber-reinforced polymer (FRP) composites with metal components in aerospace and automotive structures presents significant mechanical and design challenges, especially when conventional bolted joints induce fiber disruption and delamination. This mini review provides a comprehensive evaluation of emerging mechanical joining techniques developed to address these limitations. Key approaches discussed include self-piercing and friction riveting, mechanical clinching, non-adhesive form-locked joints, pin and loop joining, and recent advances enabled by additive manufacturing technologies. Each technique is examined in terms of joining mechanism, material compatibility, process constraints, and structural performance. Additionally, the role of nanofiber reinforcement in enhancing the interlaminar toughness of composite laminates is explored, emphasizing its effect on joint durability and resistance to failure. Comparative insights are offered on joint reversibility, complexity, galvanic behavior, and suitability for thermoplastic and thermoset matrices. Despite notable progress, most advanced joining strategies still face practical hurdles related to manufacturability, scalability, and long-term environmental durability. The review highlights that minimizing fiber damage often entails increased process complexity and cost. Therefore, future directions should focus on developing standardized evaluation protocols, optimizing additive manufacturing for multi-material interfaces, and integrating nanoscale reinforcements to achieve structurally robust, lightweight, and corrosion-resistant hybrid assemblies. This synthesis serves as a technical guide for engineers and researchers aiming to design next-generation composite–metal joints for high-performance applications.

Keywords: Composite–metal Joints; Additive Manufacturing; Fiber Reinforcement; Mechanical Joining; Hybrid Structures

1. Introduction

The integration of fiber-reinforced polymer (FRP) composites with metallic components is increasingly critical in aerospace and automotive industries due to the need for lightweight, high-performance hybrid structures. However, the conventional application of bolted joints in composite assemblies introduces several disadvantages, such as fiber disruption, delamination, and elevated stress concentrations [1–3]. These issues undermine structural integrity and reduce fatigue life. In response to these challenges, alternative mechanical joining techniques have been developed to improve compatibility with composite architectures and to optimize joint performance. Prominent among these techniques are self-piercing riveting (SPR), friction riveting (FR), mechanical clinching, pin-and-loop joining, and adhesive-free form-locked joints [4–6]. These methods aim to enhance joint strength, minimize material degradation, and streamline assembly operations. While certain techniques, such as SPR and clinching, have achieved commercial viability in automotive applications, others—such as pin-and-loop joining—remain under experimental investigation.

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These joining approaches differ in terms of reversibility, manufacturing feasibility, added weight, and their applicability to thermoset or thermoplastic matrix systems [7, 8]. This mini-review presents a synthesis of current mechanical joining strategies for FRP-metal interfaces. The review outlines their underlying principles, benefits, limitations, and key experimental findings. The objective is to inform materials engineers and structural designers in selecting suitable joining techniques based on specific performance requirements, damage tolerance, and manufacturing constraints.

2. Riveted Joints

Riveted joints are among the most established mechanical fastening methods and continue to be widely used in structural applications within the aerospace and automotive industries. However, the implementation of traditional riveting in fiber-reinforced polymer (FRP) composites presents significant challenges. The process typically requires hole drilling, which may induce matrix cracking, fiber breakage, and delamination, thereby compromising the mechanical integrity of the composite assembly [1–3]. To mitigate these issues, advanced variants such as self-piercing riveting (SPR) and friction riveting (FR) have been introduced. These methods are engineered to minimize or eliminate the need for pre-drilled holes, thereby reducing stress concentrations and material damage. Additionally, SPR and FR have demonstrated improved joint reliability and mechanical performance in hybrid FRP-metal structures [7, 4].

2.1. Self-Piercing Riveting (SPR)

Self-piercing riveting (SPR) is a mechanical fastening technique that facilitates the joining of two or more sheets of similar or dissimilar materials without the need for pre-drilled holes. In this process, a semi-tubular rivet is driven into the material stack, penetrating the upper layers and flaring within the bottom layer to form a mechanical interlock. The SPR technique eliminates pre-drilled holes by plastically deforming the rivet into a mechanical interlock with the bottom layer, as illustrated in Fig. 1.

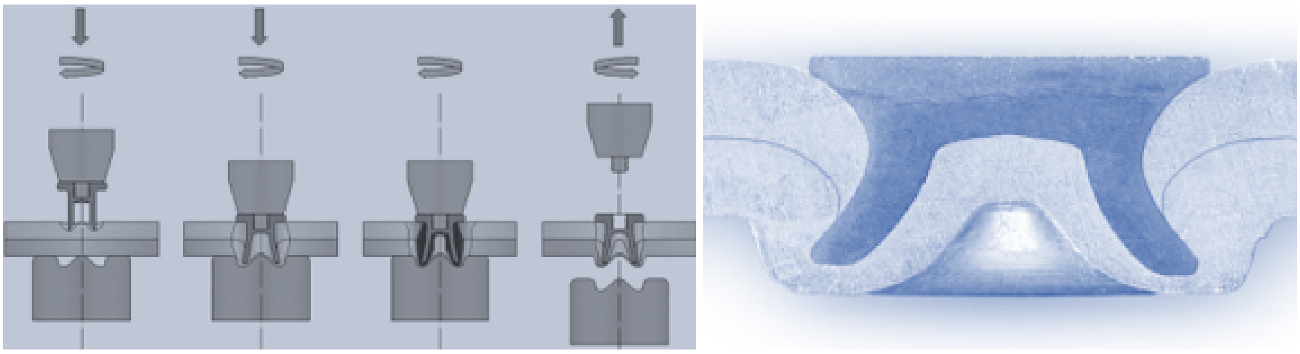


Figure 1: Self-Piercing Riveting (SPR): Schematic of the joining process and a cross-sectional view of a dissimilar material joint.

This method is particularly beneficial for hybrid joints involving fiber-reinforced polymers (FRPs) and metals, as it eliminates the need for drilling and thereby preserves the structural integrity of the composite material [9, 4]. SPR has been extensively adopted in the automotive sector and is increasingly being applied in aerospace and other high-performance fields. Displacement of composite plies without visible delamination in FRP-metal assemblies has been reported, suggesting a favorable stress distribution mechanism. Strong mechanical joints between polyamide-based composites and aluminum substrates have also been demonstrated, supporting the suitability of SPR for thermoplastic matrix composites [10]. The geometric design of the rivet and die significantly influences joint quality. Parameters such as rivet diameter, head geometry, and die cavity profile have been shown to affect the mechanical interlock and load-bearing capacity [11]. Fatigue testing of SPR joints indicates improved durability with optimized rivet head configurations [12]. A detailed cross-sectional analysis of SPR in CFRP laminates reveals the rivet flare geometry, residual thickness ($t_{\min}$), and key load-bearing features (Fig. 2). Hybrid joints combining SPR with adhesives have exhibited enhanced shear strength and energy absorption [13]. Despite its advantages, SPR has certain limitations. The joints are generally irreversible, and galvanic corrosion may occur when dissimilar materials are joined. Furthermore, under cyclic loading or in aggressive environments, minor delamination or micro-cracking may still develop, potentially affecting long-term durability.

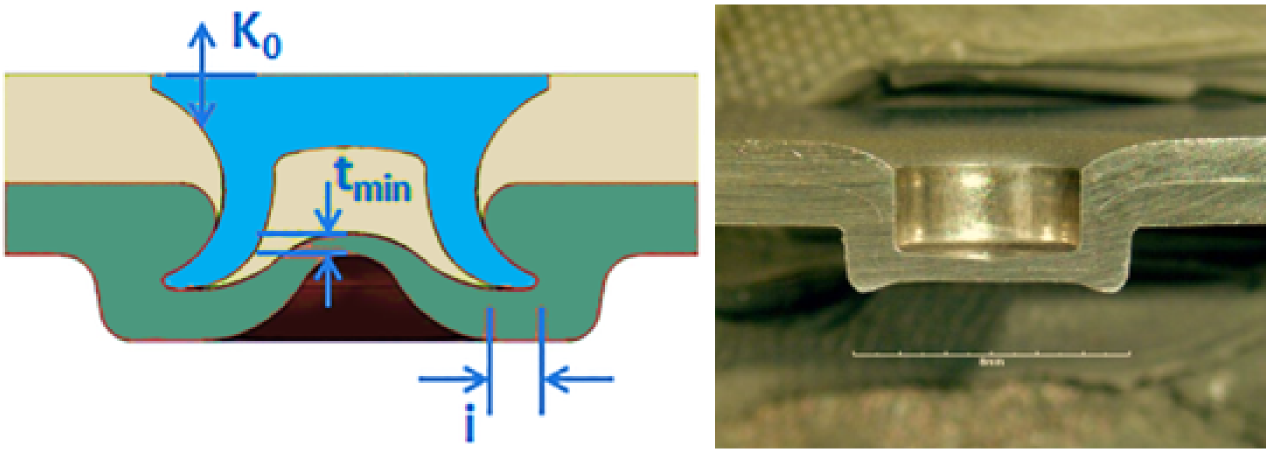


Figure 2: Cross-sectional insight into Self-Piercing Riveting (SPR) joining of Carbon Fiber Reinforced Plastic (CFRP) laminate: Photographic and schematic representation showing residual thickness ($t_{\min}$) and stress directions.

2.2. Friction Riveting (FR)

Friction riveting (FR) is a thermomechanical joining technique primarily designed for thermoplastic composites, wherein a rotating metallic rivet is inserted into a polymeric base, generating heat through friction. This heat softens the polymer, allowing the rivet to plastically deform and anchor into the matrix, thereby forming a mechanical interlock. The process eliminates the need for pre-drilled holes, adhesives, or additional fasteners [7]. FR is particularly effective for joining thermoplastic matrix composites to metallic substrates. Experimental studies have shown that higher rotational speeds enhance pull-out strength, while controlled temperatures help minimize thermal degradation [14]. Strong and stable joints have been achieved between glass fiber-reinforced polyester composites and metallic rivets, demonstrating high mechanical performance with limited thermal impact [15]. An evolution of this technique, known as Friction Stir Blind Riveting (FSBR), has been applied to carbon fiber-reinforced plastic (CFRP) and aluminum alloy (AA6111) joints, confirming robust interfacial bonding and effective load transfer in brittle laminates [16]. Further research has indicated that threaded titanium rivets can achieve joint strengths up to 199 MPa in glass fiber laminates, surpassing those of conventional bolted joints. In short carbon fiber-reinforced polyether ether ketone (PEEK), pull-out strengths of 10.7 kN have been reported, with deformation modes such as rivet mushrooming—observed at approximately 70% deformation—indicating efficient energy absorption [15]. Despite its advantages, FR is inherently irreversible and limited to thermoplastic systems. Precise thermal control is essential to prevent degradation of the polymer, especially at elevated speeds or during prolonged friction cycles. Nonetheless, due to its efficiency, mechanical reliability, and compatibility with automated processes, FR presents a promising solution for advanced composite-metal joining applications.

3. Mechanical Clinching

Clinching is a mechanical fastening process that joins sheet materials through localized plastic deformation, forming a mechanical interlock without the need for auxiliary elements such as rivets or adhesives. Originally developed for ductile metals, this technique has been adapted for joining fiber-reinforced polymer (FRP) composites to metals through the use of modified tool geometries and thermal assistance [5, 8]. In hybrid structures, the more malleable metal sheet is typically placed on the punch side, enabling it to deform into the composite layer, which may require localized softening to avoid brittle fracture and delamination. Thermal assistance, including thermo-clinching and induction heating, is often employed for this purpose. Although the process is irreversible, it is rapid, cost-effective, and well-suited for lightweight structural applications, particularly with thermoplastic matrix composites [17]. Investigations into the influence of tool geometry and composite thickness have shown that parameters such as punch diameter, corner radius, and die depth significantly affect joint integrity and strength. Various die configurations—including round grooved, split, and flat dies—have been found to influence material flow and mechanical entrapment behavior [18].Different clinching die geometries—such as round split, grooved, flat, and rectangular shear—are shown in Fig. 3, each contributing uniquely to material flow and joint strength.

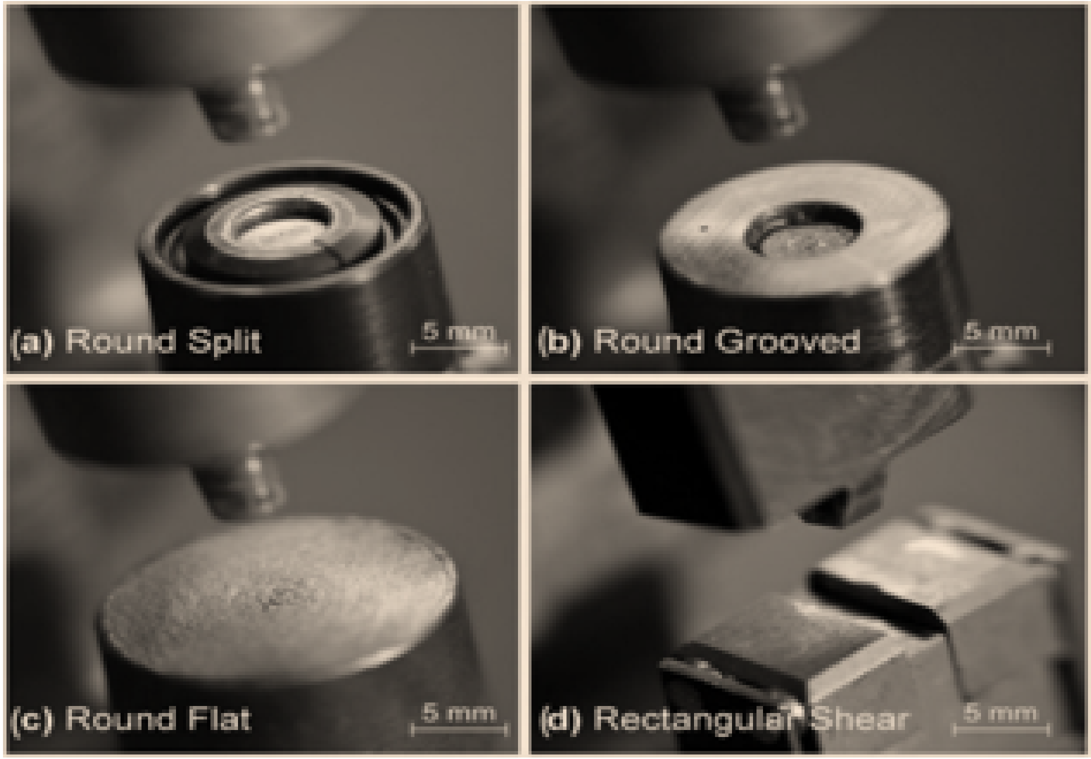


Figure 3: Clinching dies: (a) round split; (b) round grooved; (c) round flat; and (d) rectangular shear.

A variation known as Injection Clinching Joining (ICJ) involves softening a polymeric stud and pressing it into a pre-formed hole, creating a form-locked joint upon cooling. This method has demonstrated enhanced load-bearing capacity while limiting material degradation [19]. The evolution of the ICJ process is illustrated in Fig. 4, showing thermal softening and subsequent mechanical interlock formation in a time-sequenced manner. Another development, friction-assisted clinching, has reduced the joining force required but occasionally led to pull-out failures under tensile loads. Hybrid approaches that integrate clinching with friction stir welding have also been explored. Typical failure modes in friction stir welded hybrid joints include shearing of surface protrusions and interfacial separation between sheets, as shown in Fig. 5. These combinations improve interfacial bonding and reduce residual stresses in joints between aluminum sheets and self-reinforced polypropylene [17]. Nonetheless, issues such as delamination, fiber misalignment, and limited applicability to thermoset composites continue to hinder broader adoption of clinching in FRP-metal hybrid structures.

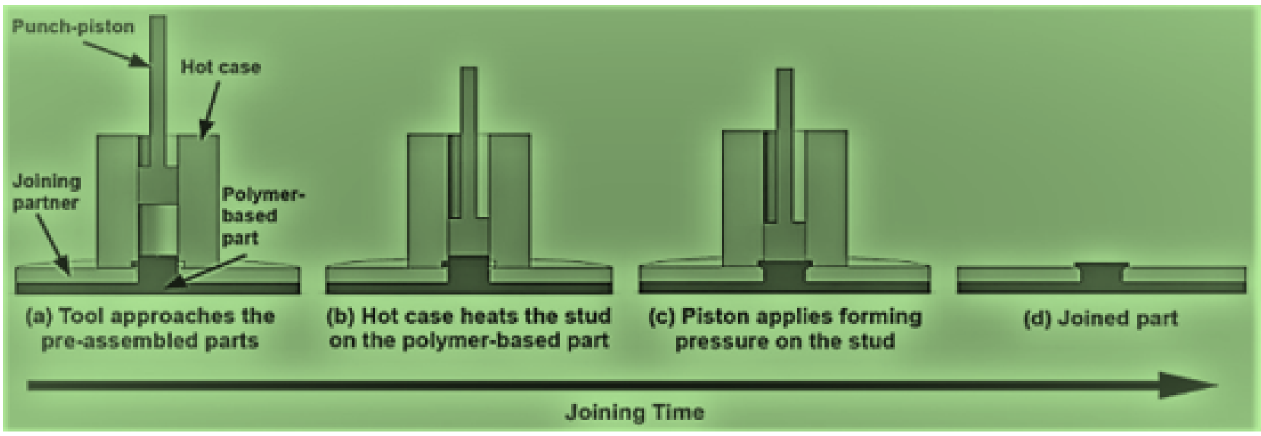


Figure 4: Stepwise evolution of the Induction Clinching Joining (ICJ) process: (a) tool approach to pre-assembled parts, (b) hot case heating the stud on polymer-based part, (c) piston applying forming pressure on the stud, and (d) joined part.

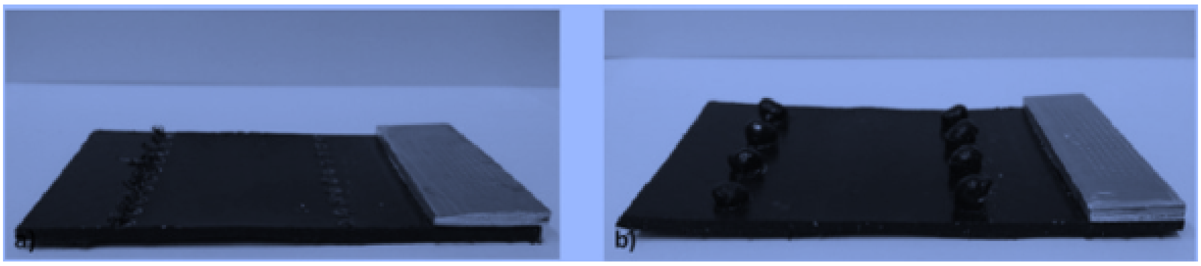


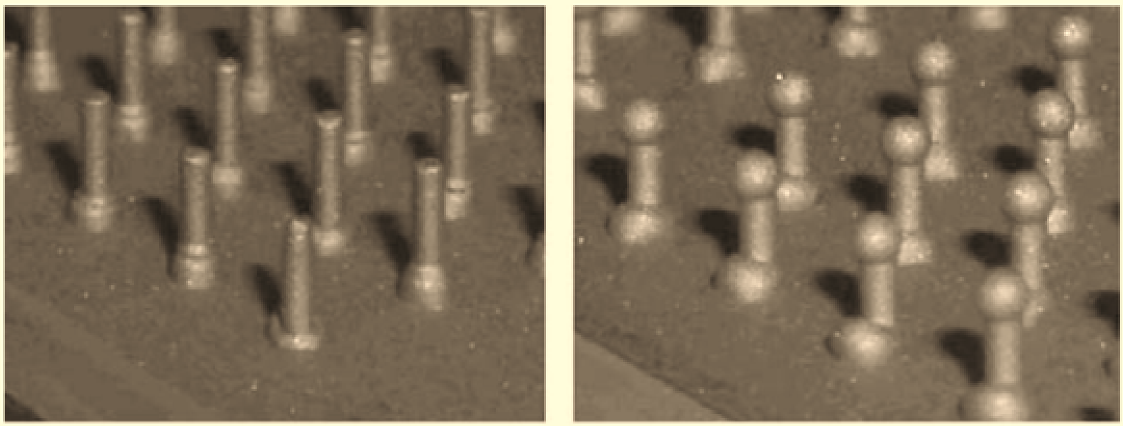
Figure 5: Unraveling failure modes in friction stir welded specimens: (a) shearing of protrusions, (b) sheets separation.

4. Non-Adhesive Form-Locked Joints

Traditional bolted joints in composite structures often induce detrimental effects such as fiber pull-out, matrix cracking, and delamination, particularly during the drilling process. To overcome these limitations, a novel non-adhesive form-locked joint configuration has been developed, utilizing metallic inserts to create a mechanical interlock with the composite laminate without the use of adhesives or bolts [5]. This design enhances joint strength while minimizing structural damage. The method has been successfully employed in the construction of composite gliders and motogliders, including models such as the PW-5, PW-6, and AOS-71. The process involves embedding a metal ring into a pre-formed hole within the composite laminate, thereby distributing mechanical loads across a broader area and reducing stress concentrations [20]. Experimental investigations have reported tensile static strengths ranging from 60 to 70 kN. Post-failure analyses using computed tomography scans revealed matrix cracking and localized delamination as primary failure mechanisms, confirming the technique's effectiveness in controlling stress distribution and resisting mechanical degradation. Despite these advantages, the incorporation of metallic rings introduces added complexity and weight. Moreover, the combination of dissimilar materials poses potential issues related to galvanic corrosion [9]. Nevertheless, non-adhesive form-locked joints represent a promising solution for aerospace and automotive applications that demand robust and damage-tolerant composite-metal connections. Their ability to preserve laminate integrity while delivering high load-bearing capacity underscores their value in the advancement of hybrid joining technologies.

5. Pin Joining

Pin joining involves embedding metallic pins, protruding from a metal adherend, into fiber-reinforced polymer (FRP) composites to establish a three-dimensional mechanical interlock between dissimilar materials. These pins, typically manufactured using Selective Laser Melting (SLM) or Powder Bed Fusion (PBF), are positioned prior to composite curing. During the fabrication process, reinforcing fibers are molded around the pins, producing robust through-thickness reinforcement [21, 22]. Figure 6 illustrates the comparative geometries of cylinder and ball-head pins used in composite-metal joints, highlighting their influence on mechanical anchoring and interfacial strength.



(a) Cylinder Pins (b) Ball-head Pins

Figure 6: Comparative shapes of metal pins: (a) cylinder and (b) ball-head, unveiling varied configurations in composite–metal pin joints.

Studies on pin pull-out behavior in hybrid metal-composite specimens have shown that single-pin configurations provide interfacial strengths approximately 3.5 times greater than those of conventional carbon-fiber z-pins. Multi-pin arrangements demonstrated a 365% improvement in Mode I fracture toughness, with finite element models accurately predicting mechanical responses without the need for recalibration [21]. Recent investigations into pin geometries produced via laser powder bed fusion (LPBF) revealed that optimized micro-pin shapes enhance pull-out strength and energy absorption while limiting fiber damage in carbon–epoxy laminates [22]. Additional research has confirmed that SLM-fabricated titanium pins, embedded within CFRP layers, substantially increase load-bearing capacity. These joints exhibit superior metal–composite adhesion and greater resistance to failure than unpinned or adhesive-only configurations [23]. Overall, joint performance is strongly influenced by pin geometry, surface texture, material compatibility, and the precision of additive manufacturing processes.The impact of geometric configuration on interfacial strength is exemplified by the distinct profiles of wedge-shaped and cylindrical pins, as shown in Fig. 7. Pin

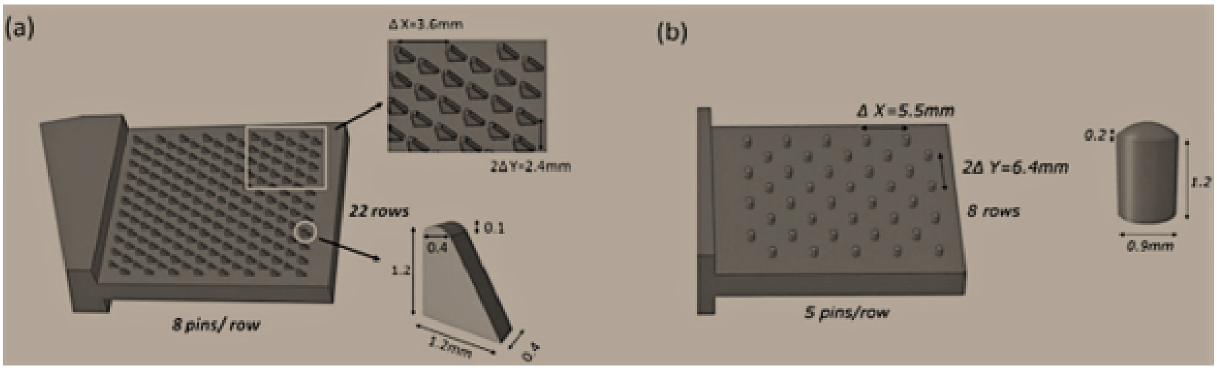


Figure 7: Profiles of different pin shapes: (a) wedge-profiled and (b) cylindrical, showing layout density and dimensional details for composite–metal joint interfaces.

joining offers notable benefits such as enhanced damage tolerance and residual strength, achieved through distributed load paths and effective fiber bridging. Nevertheless, challenges remain, including high manufacturing costs, galvanic corrosion risks, and the need for precise insertion techniques to prevent micro-cracking within the composite structure.

6. Loop Joining

Loop joining is an emerging mechanical technique designed for connecting carbon fiber-reinforced polymer (CFRP) composites to aluminum substrates. This approach involves the integration of metallic or fiber-based loops into the aluminum surface through welding or casting. The open ends of these loops are subsequently threaded with composite fibers, forming a mechanical interlock upon resin consolidation [5, 24]. To address the galvanic corrosion commonly observed in aluminum–CFRP hybrids, transitional materials such as titanium, glass, or boron are introduced to mitigate electrochemical potential mismatches [5]. One notable implementation—the “wire loop” concept—utilizes laser- or conduction-welded titanium loops affixed to aluminum substrates. Composite fiber rovings are threaded through the loops, preloaded, and embedded in resin. Static tensile tests have reported strengths of approximately 3,000 N for three-loop configurations and 8,000 N for five loops, with failures typically occurring via loop fracture rather than composite delamination [5]. Further studies have verified this technique using 0.8 mm titanium loops laser-joined to aluminum, followed by composite embedding. Observed failure consistently occurred in the loop alloy prior to composite separation [5]. Additional developments have employed glass fiber loops to reduce weight and improve corrosion resistance; however, mechanical performance data for these configurations remain limited [5]. Another variation incorporated titanium foil loops bonded within a groove on the aluminum surface, creating a hybrid Al–Ti–CFRP laminate.Figure 8 illustrates three joining strategies—loop, foil, and fiber concepts—used for integrating CFRP to aluminum, each addressing mechanical anchoring and galvanic isolation in different ways. Tensile strength data for this configuration also remain insufficient [5]. Despite its innovative interlocking potential and inherent galvanic isolation, loop joining faces several limitations. These include a complex, labor-intensive manufacturing process, relatively low joint strength, and failure modes concentrated within the loop element. Consequently, this technique remains in the experimental phase and requires further refinement for broader industrial adoption.

7. Additive Manufacturing

Additive manufacturing (AM) techniques such as Selective Laser Melting (SLM), Laser Metal Deposition (LMD), and Cold Metal Transfer (CMT) provide advanced capabilities for fabricating pin arrays and interlocking structures directly onto metallic substrates for composite-metal joints. These technologies offer precise control over geometry, surface texture, and material transitions, enabling enhanced mechanical interlocking and improved damage tolerance [25, 26].

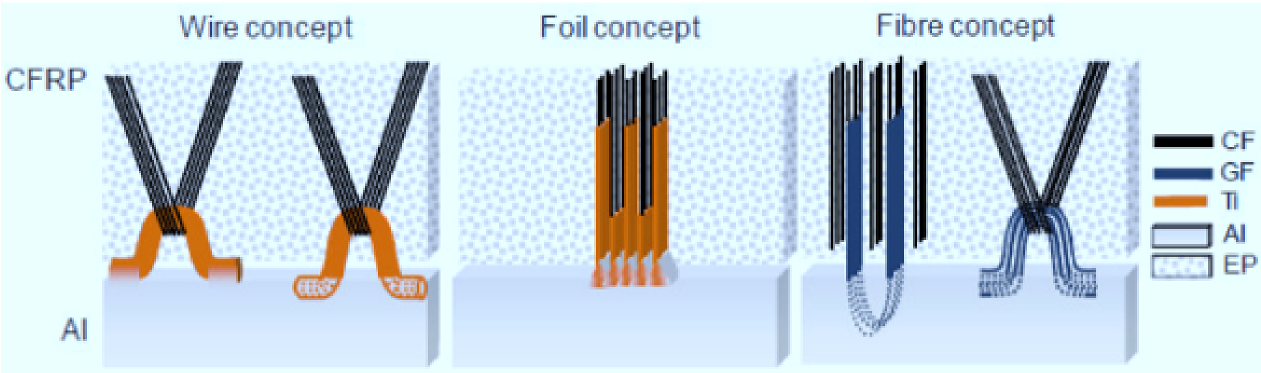


Figure 8: Concepts of joining CFRP to aluminum by (left) wire loops, (middle) foil inserts, and (right) fiber bridging. Abbreviations: CF—Carbon Fiber, GF—Glass Fiber, Ti—Titanium, Al—Aluminum, EP—Epoxy.

SLM and LMD support the creation of complex, high-density microstructures on aluminum and titanium surfaces with fine resolution, promoting improved pull-out strength through enhanced interlock and fiber engagement within composite layups [26]. Micro-pin anchors fabricated using laser powder bed fusion (LPBF) have demonstrated increased pull-out strength with minimal fiber disruption in composite materials [22]. Cold Metal Transfer (CMT)-based Wire Arc Additive Manufacturing (WAAM) allows for scalable production of larger pin and stud arrays via controlled metal deposition. These structures form effective mechanical interlocks for overmolded composite layers and are adaptable to various interfacial and thickness requirements [27]. CMT-deposited pins with adjustable heights ranging from 2.5 mm to 15 mm enable flexibility for diverse joint designs [28]. Hybrid AM approaches that combine metal and polymer processing—such as powder-bed fusion with fused filament fabrication—have been used to fabricate integrated metal–composite assemblies. A representative hybrid system used for additive manufacturing of metal–polymer joints is shown in Fig. 9, combining powder spraying and filament extrusion for integrated part fabrication.

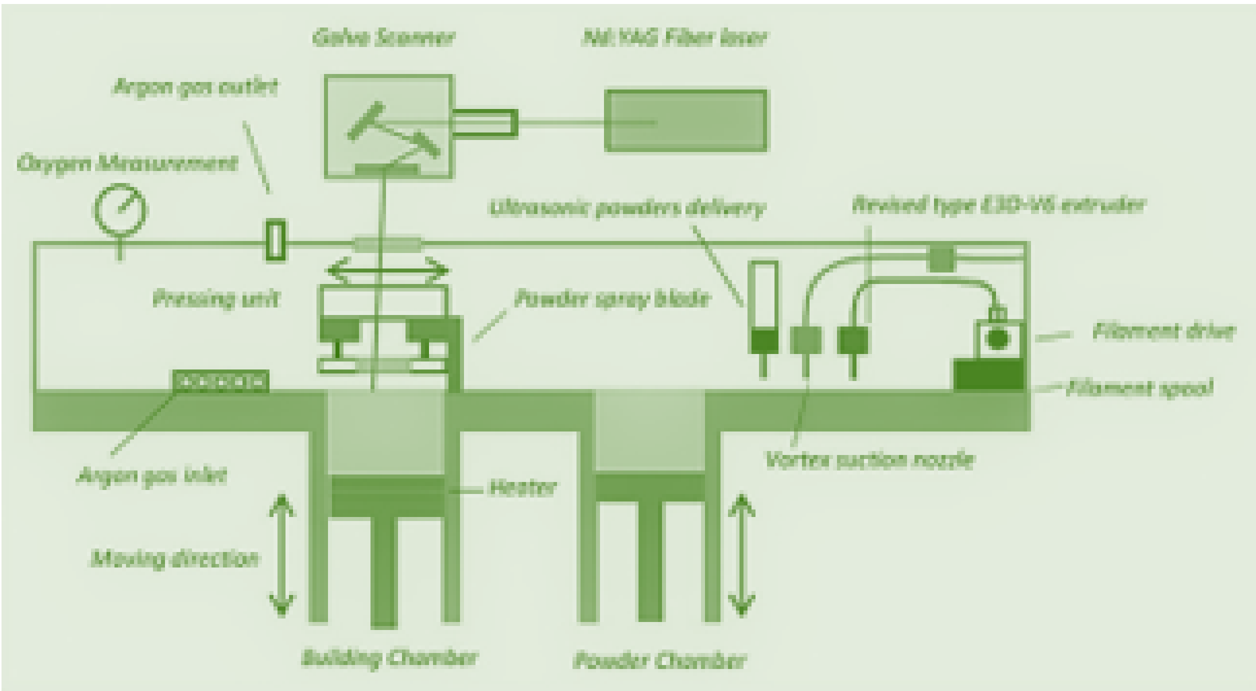


Figure 9: Printing system developed for additive manufacturing of joined metallic and polymer parts, integrating powder spray and filament extrusion modules.

Reported interface strengths exceeding 20 MPa for stainless steel–PET laminates highlight the viability of this approach [29]. Despite these advancements, AM-enabled joint designs face ongoing challenges related to thermal compatibility, material integration, cost, and cycle time. Nevertheless, AM offers significant potential for engineering high-performance, tailored metal–composite joints in aerospace and industrial applications.

8. Mechanical Joining with Nanofiber-Reinforced Composites

Carbon nanotubes (CNTs) and carbon nanofibers (CNFs) have been extensively utilized to reinforce polymer matrices, significantly improving interlaminar toughness and out-of-plane strength—properties essential to the performance of mechanically joined composite structures [30, 31]. These reinforcements delay crack initiation and propagation, thereby enhancing delamination resistance. Electrospun nanofiber veils interleaved between laminate layers have been shown to improve both Mode I and Mode II fracture toughness by up to 60%, without increasing structural weight or complexity near joint areas [32, 30]. The improved fracture resistance enhances tolerance to damage induced by drilling and mechanical fastening techniques, supporting the durability of joints formed by self-piercing riveting, clinching, and pin embedding. Despite these mechanical benefits, direct integration methods for combining nanofiber-reinforced composites with metals remain limited. Current research has primarily emphasized adhesive bonding and laminate-level enhancements. As a result, repurposing existing mechanical joining strategies for use with nanofiber-toughened composites appears to be the most viable near-term approach for achieving improved durability and mechanical resilience in hybrid structures.

9. Conclusions

This mini-review synthesized current advancements in mechanical joining techniques for hybrid metal–composite structures. Self-piercing and friction riveting offer significant advantages over conventional riveting by minimizing damage, although they are limited by irreversibility and, in the case of friction riveting, by compatibility with thermoplastic matrices. Mechanical clinching enables efficient, bolt-free joints with moderate damage control, primarily benefiting thermoplastic composites. Non-adhesive form-locked joints provide high-strength, reversible connections using metallic inserts but introduce added weight and design complexity. Pin and loop joining techniques, although promising due to their superior mechanical interlocks, are still under experimental development and require optimization in terms of manufacturability and corrosion resistance. Additive manufacturing enhances joint design by enabling complex interlocking pin geometries tailored to specific interfaces, yet cost and scalability remain hurdles. Lastly, the integration of nanofiber-reinforced composites significantly improves interlaminar strength and delamination resistance, suggesting potential for enhanced joint durability, though current joining techniques require further adaptation to fully leverage these materials. In summary, the trade-off between reducing damage and increasing process complexity remains a central challenge. Future research should focus on standardizing testing protocols, refining additive manufacturing applications, and integrating nanomaterial technologies to develop robust, scalable, and corrosion-resistant joints for demanding aerospace and automotive environments.

Declaration of Competing Interests

The author declares no known competing financial interests or personal relationships.

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Author Contributions

Suresh Tiwari: Conceptualization, Methodology, Investigation, Data Analysis, Writing – Original Draft, Review and Editing, Visualization.

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