

Article

A New Methodology to Fabricate Polymer–Metal Parts Through Hybrid Fused Filament Fabrication

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Abstract: This paper introduces a new methodology that enables the production of polymer–metal parts through hybrid additive manufacturing. The approach combines fused filament fabrication (FFF) of polymers with adhesive bonding of metal inserts, applied during layer-by-layer construction. The work is based on unit cells designed and fabricated using eco-friendly materials—polylactic acid (PLA) and aluminum—which were subsequently analyzed for build quality and for mechanical performance under tensile lap-shear and three-point bending tests. The acquired knowledge in terms of optimal processing parameters for attaining strong polymer–metal bonds was then applied for the fabrication and testing of prototypes representing modular corner connectors for framing applications. Results on build quality demonstrate that issues, such as lumps and warping, can be solved by finetuning the 3D printing stages of the proposed methodology. In terms of destructive testing, significant improvements in the mechanical performance of PLA can be achieved, demonstrating the feasibility of the proposed methodology in integrating the lightweight properties of polymers with the stiffness of metals. This enables the development of innovative, sustainable and eco-friendly solutions that align with the growing demand for eco-friendly materials and processes in manufacturing.

Keywords: additive manufacturing; fused filament fabrication; adhesive bonding; polymer–metal parts



Academic Editor: José Ignacio Alvarez

Received: 21 March 2025

Revised: 2 May 2025

Accepted: 5 May 2025

Published: 8 May 2025

Citation: Silva, S.F.; Rosado, P.M.S.; Sampaio, R.F.V.; Pragana, J.P.M.; Bragança, I.M.F.; Assunção, E.; Silva, C.M.A. A New Methodology to Fabricate Polymer–Metal Parts Through Hybrid Fused Filament Fabrication. *Sustainability* **2025**, *17*, 4254. <https://doi.org/10.3390/su17104254>

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1. Introduction

In recent years, the industry’s need to lower its ecological footprint has become one of the critical aspects of the technological development of manufacturing processes. With resource scarcity and the growing importance of circular economy principles, it is vital to reduce the environmental impact of production. This includes adopting sustainable materials that match or exceed the performance of traditional ones. For instance, thermoplastics such as PLA are derived from organic and renewable sources such as corn starch and sugarcane, making them more eco-friendly than most plastics, which are typically derived from fossil fuels [1]. However, many of the biopolymers, like PLA, suffer from weaker mechanical performance when compared to other materials. To address this, these materials must be somewhat enhanced to enable their use in more mechanically-demanding applications [2].

One solution to the above challenge is to combine the lightweight nature of polymers with the stiffness of other materials, such as metals [3,4], by incorporating so-called metal inserts. This approach differs from conventional methods for producing fiber-reinforced polymers, as it focuses on providing additional strength, durability, or functionality to polymers while preserving their original characteristics, such as ease of processing, recyclability, lightweight nature, and cost. To achieve this, specific manufacturing processes are available for fabricating polymers with metal inserts. Overall, these processes can be categorized into three distinct manufacturing technologies (Figure 1).

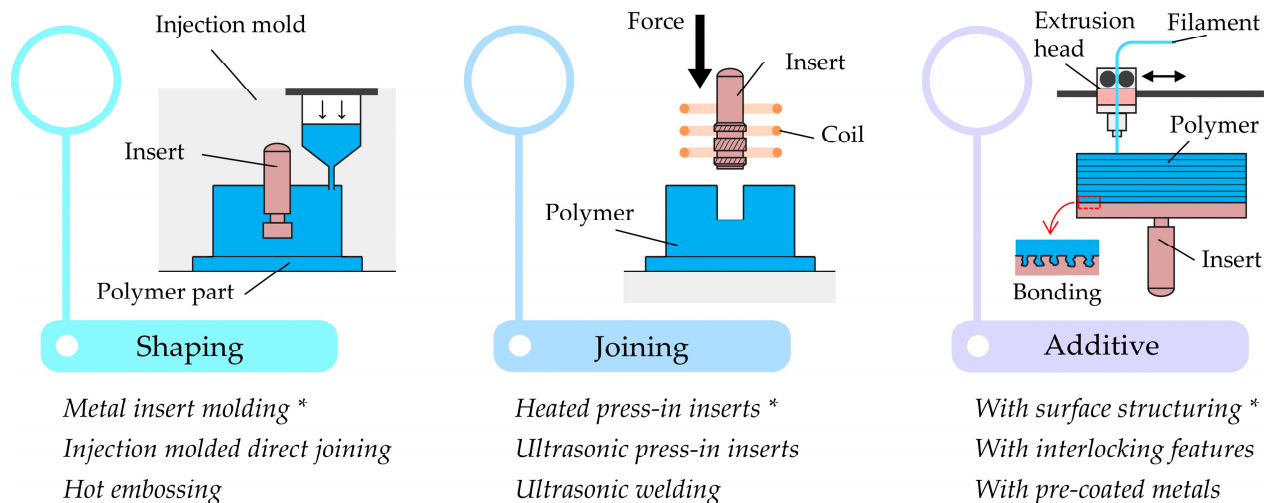


Figure 1. Classification of the main manufacturing technologies that allow producing polymer parts with metal inserts. The asterisk * refers to the schematized process for each technology.

Shaping processes involve changing the geometry of polymers through heat and/or pressure without altering their chemical composition. One good example is injection molding with metal inserts (also known as metal insert molding), where the metal inserts are first undercut or slotted through metal cutting and positioned within the mold. Afterward, the melted polymer is injected into the mold and surrounds the metal, creating bimaterial connections [5]. A variant known as injection molded direct joining replaces the undercutting stage of metal inserts with special surface treatments for creating a fine surface texture, which is then infiltrated by the melted polymer [6]. Hot embossing is also a possibility for coupling micro or nano inserts with polymers [7]. In general, these processes share the same benefits as conventional injection molding, such as low lead times and high reliability, but the resulting part geometries are mold-dependent. This makes the processes cost-effective only for large batch production, lacking the flexibility needed for other industrial scenarios.

Extrusion processes can also be used to create polymer products with metal inserts, particularly for thin multilayer structures that use polymers as a coating material [8]. Parts can be made in different shapes and materials, but applications are restricted to primary shape products that sometimes serve as raw material to further manufacturing processes.

Joining processes applicable to polymers with metal often fall into the categories of mechanical joining and adhesive bonding. The first makes use of special inserts that are pressed or threaded into the polymer parts with or without the application of active energy, such as heat or ultrasonic vibrations [9,10]. The second relies on the chemical bond formed by the cured adhesive at the interfaces between the polymer and metal materials [11]. Other alternatives, such as ultrasonic welding, can also be employed to weld polymer foils to plates with enclosed micro-cavities, where metal inserts can be placed beforehand [12]. However, most applications involving joining processes require easy access to the polymer surfaces where the inserts will be positioned. This limitation imposes challenges in creating

more complex configurations, such as those involving completely enclosed inserts within polymers, which are often difficult, if not impossible, to produce.

Finally, additive manufacturing (AM) processes have recently been investigated to expand their applicability domain beyond prototyping [13]. These processes allow users to select materials and customize their properties for specific parts, enabling the creation of diverse and complex geometries with far fewer design constraints compared to traditional methods [14]. For producing polymer parts with metal inserts, Butt and Shirvani developed a hybrid process that combines fused filament fabrication (FFF), vacuum forming, and CNC machining to introduce a near-pure copper mesh into the additively manufactured polymer during layer-by-layer construction [15]. Other approaches, also centered on FFF, involve printing layers of melted polymer onto pre-coated or surface structured metals [16,17] or onto a polymer baseplate for interlocking with pre-holed metals [18]. These solutions show potential for achieving polymer–metal joints by means of layer-by-layer deposition, but are limited in their ability to fully enclose metal inserts within the polymer parts and in the resulting joint strength, which is highly sensitive to the surface morphology along the polymer–metal interfaces.

The reinforcement of feedstock materials using additives, such as powders or filaments blended into polymer binders, is a promising solution for enhancing the properties of additive manufactured polymers, particularly in material extrusion-based processes such as FFF [19]. This is a parallel research area to that of this work with focus on the reinforcement of feedstock materials for AM [20,21].

Considering the above, it is clear that the current state of AM has not yet reached the necessary technology-readiness level for producing polymers with metal inserts when compared with conventional solutions based on shaping and joining processes. Nevertheless, the layer-by-layer construction principles of AM offer a level of design flexibility that is not easily achievable with the aforementioned conventional processes [22]. When applied effectively, these principles can overcome drawbacks such as mold dependency and limited configurations, enabling the creation of innovative polymer–metal products with enhanced performance compared to the individual materials used separately.

Under these circumstances, this paper explores a novel methodology for producing polymer parts incorporating metal inserts. The innovation lies in the hybridization [23] of FFF with adhesive bonding, applied in situ during layer-by-layer construction. This concurrent application represents a significant shift from the remaining traditional approaches, enabling stronger and more seamless integration between materials that profit from the design flexibility provided by FFF. Unit cells were designed and fabricated using PLA combined with aluminum inserts, which were subsequently analyzed for build quality, and for mechanical performance under tensile lap-shear and three-point bending tests. Finally, a prototype of a modular corner connector for window framing was produced and analyzed by means of corner tensile tests to confirm the feasibility and eco-friendly potential of the proposed methodology for fabricating polymer–metal parts.

2. Materials and Methods

2.1. Hybrid Additive Manufacturing Sequence

The proposed methodology for hybrid additive manufacturing of polymer parts incorporating metal inserts is schematically shown in Figure 2. It begins with a pre-processing stage (Figure 2a) focused on the preparation of the polymer part geometry and dimensions through computer-assisted design (CAD), including the incorporation of hollow (empty) regions without polymer material, designed to accommodate the inserts. A slicing software is then used to define the deposition strategy during the layer-by-layer construction (3D printing). Meanwhile, the metal inserts are shaped to fit the format and

dimensions of the hollow regions within the polymer part. The illustrative schemes in Figure 2 show sheet-shaped inserts, prepared by water jet cutting, to facilitate their easy placement in strategic regions of a polymer part. This allows for critical improvements in specific areas without compromising the overall part weight. Nonetheless, other insert formats can also be considered, depending on consumer needs.

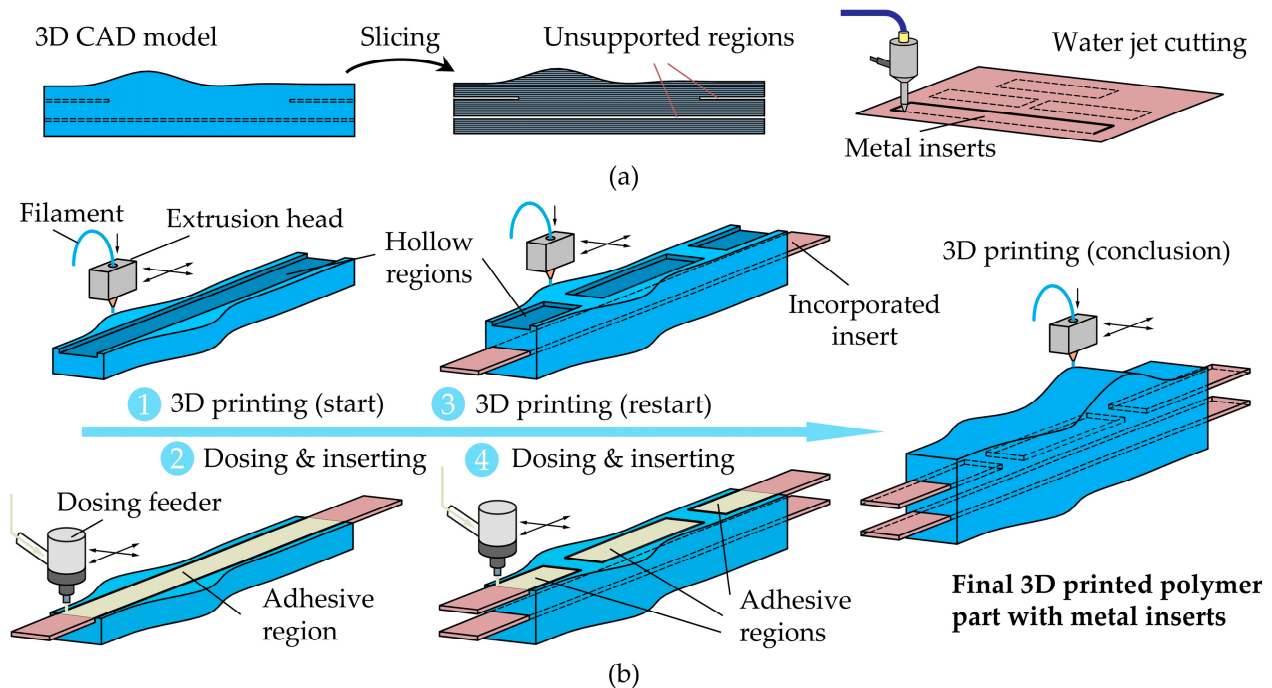


Figure 2. Schematic representation of the new methodology for producing polymer parts incorporating metal inserts during (a) pre-processing of the designs for both materials and (b) hybridization of 3D printing under fused filament fabrication (FFF) with adhesive bonding.

Once the pre-processing stage is completed, the pre-designed polymer part starts to be 3D printed until the first hollow regions are fully defined (Figure 2b). At this point, the metal inserts are placed in position which, together with the adhesive material, allow complete filling of the regions without polymer material. This enables the additive manufacturing process to resume, with the metal inserts serving as support material for the subsequent polymer layers. This cycle repeats as necessary, depending on the amount of metal inserts to be incorporated within the polymer part.

To ensure proper polymer–metal bonding, adhesive bonding is applied along the interfaces between the metal inserts and the polymer part. The adhesive is added firstly to the hollow regions of the 3D printed polymer and then onto the surfaces of the metal inserts after they are inserted into the polymer part. This is intended for securing the connections between the polymer and metal materials without the need for surface structuring, as commonly required in injection-molded direct joining processes [24].

2.2. Additive Manufacturing and Adhesive Bonding

Material deposition was carried out using FFF with an Ultimaker 3S 3D printer (Utrecht, The Netherlands) and PLA Ingeo 4043D provided by NatureWorks (Plymouth, MA, USA) with a diameter of 2.85 mm [25]. For this purpose, a brim build-plate adhesion type with a width of 7 mm was used to support the first layers of the deposited polymer. The printing temperature and speed were set to 200 °C and 30 mm/s, respectively, while the layer height and line width were 0.1 mm and 0.4 mm, in accordance with the printing guidelines provided by Ultimaker (Utrecht, The Netherlands).

The metal inserts were fabricated in the aluminum alloy 6082-T6. Their geometries were prepared using water jet cutting from 2 mm thickness aluminum sheets, ensuring the dimensions were compatible with the corresponding hollow regions of the polymer parts under a geometric precision of ± 0.05 mm. The resulting geometries were made according to the unit cells meant for mechanical testing, which will be further detailed in Section 2.3.

Lastly, adhesive bonding at the polymer–metal interfaces was achieved using the epoxy resin Araldite Ultra Strong supplied by Huntsman Advanced Materials (Cambridge, UK), with a glass transition temperature of 75 °C. The adhesive was selected for its accessibility and ability to connect the majority of engineering materials under strong and durable bonds by cold curing.

2.3. Experimental Workplan

The experimental workplan is focused on assessing the build quality and mechanical performance of the polymer–metal joints that result from the proposed methodology. For this purpose, two types of unit cells were designed and fabricated according to the geometries shown in Figure 3a. In terms of functionality, these unit cells are aimed at representing the partial (outer) or complete (inner) incorporation of the metal inserts within the polymer part built by FFF.

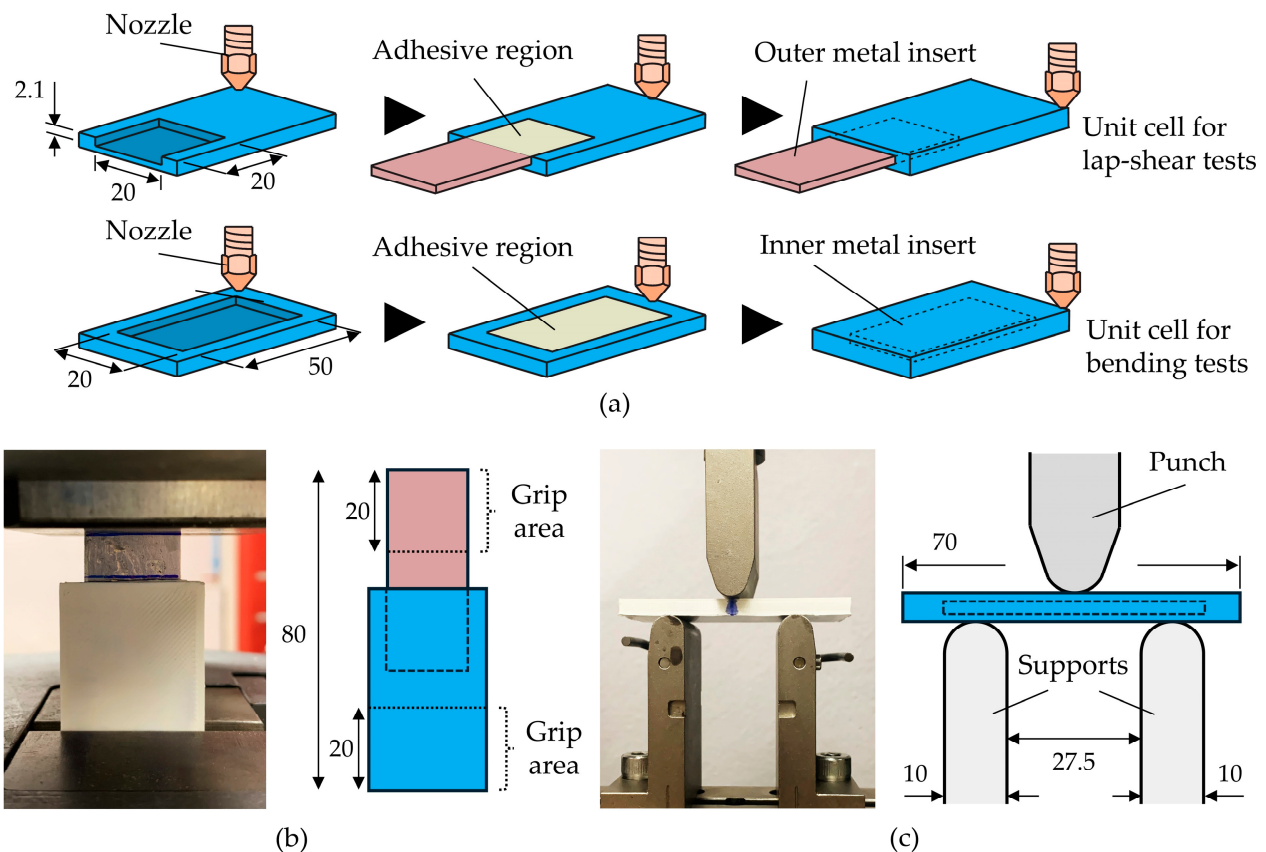


Figure 3. (a) Fabrication of unit cells made in PLA with outer and inner aluminum inserts. Photographs and dimensions of the experimental setup used for (b) tensile lap-shear and (c) three-point bending tests. All dimensions are in millimeters.

The analysis of the build quality was firstly carried out through visual inspection and afterwards by local coordinate measurements along the top surfaces of the unit cells. These measurements were made using the TESA MICRO-HITE 3D coordinate measuring machine (Renens, Switzerland) and extracted using the TESA-REFLEX V2 software [26].

The mechanical performance of the joints was evaluated by destructive testing. For this purpose, each type of unit cell was used for a specific destructive test: tensile lap-shear or three-point bending testing for partially or completely incorporated inserts, respectively (Figure 3b). The tests were carried out at room temperature under the guidelines provided by the universal standards ISO 4587:2003(E) [27] and ISO 7438:2016 [28] using the INSTRON 5966 universal testing machine (Norwood, MA, USA).

The interfacial characteristics between both materials are expected to significantly dictate the mechanical performance of the overall unit cells. For this reason, the above tests were conducted under varying conditions along the polymer–metal interfaces where the adhesive was applied, which were investigated according to three processing parameters: the build-plate temperature during 3D printing, and the surface quality and temperature of the metal insert immediately before the application of the adhesive. The main goal of the mechanical tests is to identify the optimal processing conditions that most effectively promote stronger metal–polymer bonds at the unit cell level.

The values for each parameter considered in the experimental tests are provided in Table 1. The build-plate temperature was set on the 3D printer within the recommended range specified by the feedstock supplier. The remaining parameters pertain exclusively to the metal inserts, all of which were dry-cleaned beforehand using acetone. The surface quality of the bonded areas was either left as-supplied (AS) or grinded with sandpaper of varying grain sizes. Lastly, the metal inserts were used at room temperature (RT) or preheated to higher temperatures using a heat gun controlled with a pyrometer.

Table 1. Processing parameters considered in the fabrication of the unit cells for testing.

ID	Build-Plate Temperature (°C)	Metal Temperature (°C)	Surface Quality
1–24	60; 80	RT ¹ ; 70; 90; 160	AS ² ; #80; #500

¹ Room temperature; ² as-supplied.

The above variations resulted in 24 possible combinations (IDs) with the parameters shown in Table 1, under a minimum of five unit cells tested per combination to ensure repeatability. A more comprehensive view of the individual parameters for each ID is shown in Table A1 of Appendix A.

2.4. Fabrication and Testing of Prototypes

The final assessment of the paper draws from the parametrization work, described in the previous subsection, for the construction of a prototype to demonstrate and validate the feasibility of the proposed methodology. The prototype consists of a conceptual polymer corner connector with three metal inserts, designed to eliminate the need for traditional corner joints between polymer profiles (e.g., as needed for modular framing applications). Additionally, the approach offers a sustainable solution due to its incorporation of eco-friendly polymer and metal materials. Modular framing systems are often customized to meet specific design and functional requirements and, for these reasons, greatly benefit from the flexibility provided by 3D printing. This aligns with one of the main missions of the ‘R2UTechnologies’ Consortium, which supported this work [29].

Figure 4a illustrates the corner connector design, including its main dimensions and the necessary hybrid additive manufacturing sequence integrating FFF and adhesive bonding for building the corner connectors with metal inserts.

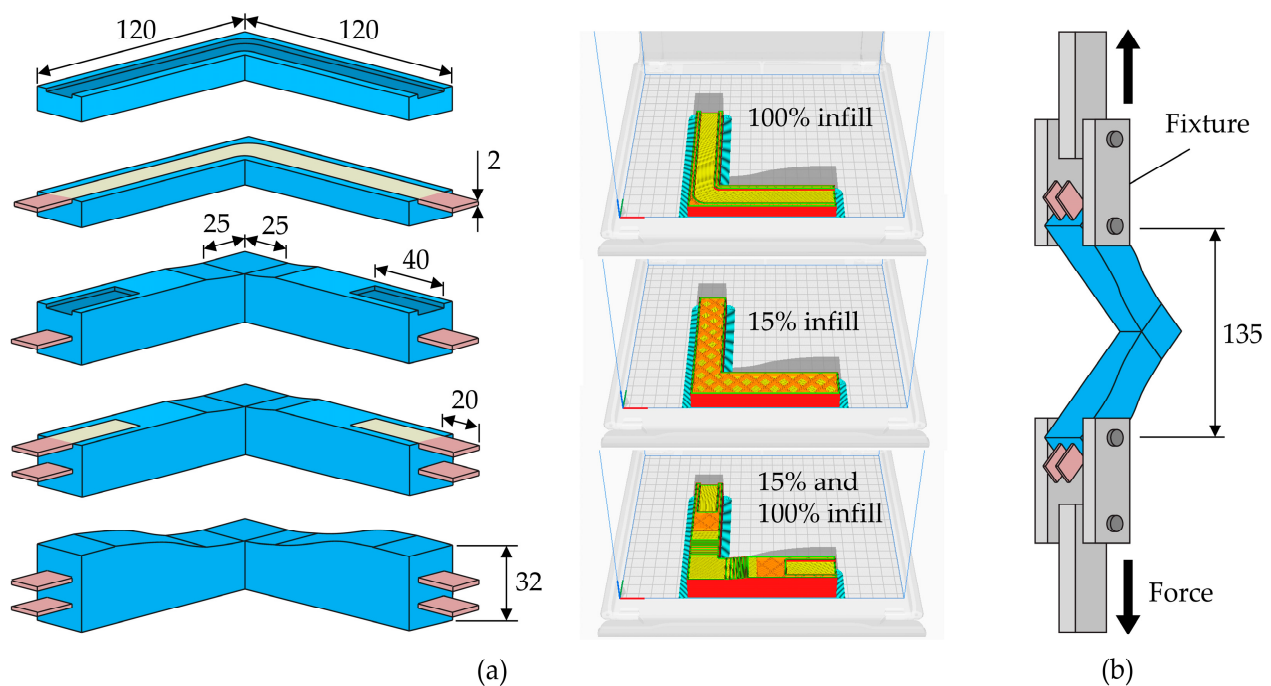


Figure 4. (a) Hybrid additive manufacturing sequence and (b) mechanical testing of corner connectors with metal inserts. All dimensions are in millimeters.

During all 3D printing stages, the infill density was selectively adjusted to 15% using an octet pattern for the bulkier regions of the corner connector. In contrast, near the metal inserts, the infill density was maintained at 100% to maximize the polymer–metal surface contact. This strategy is depicted in Figure 4a with software screenshots that highlight the infill densities (orange and yellow vectors representing 15% and 100%, respectively). The remaining 3D printing and adhesive bonding parameters were selected based on the most suitable results from the mechanical tests on unit cells, that will be evaluated and disclosed in Section 3.

After fabrication, the mechanical performance of the corner connectors was assessed through corner tensile tests (Figure 4b). These tests are carried out until the onset of fracture and were conducted at room temperature using an INSTRON 5966 universal testing machine (Norwood, MA, USA). Additionally, corner connectors with an identical geometry were fabricated entirely by FFF—i.e., without metal inserts—and tested under the same conditions for reference purposes.

3. Results and Discussion

3.1. Build Quality

The analysis of build quality focused on polymer–metal unit cells to detect the most likely manufacturing defects and implement the necessary solutions to overcome them. The observed defects were linked to different stages of the proposed hybrid additive manufacturing sequence: warping caused by the 3D printing stages and lumps caused by the adhesive bonding stages, as exemplified in Figure 5.

Warping was found along the edge surfaces of the unit cells, becoming more noticeable at the corners (Figure 5a). This phenomenon was evident in unit cells printed at build-plate temperatures of 80 °C, compromising the geometric precision of the polymer–metal parts. Although reducing the build-plate temperature could mitigate this issue, it might also compromise interlayer bonding during 3D printing and, consequently, the mechanical behavior of the deposited polymer. For these reasons, a build-plate sticking glue was used to enhance brim adhesion and control warping [30]. This strategy proved successful,

as shown in Figure 5a, which includes a measurement plot along the top surface of unit cells printed at a build-plate temperature of 80 °C, showing negligible deviations for those printed with sticking.

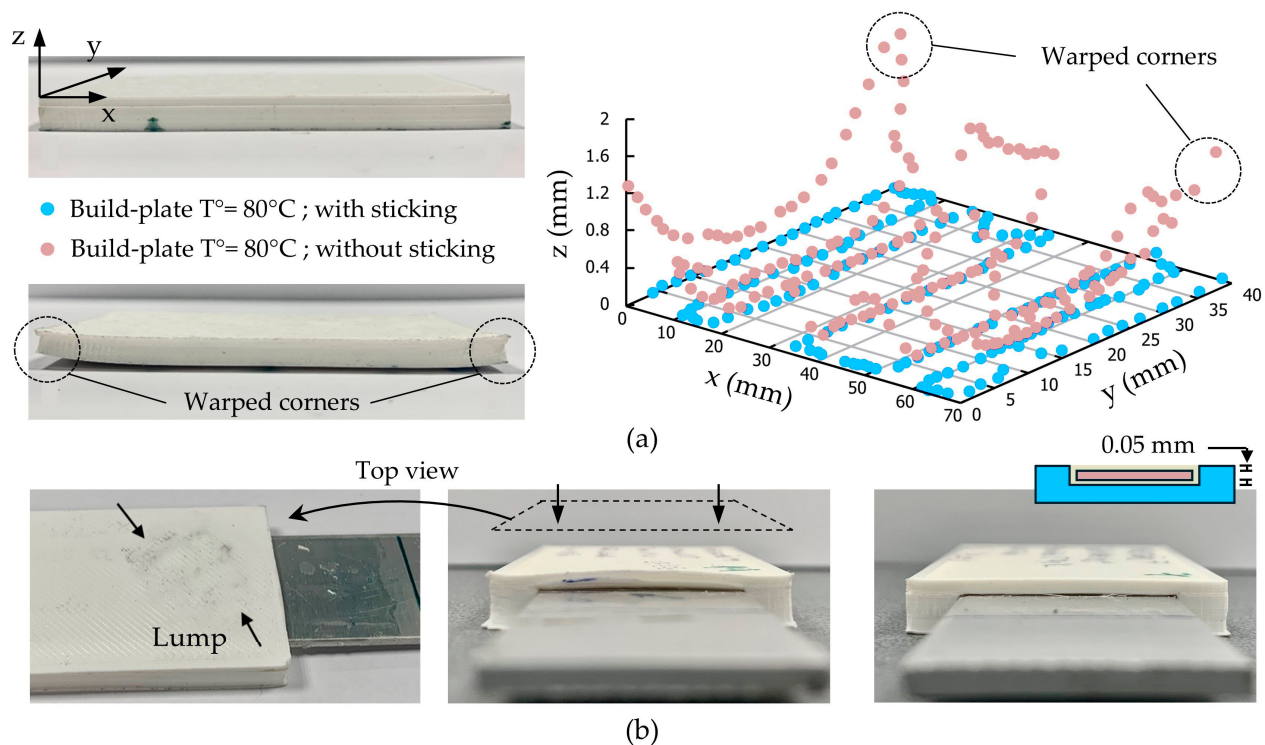


Figure 5. Representation of the manufacturing defects and corresponding solutions for unit cells affected by (a) warping and (b) lumps.

The formation of lumps (see the left and middle photographs in Figure 5b) also occurred in certain unit cells, which, similarly to warping, deteriorated the geometric precision and overall quality of the parts. This issue arose due to an uneven distribution of adhesive in correspondence with the volumes of the hollow regions and metal inserts. To resolve this, the hollow regions were oversized to include a clearance that could accommodate the adhesive. The rightmost photograph in Figure 5b exemplifies a unit cell built with a 0.05 mm clearance between the metal inserts and the corresponding hollow regions, successfully preventing the formation of lumps.

3.2. Tensile Lap-Shear Tests

The analysis of the tensile lap-shear tests was conducted according to the guidelines provided by the universal standard ISO 10365:2022(E) [31], adapted to the unit cell geometry for categorizing the corresponding failure modes. These failure modes include adherend failure (substrate or delamination), adhesive failure (cohesive or adhesive), and mixed failure. Figure 6a illustrates examples of these failure modes, while Tables A1 and A2 in Appendix A provide a comprehensive overview of the predominant failure modes as a function of the processing parameter combinations used for each unit cell.

Figure 6 also presents the average maximum loads obtained from tensile lap-shear tests on unit cells with outer aluminum inserts, based on the processing parameters under investigation. As shown, the results are divided into two plots for different build-plate temperatures—60 °C and 80 °C, depicted in Figures 6a and 6b, respectively.

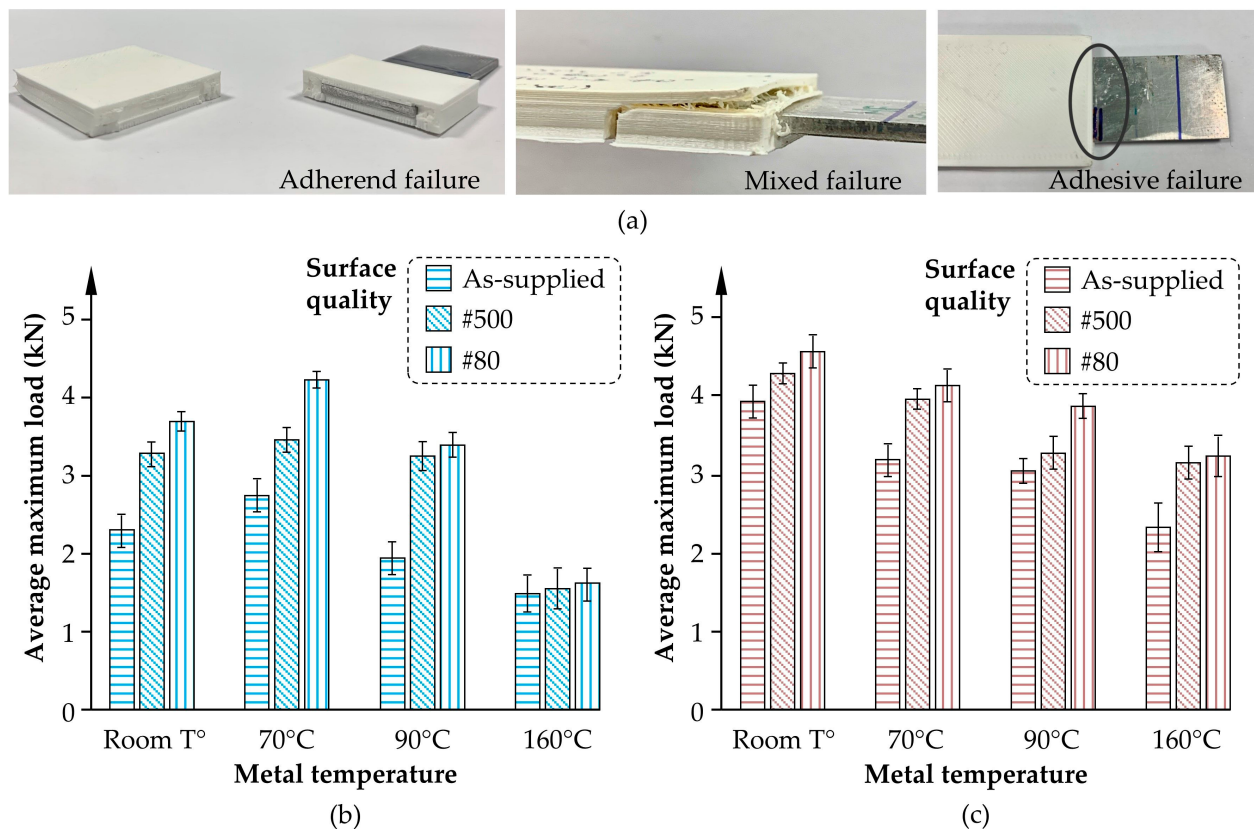


Figure 6. (a) Examples of the obtained failure modes and average maximum loads for tensile lap-shear tests carried out in unit cells printed over build-plate temperatures of (b) 60 °C and (c) 80 °C.

The first key observation from these results is that using a highly ground surface on the adhesive regions of the metal inserts promotes a stronger bond, which withstands higher shear loads, regardless of the remaining processing parameters. This is because the rougher surface texture of the metal inserts creates asperities that are subsequently filled by the adhesive, promoting a greater surface area along the adhesive regions.

The second observation is that increasing the build-plate temperature from 60 °C to 80 °C enhances mechanical performance. This is drawn by comparing the plots in Figure 6a,b for identical remaining parameters. The improvement is attributed to a more efficient adhesive flow and wetting along the polymer–metal interfaces at a build-plate temperature of 80 °C, leading to unit cells secured by stronger bonding conditions. This explains why adherend failure modes are more likely to occur at a build-plate temperature of 80 °C (see Table A2), indicating that failure is primarily imposed by the mechanical behavior of the PLA itself rather than the bonded regions.

Finally, the metal temperature has a predominantly negative effect on the mechanical behavior of the unit cells, leading to lower shear loads. In fact, if the metal insert is heated to very high temperatures, failure occurs primarily within the adhesive. This suggests that, for the given epoxy adhesive—which performs well under cold curing—introducing the metal insert at room temperature is more suitable for maximizing the bonding conditions between the outer inserts and the 3D-printed polymer. This occurs at a #80 surface quality and an 80 °C build-plate temperature, achieving a maximum shear load of approximately 4.6 kN.

3.3. Three-Point Bending Tests

The load–displacement evolutions for three-point bending tests conducted on unit cells with inner metal inserts are shown in Figure 7. To ensure the readability of the results,

the evolutions are plotted for the cases that exhibited the highest shear loads, as identified in the previous subsection (refer to the results shown in Figure 6 and to Tables A1 and A2 for the nomenclature used).

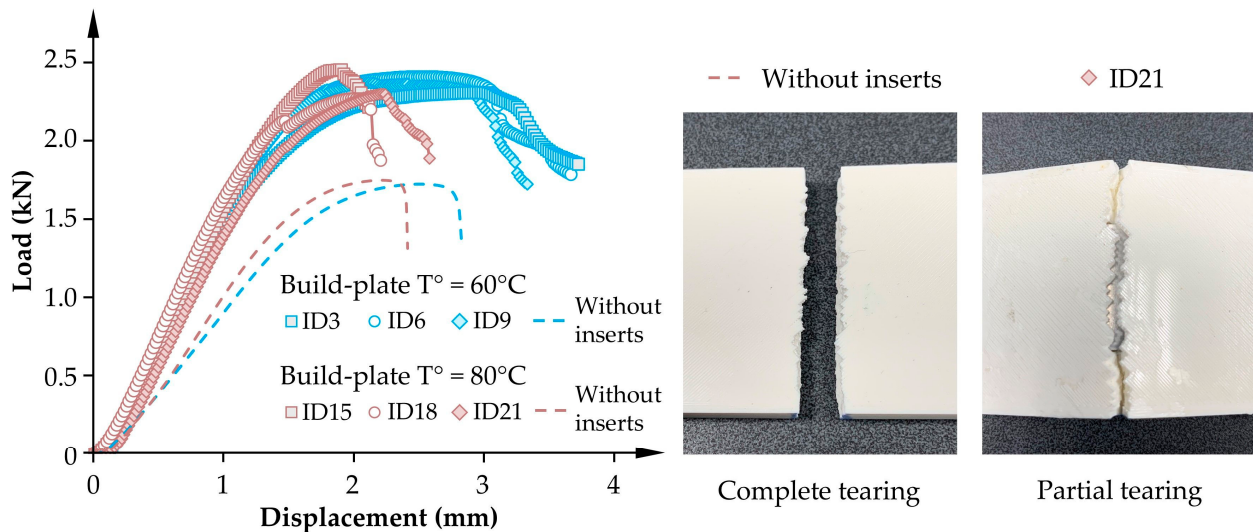


Figure 7. Load–displacement evolutions for three-point tensile tests printed over build-plate temperatures of 60 °C and 80 °C. Photographs of the representative failure modes are included.

In contrast to the findings from the tensile lap-shear tests, the mechanical behavior of unit cells with inner metal inserts, when subjected to bending loads, does not appear to be significantly affected by the processing parameters under investigation. In fact, the force evolutions reach maximum bending loads between 2.2 kN and 2.5 kN, with negligible variations in their profile, meaning that the dominant factor consists of the flexural properties of both the polymer and metal materials rather than their interfacial characteristics. The only noticeable difference lies in the displacement: unit cells fabricated at a build-plate temperature of 60 °C exhibit greater flexural deformations, but this does not significantly impact the corresponding maximum loads.

The results shown in Figure 7 also include reference evolutions obtained from specimens made entirely of 3D-printed PLA (i.e., without inserts). These results are represented by the dashed curves for each build-plate temperature under analysis and indicate a similar behavior to that described above for the unit cells. However, the maximum bending loads for PLA specimens are approximately 32% lower than those observed in unit cells with inner metal inserts, and the corresponding failure mode is more abrupt, leading to complete tearing (refer to the photographs shown at the righthand side of Figure 7). In contrast, the metal insert remains unaffected by fracture in the unit cells, allowing it to partially support the PLA material while also enhancing its structural stiffness.

3.4. Corner Connectors with Metal Inserts

The last subsection of this paper covers the fabrication and testing of prototypes representing polymer corner connectors that incorporate metal inserts to demonstrate the feasibility of the proposed methodology based on the hybridization of 3D printing with adhesive bonding.

The hybrid additive manufacturing sequence necessary for producing the corner connections followed the same procedure that was described in Section 2.4. Figure 8a contains photographs taken at the stages when the metal inserts are inserted onto the hollow regions left during 3D printing. The inserts were designed with a clearance of 0.05 mm and cut by water jetting. The bottom photograph of Figure 8a also allows visualizing the

layer-by-layer construction with 15% infill density in the regions distanced away from the metal insert, as intended (refer to Section 2.4).

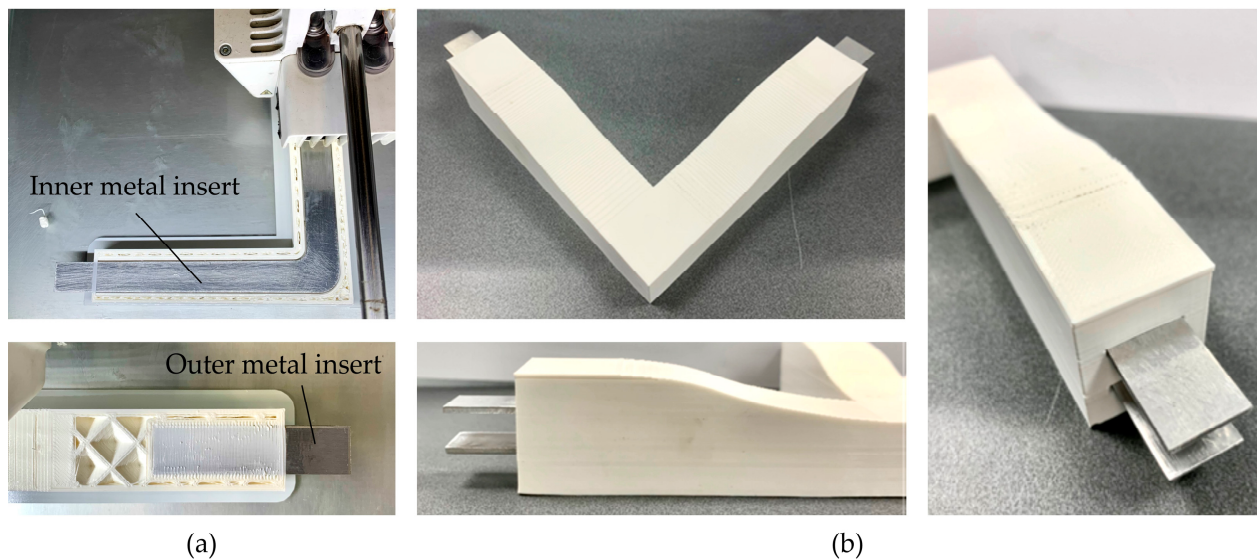


Figure 8. Photographs taken of (a) the stages where the inner and outer metal inserts are incorporated during 3D printing and of (b) the final corner connector with metal inserts.

Figure 8b shows an example for the corner connector after construction. Through visual inspection, it was possible to denote that the strategies described in Section 3.1 were successful in circumventing defects such as warping and lumps from compromising the geometric precision and surface quality of the connectors.

After construction, the connectors were subjected to corner tensile tests to evaluate their mechanical performance. For this purpose, the corner connectors were built using the optimal processing parameters identified in the previous subsections for the two build-plate temperatures of 60 °C and 80 °C (IDs 6 and 15 in Tables A1 and A2). The same build-plate temperatures were also used in the 3D printing of PLA corner connectors without metal inserts that were tested for reference purposes.

The results of the corner tensile tests are shown in Figure 9, which includes a plot of the load–displacement evolutions (Figure 9a) and photographs providing further insight into the failure modes exhibited by the corner connectors without and with metal inserts (Figures 9b and 9c, respectively).

Firstly, the load–displacement evolutions support similar findings to those presented in Section 3.3, where the build-plate temperature does not significantly influence the maximum load values from the tests. This trend is consistent for both types of corner connectors analyzed, although in the case of connectors with metal inserts, the maximum load is slightly higher at a build-plate temperature of 80 °C. However, the higher build temperature also leads to a reduction on the maximum displacement during testing of the corner connector, as seen by the load–displacement evolutions of Figure 9a. Both results are consistent with those previously discussed in Sections 3.2 and 3.3.

Finally, the most significant result is the substantial 100% increase in the maximum force experienced by the corner connector when built using the proposed methodology. At this point, the PLA begins to tear along the 90-degree corner region, as shown in the photographs of Figure 9b, taken from a fully PLA connector. However, the same does not occur in the corner connector with metal inserts, where the tearing is successfully delayed, and the inner aluminum insert remains free of any fracture whatsoever, as seen in Figure 9c. These results demonstrate the structural benefits of incorporating metal inserts in 3D-printed parts, which can be effectively achieved using the proposed methodology.

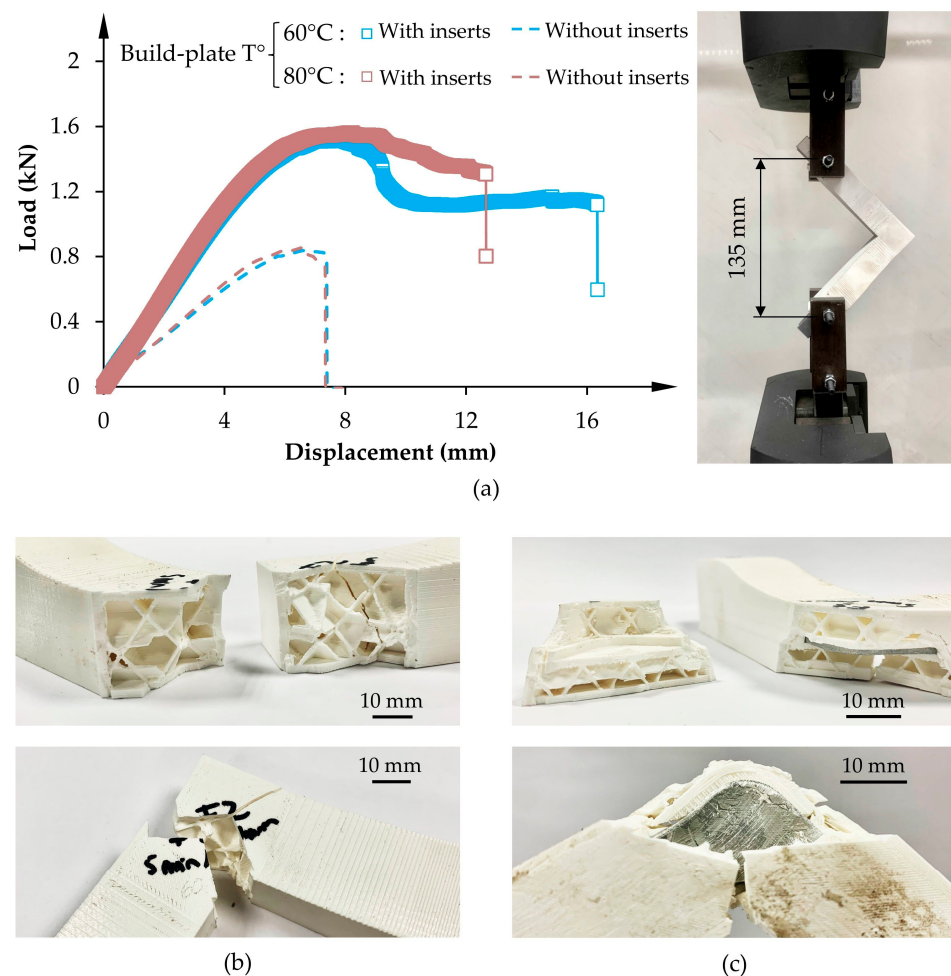


Figure 9. (a) Load–displacement evolutions and representative photograph of the corner tensile tests carried out on the prototypes, and corresponding failure modes for the corner connectors (b) without metal inserts and (c) with metal inserts.

4. Conclusions

The proposed methodology, focused on a novel hybridization of additive manufacturing, represented by the FFF process, with adhesive bonding, has proven effective for integrating metal inserts into polymers, suitable for both outer and inner configurations. The proposed methodology demonstrated no adverse effects on build quality, with potential issues like warping and lumps to be thoroughly solved by means of an enhanced brim adhesion and by slightly oversizing the hollow regions for fitting the metal inserts.

Tensile lap-shear tests confirmed that adhesive bonding ensures the integrity of the polymer–metal bonds without the need for additional surface structuring techniques. Furthermore, three-point bending tests revealed a significant improvement in the mechanical performance of polymers when reinforced with internal metal inserts, with consistent results observed across the different unit cells.

The feasibility of the proposed methodology was successfully demonstrated through a prototype of a corner connector, which exhibited a 100% increase in mechanical performance, accompanied by a modest 7% rise in total weight. This highlights the potential of the methodology to enhance parts made from eco-friendly materials while maintaining their complexity and quality through additive manufacturing.

The proposed methodology was validated with PLA serving as the ideal polymer material for prototyping, but the resulting polymer–metal parts could contain limitations related to UV stability, thermal resistance, and gas permeability that have not yet been

investigated. Therefore, future work will focus on strengthening the proposed methodology by extending its application to polymers with improved heat and UV resistance (e.g., ASA or PETG) and to specific adhesives designed for closed-loop recycling (e.g., stabilized α -lipoic acid-based adhesives).

Author Contributions: Conceptualization, J.P.M.P. and C.M.A.S.; methodology, S.F.S., J.P.M.P. and C.M.A.S.; software, P.M.S.R. and I.M.F.B.; validation, S.F.S. and R.F.V.S.; formal analysis, S.F.S.; investigation, S.F.S., P.M.S.R., R.F.V.S. and I.M.F.B.; resources, E.A. and C.M.A.S.; data curation, S.F.S. and J.P.M.P.; writing—original draft preparation, S.F.S. and J.P.M.P.; writing—review and editing, P.M.S.R., R.F.V.S., I.M.F.B., E.A. and C.M.A.S.; visualization, S.F.S., P.M.S.R. and R.F.V.S.; supervision, J.P.M.P., I.M.F.B. and C.M.A.S.; project administration, E.A. and C.M.A.S.; funding acquisition, E.A. and C.M.A.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was funded by the Fundação para a Ciência e a Tecnologia of Portugal (FCT) and IDMEC via the project LAETA Base Funding (DOI: 10.54499/UIDB/50022/2020), and by the Innovation Pact “R2UTechnologies—modular systems” (C644876810-00000019), by the “R2UTechnologies” Consortium, co-financed by NextGeneration EU, through the Incentive System “Agendas para a Inovação Empresarial” (“Agendas for Business Innovation”), within the Recovery and Resilience Plan (PRR).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Dataset available on request from the authors.

Acknowledgments: The authors would like to acknowledge the support provided by Fundação para a Ciência e a Tecnologia of Portugal (FCT) and IDMEC for its financial support via the project LAETA Base Funding (DOI: 10.54499/UIDB/50022/2020). This work is a result of the Innovation Pact “R2UTechnologies—modular systems” (C644876810-00000019), by the “R2UTechnologies” Consortium, co-financed by NextGeneration EU, through the Incentive System “Agendas para a Inovação Empresarial” (“Agendas for Business Innovation”), within the Recovery and Resilience Plan (PRR).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Complete overview of the processing parameters considered in the fabrication of the unit cells for testing.

ID	Build-Plate Temperature (°C)	Metal Temperature (°C)	Surface Quality	ID	Build-Plate Temperature (°C)	Metal Temperature (°C)	Surface Quality
1	60	RT ¹	AS ²	13	80	RT	AS
2	60	RT	#80	14	80	RT	#80
3	60	RT	#500	15	80	RT	#500
4	60	70	AS	16	80	70	AS
5	60	70	#80	17	80	70	#80
6	60	70	#500	18	80	70	#500
7	60	90	AS	19	80	90	AS
8	60	90	#80	20	80	90	#80
9	60	90	#500	21	80	90	#500
10	60	160	AS	22	80	160	AS
11	60	160	#80	23	80	160	#80
12	60	160	#500	24	80	160	#500

¹ Room temperature; ² as-supplied.

Table A2. Predominant failure modes for each combination of processing parameters previously disclosed in Table A1.

ID	Adherend	Mixed	Adhesive	ID	Adherend	Mixed	Adhesive
1		●		13		●	
2		●		14	●		
3		●		15	●		
4		●		16			●
5		●		17	●		
6		●		18	●		
7			●	19			●
8		●		20		●	
9		●		21	●		
10			●	22			●
11			●	23			●
12			●	24		●	

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