RECENT ADVANCES IN ADHESIVE BONDING OF 3D-PRINTED PARTS AND METHODS TO INCREASE THEIR MECHANICAL PERFORMANCE

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ABSTRACT

The use of additive manufacturing (AM) has revolutionized the production of polymer-based materials, offering a wide range of design possibilities and geometric complexity. However, due to the limitations of 3D printers to produce large parts, the parts often must be printed in several separate components and further joined together to obtain the final 3D-printed part. 3D printing can be used to produce only the most complex parts, which can be further combined with simple, non-printed parts from other materials to make the final product. One way to join 3D-printed part is an adhesive-bonded method. This paper focuses on the recent advances in adhesive bonding techniques for 3D-printed parts and explores various methods to enhance their mechanical performance. The benefits and limitations of each technique were discussed, and highlighted promising paths for future research. Finally, this paper provides a comprehensive overview of the current strategies to improve the mechanical performance of adhesive joints with AM-based adherents, offering guidance for the design and fabrication of high-performance structures in a range of applications. It was concluded that the configuration of the bonding area represents an essential parameter that directly influences the bonding strength and overall structural integrity of AM adhesive joints, and that the implementation of customized joint geometries can lead to a substantial enhancement in the joint strength of 3D-printed parts. The incorporation of reinforcing materials, optimization of the printing parameters of adherents, pre and post-treatment methods show potential in enhancing the bonding strength of the 3D-printed joints. The synergistic integration of these cutting-edge technologies can yield mutual advantages that complement each other, ultimately resulting in an enhanced overall performance for AM parts.

KEYWORDS: adhesive joints, additive manufactured adherends, polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), mechanical performance

1. INTRODUCTION

Additive Manufacturing (3D printing technology) is a process in which 3D components, with high precision and complexity, are made by depositing materials in a layer-by-layer fashion as opposed to conventional machining or forming methods [1]. It is considered to be the next industrial revolution and has seen growing interest in the last decade, one of the major drivers behind the development of modern 3D printer machines. In that sense, fabrication of prototypes and functional end-products has continuously increased ranging from aerospace and electronics to dentistry and healthcare.

AM have numerous promising applications and the process itself presents unique capabilities, allowing for the fabrication of parts that cannot be produced otherwise or even multi-material simultaneous processing. It can shorten product development time while being cost-effective as multiple machines avoid complete production stops, besides the great number of small pieces with highly different geometries that can be quickly and cheaply produced [2].

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One of the most common methods for 3D printing of polymeric materials is the Fused Filament Fabrication (FFF) or Fused Deposition Modelling (FDM) technique [2]-[4]. This method has proven to be a cost-effective method of manufacturing parts for both household and industrial applications. However, this method presents challenges as the printing properties, such as, raster angle, raster width [5], printing orientation [6], printing temperature [7], printing speed and infill characteristics will affect the mechanical characteristics of the finished part.

Nevertheless, due to the limitations of 3D printers to produce large parts, the parts often must be printed in several, separate components and further joined together to obtain the final printed part. In addition, 3D printing can be used to produce only the most complex parts, which can be further combined with simple, non-printed parts from other materials to make the final product [8]-[11]. One way to join additive manufactured parts is adhesive bonded method. Adhesively bonded joints are used in structural application, especially in automotive and aerospace sectors, because of high strength to weight ratio, design flexibility, damage tolerance, fatigue resistance, etc. [10]-[13].

However, the mechanical performance of adhesive joints in 3D-printed parts can raise concerns. The intrinsic variability in material properties and surface roughness, attributed to the nature of 3D printing, can culminate in diminished bond strength [10], [13]-[15]. Therefore, strategies to enhance the mechanical performance of adhesive joints within 3D-printed components garner importance, proving the reliability and longevity of the final product. Considering these factors, this paper is dedicated to an exploration of diverse techniques and methodologies designed to strengthen adhesive joints in the field of 3D printing.

The methodologies delineated encompass surface modification, cautious material selection, adhesive optimization, innovative joint design, filament, and part reinforcement, among other relevant aspects. A comprehensive understanding of these strategies and their consequences provides manufacturers and engineers with the means to guarantee that adhesive joints, when incorporated into 3D-printed adherends, demonstrate the necessary strength, dependability, and longevity, thereby projecting the course for a robust and enduring industrial future.

2. METHODS TO INCREASE THE MECHANICAL PERFORMANCE OF ADHESIVE JOINTS MADE OF 3D-PRINTED PARTS

The optimization of bonded joints is a crucial factor in increasing the mechanical performance of 3D-printed parts. The design strategies applied in additive manufacturing (AM) play a significant role in achieving this goal, as emphasized by Frascio et al. [14]. The traditional approach of selecting better materials and maximizing bond area in the science of adhesion has been expanded to include alternative joint design strategies. One such strategy is to control stresses on the adhesive interface, adhesive, and adherend, thus achieving higher mechanical strength. Geometrical modifications of the adherend and adhesive are essential in this regard [16].

The science of adhesion has traditionally relied on selecting better materials and maximizing bond area [12]. However, with a better understanding of the physics of adhesion, alternative joint design strategies have been studied. An effective approach involves managing the stresses acting on the adhesive interface, the adhesive material, and the adherend, ultimately leading to enhanced mechanical strength. This is done by configuring stress distribution in a way that minimizes peel and/or cleavage stresses. For instance, Fuse Deposition Modelling (FDM) is a widely used AM technique that produces parts with complex geometries by extruding semi-molten thermoplastic filaments through a heated nozzle [1], [17]. Due to the limited size of the machine's chamber physical dimensions, adhesive joining processes have become necessary to build larger products from smaller assemblies, and adhesively bonded components can address this challenge. In conclusion, optimizing the design of bonded joints involves the application of strategies that can maximize load carrying capacity, and controlling stress distribution is an effective approach to achieve higher bond strength in AM-produced parts.

Khosravani et al. [18] observed that while AM enables a wide range of techniques, there are relatively few publications on the mechanical performance and structural integrity of adhesively bonded parts assembled with 3D-printed adherends, compared to those on adhesively bonded structures. Figure 1 shows different tailoring techniques for improving joints strength, categorized following their form and narrowing by location in the structure.

Overlap geometry tailoring modifies surface properties by modifying the overlap interfaces between adherend and adhesive. This can be achieved through techniques such as printing interfaces in a wavy pattern or adjusting process parameters, like infill density to modify surface morphology. These modifications increase the bonding area and promote mechanical interlocking, resulting in altered stress distribution on the joint.

Bürenhaus et al. [9] investigated the effects of adhesive type, surface character, and bond area design on bond strength. They found that modifying printing parameters by adding a positive air gap or interface structure and varying the raster angle on the top layer improved bond strength. Specifically, a positive air gap was the most effective modification, while a raster angle of 90º should be avoided as it can create a notch effect. However, optimizing adhesion cannot be achieved solely by adjusting the raster angle.

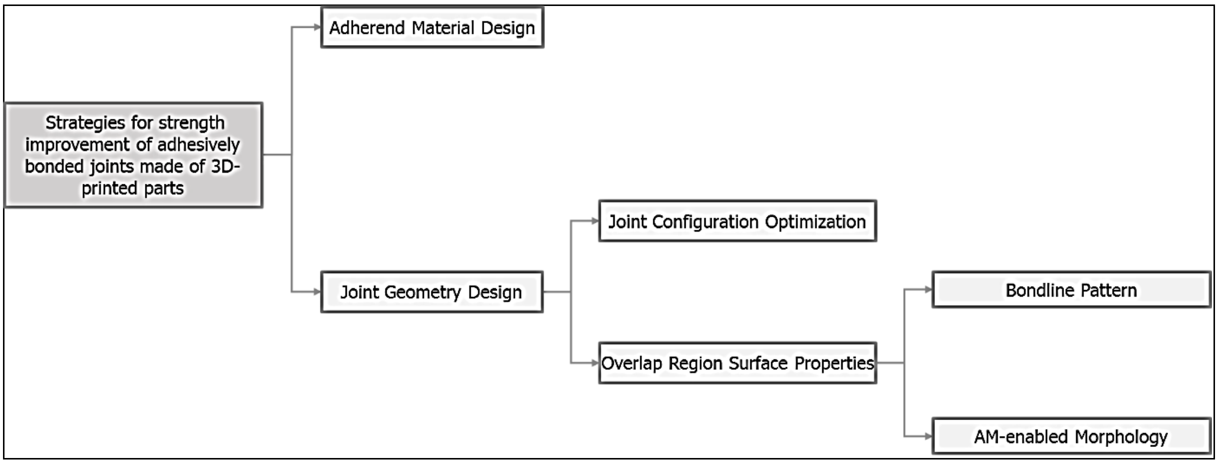

Fig. 1. Schematic of design strategies to improve joint strength for adhesively bonded joints made of 3D parts

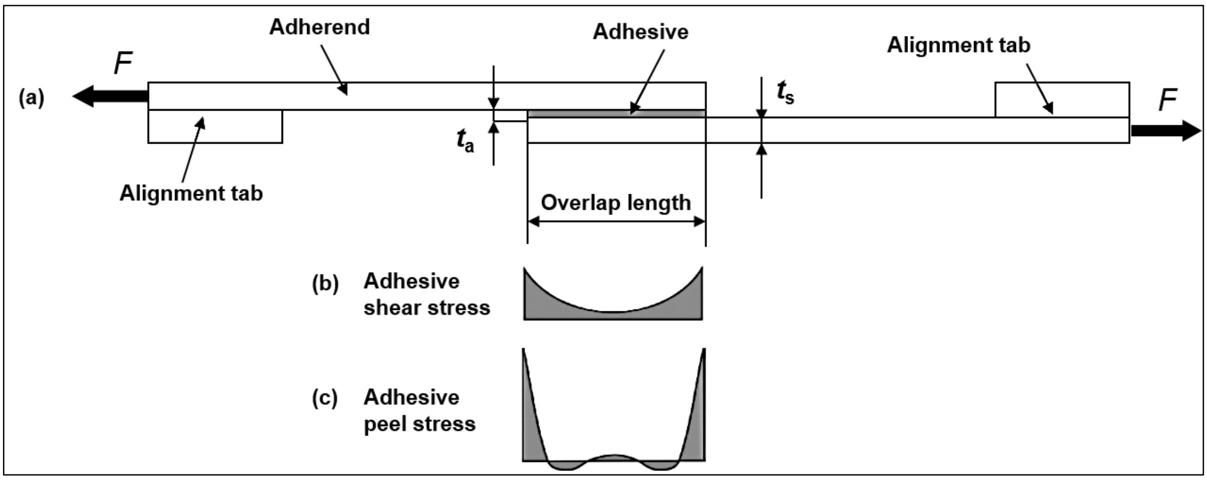

Fig. 2. Stress distribution on a single lap joint

Khosravani et al. [19] investigated the mechanical performance and fracture behaviour of adhesively bonded 3D printed single-lap joints made of Polyethylene terephthalate glycol (PETG) using varying adhesive layer thickness and printing parameters, specifically raster angle and width. Finite element modelling and uniaxial tensile testing were used to analyse the stress distribution and failure behaviour, with a focus on peel and transverse shear stress. Cohesive failure was the dominant failure mode (66% of samples), indicating proper joint fabrication, and specimens with higher stiffness than the rest were obtained. The optimal adhesive layer thickness was found to be 0.2 mm, providing maximum fracture load regardless of printing parameters' effect on the results. Figure 2 illustrates how peel and shear stress is usually distributed along the overlap region of a single-lap joint (SLJ).

Dugbenoo et al. [20] suggested that AM approaches will eventually replace or evolve traditional machining and joining methods. They used an FDM printer with two nozzles to enable AM bonding of continuous carbon fiber composite laminates. The subsequent tailoring design approach increased the available surface area for bonding in SLJ by 150% through setting the infill density parameter for the Nylon matrix at 50%, creating a porous surface on the top layer. Compared to standard surface preparation, they obtained a maximum increase of 145% in ultimate strength and 800% in toughness while maintaining joint stiffness, indicating a higher load capacity can be achieved with cohesive failure between adherend layers.

Kovan et al. [21] investigated the influence of 3D printing parameters and adhesive thickness on the mechanical performance, structural integrity, and failure behaviour of single-lap joints made of industrial-grade epoxy and polylactic acid (PLA) adherends. Tensile tests confirmed that an adhesive layer of 0.2 mm was optimal for joint strength, and cohesive failure was the predominant failure mode, indicating good joint compatibility regardless of the parameters used. Finite element analysis validated their results, suggesting that tools could play a crucial role in optimizing 3D-printed adhesive joints' design.

Garcia & Prabhakar [10] used FDM to modify the joint surface of carbon fibre composite adherends with layers of ABS-M30. They altered the bonded interface geometry by creating different patterns and tested the peak loads, shear stress, and failure types of each specimen. The flat joint had higher peak loads and shear stresses with cohesive failure, while joints reinforced only towards the edges of the interface showed the highest strength. Stress concentrations at the ends of the bond overlap causing peeling and premature failure were previously noted by Banea and da Silva [12].

The use of fibre reinforcements with additive manufacturing was also investigated by Cavalcanti et al. [22]. The effect of natural and synthetic fiber reinforcement on the mechanical properties of 3D-printed PLA and ABS core composites was studied.

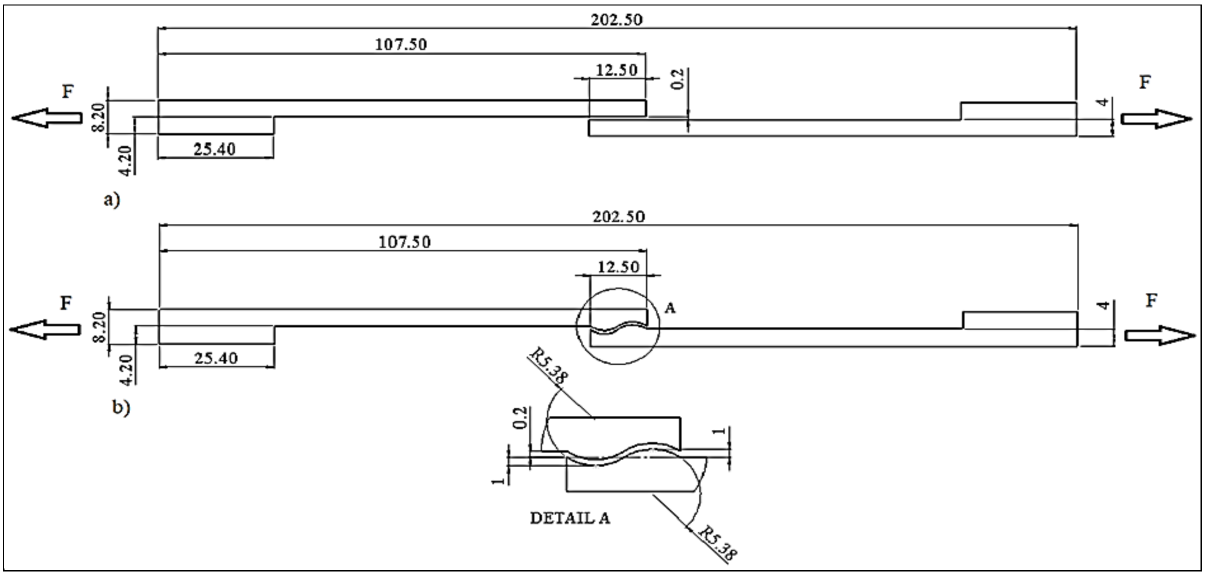

Fig. 3. SLJs specimen geometry (dimensions in mm): a) Group A, b) Group B

It was found that adding fiber reinforcement significantly improved the mechanical properties of both materials. The PLA specimens presented brittle failure, while ABS specimens showed delamination at the resin/printed part interface. These results suggest that fiber reinforcement can enhance the mechanical properties of 3D-printed materials, making them suitable for high load-bearing applications. The results are in line with other works and methodologies found in the literature, where the application of natural fibres, both long and short, has provided an increase in mechanical properties [4]. As seen in Santos et al. [23] the addition of long natural fibres provided a significant increase in both strength (71.6 ± 2.6 MPa) and rigidity (4.0 ± 0.5 GPa) of the printed parts, when compared to the neat-PLA. The application of short fibres have also presented themselves as a possible reinforcing agent within the 3D printed matrices, however with lower mechanical improvements, as seen in Cavalcanti et al. [24], where the addition of short curauá fibres provided an increase in mechanical properties, with values of 56.45 ± 3.34 MPa for tensile strength and 3.00 ± 0.13 GPa for Young’s modulus.

Cavalcanti et al. [25] applied these concepts of adherend reinforcement by using a methodology akin to Cavalcanti et al. [22], through the incorporation of natural and synthetic fibres. This reinforcement strategy yielded notable enhancements in the mechanical performance of adhesively bonded single lap joints (SLJs). Notably, curauá fiber-reinforced specimens exhibited substantial improvements attributed to their superior fiber mechanical properties, favourable fiber/epoxy resin interfacial characteristics, and heightened energy requirements for complete fiber failure. These enhancements ranged from approximately 110% to 150% when contrasted with the neat-ABS SLJs. Consequently, it is deduced that judiciously implementing fiber reinforcements in 3D printed components can ameliorate their mechanical properties in the context of SLJ applications.

Haghpanah et al. [26], studied the effect of interlocking toothed zigzag pattern on the mechanical behaviour of single-lap joints. They compared the interlocking toothed zigzag pattern to a flat joint and used experimental testing with different interface morphologies to validate the associated finite element modelling. The study aimed to understand the fracture mechanics, the role of tooth dimensions, stress distribution, and the crack propagation. The specimens with positive teeth that thickened as they entered the bond region had similar yield strength as the flat joint, while specimens that thinned were weaker. However, a more detailed finite element evaluation suggested that a tooth or wave angle of value between 10 and 35 degrees could significantly reduce stress in the SLJ and lead to optimization.

Ashrafi et al. [27] conducted experiments and finite element simulations to study the performance of single-lap joints (SLJs) with non-flat interfaces. They found that the geometrical tailoring of the adherends had a significant effect on the mechanical behaviour and strength of the bonded joints. The goal was to alter the mechanics of load transfer to increase strength without altering the joint's dimensions. They achieved this for specimens with a positive configuration, which had a 40% higher failure load than the standard flat joint for the same overlap length and adhesive thickness. Their finite element analysis revealed that the maximum peeling stresses generally occur at the edges of the bonded joint and are much higher than the maximum shear stresses, suggesting that peeling is the primary cause of failure

Razavi et al. [29] further investigated the role of sinusoid interface shapes on stress distribution and load bearing capacity of adhesively bonded SLJs. They proposed five different profiles for the aluminium adherend and found considerable discrepancy in load bearing capacity for each. The highest strength gain was 51% compared to the flat joint. Geometrical tailoring of the interface was found to influence the adhesive joint strength in agreement with experimental and numerical approaches. The finite element method allowed the authors to study the effect of multiple joint parameters on the stress distribution. They found that the lower wave lengths and the higher wave heights decreased peak stresses, increasing joint strength, whereas lower adhesive thickness and stiffness ratio increased the efficiency of the SLJ configuration.

Cavalcanti et al. [2], applied Ashrafi et al. [27] and Razavi et al. [29] patterns to bonded joints made of additively manufactured PLA adherends. Two methodologies were used to increase joint strength: geometrical tailoring of the adherends and two build orientations. Sinusoidal patterns were printed on the adherends, and experiments were conducted on single-lap joints bonded with an epoxy adhesive (see Fig. 3). The flatwise specimens showed a 62% increase in load-bearing capacity, while the edgewise specimens showed a 35% increase compared to the conventional flat joints. Adherend delamination failure was predominant, but the epoxy adhesive and PLA polymer adherends were found to be compatible for all conditions.

Molino et al. [30], performed an experimental investigation of adhesive joints with mechanical interlocking in ABS parts fabricated using FDM. Two different types of mechanical interlock (truncated pyramid and cylindrical pin) and the dimensions of each type of mechanical interlock was considered. They found that the specimen that incorporated a mechanically reinforced joint, characterized by a cylindrical pin measuring 5.45 mm in radius and 4.6 mm in height, demonstrated the highest tensile and yield strength.

García-Guzmán et al. [31], studied DCB bonded specimens with different configuration (flat or structured) and compared to the flat specimen’s configuration. A series of tests demonstrated a noteworthy disparity between specimens with trapezoidal and flat bonding interfaces. Experimental results revealed that the optimal trapezoidal interface configuration led to an impressive 803% improvement in energy release rate.

Enhancements in strength can be also achieved through localized geometric modifications. This involves adjusting the local geometry of adherends, adhesive materials, or combinations thereof. It is well known that, in the case of single-lap joints, the distribution of load is often uneven along the overlap region, resulting in stress concentration at the ends of the overlap [12]. When it comes to geometric design, increased joint strength can be attained using double-lap joints, stepped-lap joints, scarf-lap joints, and tapered-lap joints. It's important to note that while these modifications can boost strength, they may also introduce additional manufacturing complexities. Several authors studied the effect of local geometry of adherends, and Table 1 provides an overview of the methodologies employed in these studies. In addition, Khosravani [18] investigated overlap geometry's effect on joint strength and used a step configuration to improve joint strength by decreasing peel stress. Stepped-lap joints of various step sizes were produced using PLA printed via FDM technology. Results revealed that adding steps significantly influenced the structural integrity and fracture load of 3D-printed adhesive-bonded joints. Structures with identical step sizes in the bonding area exhibited superior load carrying capacity and fracture load. A finite element model simulated load carrying performance of adhesively bonded single-lap joints and confirmed experimental outcomes, revealing cohesive failure and damage evolution mechanisms in PLA-printed bonded structures. Recently, they studied [32] the influence of steps on the mechanical performance of adhesively bonded joints with 3D-printed PLA adherends

Tiwary et al. [33] investigates the adhesive bonding of dissimilar 3D-printed parts (ABS and PLA), with different geometric joint configurations (i.e. lap, scarf, stepped). Various adhesives, including epoxy, cyanoacrylate, and polyurethane-based adhesives, were employed in combination with varying surface treatments, such as sanding, vapor treatment, and plasma treatment. The results underscore the hierarchy of process parameters in terms of their impact: material type, joint configuration, adhesive selection, and surface pre-treatments. ABS + ABS, configured in a stepped arrangement, treated with plasma, and bonded with Loctite adhesives, emerged as the optimal combination, delivering a noticeable enhancement in performance.

To summarize, the configuration of the bonding area represents an essential parameter that directly influences the adhesive bonding strength and overall structural integrity of AM joints. Although, different bonding area shapes, including flat, stepped, and scarf configurations, were investigated in the literature, a comprehensive investigation that systematically identifies the optimal bonding area shape has not been undertaken to date. Therefore, a research gap still exists to identify the most advantageous bonding area configuration for these adhesive joints.

The effect of other parameters (i.e., pre and post-treatment, loading rate, etc) that directly impacts the bonding strength of the joints.in adhesively bonded joints with 3D-printed adherends was investigated in the literature. For instance, Leicht et al. [13] conducted an investigation into the influence of pre- and post-treatments on the fracture behaviour of 3D-printed SLJs. Post-processing involved surface modification, while pre-treatment was achieved using an atmospheric plasma process. Different adhesives (epoxies, polyurethanes, cyanoacrylates, and two-component methyl methacrylates) were employed to bond the joints. It was found that the orientation of the printing direction was found to have a minimal impact on the mechanical strength of the joints. Experimental results indicated that the initial strength of the joints ranged from 5 to 10 MPa, and through the utilization of the specified pre- and post-treatments, this strength was significantly enhanced to 27 MPa.

Atahan and Apalak [28] investigated the effects of loading rate on the strength of single-lap joints composed of additively manufactured PLA adherends and Araldite 2015 adhesive under tensile, three-point, and four-point bending loadings. Their findings showed that increasing loading rates improved strength for tensile and three-point bending tests at the cost of a lower tensile failure strain. However, strength for four-point bending tests decreased, benefiting bending stiffness. Failure initiated at the free edges of the top adherend for all tests, with propagation happening along the interface, following a through-the-thickness path for tensile specimens. The adherends had better on-layer mechanical behaviour following the raster angle/direction, then on building orientation.

Yap et al. [34] investigated the effect of adhesive type (epoxy and cyanoacrylate) on joint performance for single lap shear tests with 3D-printed Acrylonitrile Styrene Acrylate (ASA) and Nylon 12 carbon fiber (NCF) adherends, with and without post-curing at elevated temperatures. The joint strength for cyanoacrylate joints, of 1810 kN and 2310 kN, respectively, was significantly higher than that of epoxy joints, of 470 kN and 860 kN. They noted that heat and surface treatment improve adhesive strength.

Several studies have explored the tailoring of fillets and spill fillets in adhesively bonded joints using AM materials. As an example, Kanani et al. [35] utilized a water-soluble filament to accurately control fillet shapes at the end of the bond line, resulting in an accurate fillet shape for any fixture geometry. The study used the finite element method (FEM) to investigate the stress distribution along the bond line for four modified bonded joints, and discrete element method (DEM) to estimate the joint failure load and crack path. The modified joints showed significantly improved mechanical performance, and the DEM model provided results in close agreement with experimental and FEM results.

Recently, Palaniyappan et al [36] evaluated the practicality of different methods for joining 3D-printed polylactic acid (PLA) and wood-reinforced PLA biocomposite materials. The strengths and weaknesses of methods such as adhesive bonding, mechanical fasteners, and heat-based fusion to determine the most suitable approach for achieving durable bonds were discussed.

Table 1. Summary of relevant publications of adhesive joints with 3D-printed adherends produced by FDM with non-conventional surface joints and treatments

Material	Parameters analysed	Best condition	Values found for failure loads or shear strengths of the joints	Ref.
PLA	Printing orientation and surface modification	Flatwise and wave geometry	3.2 kN Substrate stock break	[2]
ULTEM 9085	Bond area design, surface treatment and raster angle	Scarf, finger joint, surface mechanically roughening and positive air gap to the surface.	Finger (12.1 kN) and scarf joints (11.4 kN)	[9]
Carbon fibre woven epoxy laminate	3D printed reinforcements - ABS-M30	Print lines only in the interior of the bond region	Increase of approx. 832% in shear strength compared to the unreinforced joint	[10]
PLA	Adhesive thickness (0.2, 0.3 and 0.4mm), Raster width (0.75 and 1 mm)	Adhesive thickness 0.2mm, Raster width 0.75mm	Cohesive Failure: 1.98 kN, Failure in structure: 2.42 kN	[18]
PETG	Adhesive thickness (0.2, 0.3 and 0.4mm)	0.2 mm adhesive layer, 0.5 mm layer thickness and raster width of 0.75 mm	Maximum linear stiffness for cohesive failure: 1.24 kN/m	[19]

Material	Parameters analysed	Best condition	Values found for failure loads or shear strengths of the joints	Ref.
Continuous Fiber Unidirectional Composite-Nylon Matrix	Baseline, industry-standard, and AM-tailored (Porosity: 50 vol%, solid (100 vol%))	AM-tailored joints	11.3 kN for cohesive failure	[20]
PLA	Printing orientation and layer thickness	Edgewise and 0.25mm	1.04 kN	[21]
PLA and ABS	3D printed core reinforced with natural and synthetic fibres (1 layer and 2 layers)	PLA- 2-layer curauá reinforced adherend - ABS- 1layer reinforced curauá reinforced adherend	C2-PLA specimens presented an increase in joint failure load of approx. 150% when compared to the Neat-PLA. For the ABS specimens, the highest improvement was found for the C1-ABS with an improvement of approx. 110% when compared to the Neat-ABS.	[25]
PLA	Loading rate 1, 10, 20 and 50mm/min	-	Failure Load for 10 mm/min, 2.57 kN, 50 mm/min (2.49 kN).	[28]
ASA and Nylon 12 Carbon Fiber (NCF)	effects of types of adhesives (epoxy and cyanoacrylate (CA)); heat-treatment conditions; adherend surface conditions	Joints bonded with CA adhesive. Heat treatment and surface treatment improve the failure load.	Failure load for CA- ASA joints: 1810 kN and NCF joints 2310 kN, ASA with epoxy failure load of 470 kN and NCF with epoxy 860 kN	[34]

4. CONCLUSIONS

As Additive Manufacturing technology gains importance in the production of the end-use components, the reliability of these parts becomes a critical concern. Adhesive bonding stands as an essential post-processing step to address these concerns, offering the potential to reinforce 3D-printed parts, joining them securely while mitigating issues related to layer adhesion, porosity, and material limitations. This paper presents the recent advances in adhesive bonding techniques for 3D-printed parts and explores various methods to enhance their mechanical performance. The methods discussed in this work include surface modification, material selection, adhesive selection, and joint design, among others.

Different strategies of surface tailoring were reviewed aiming to illustrate how combining the possibilities offered by AM and the specific qualities of adhesive bonded joints could be mutually beneficial to both domains. It was seen that both share lightweight applications, and if on one hand AM was restricted by part size, on the other hand adhesive joints lacked how all its design strategies could be implemented at once. It is not difficult to see that one efficiently complements the other.

The implementation of customized joint geometries can lead to a substantial enhancement in the joint strength of AM parts, thereby expanding the scope of their applicability and augmenting their potential for weight reduction and cost-effectiveness. The synergistic integration of these innovative technologies affords mutual benefits that reinforce each other, leading to superior overall performance of AM parts.

Additionally, the strengthening of the adherends by incorporation of reinforcing materials have shown significant potential in enhancing the mechanical performance of the joints.

Finally, this review points out that joining of AM parts is, still relatively unexplored. However, it is evident that this area will certainly prove itself to be one of the most promising solutions to improve the performance of adhesively bonded joints. The works reviewed in this paper may define the foundations that should provide support for further research in this area.

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