Manufacturing of Metal–Polymer Hybrid Parts Using a Desktop 3-Axis Fused Filament Fabrication 3D-Printer

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Abstract: This study evaluated the manufacturing of metal–polymer hybrid parts using a 3-axis desktop Fused Filament Fabrication (FFF) printer. Two printing strategies were employed: a more trivial one, consisting of 3D-printing the polymer directly onto the metal surface, and an alternative one, consisting of encasing the metal with printed polymer. Materials used were Ti-6Al-4V (both rolled/sandblasted and 3D-printed by laser powder bed fusion) and polyamide-based polymers. Demonstrators were designed to resemble omega-shaped skin stringers commonly used in vehicular applications. Several challenges were addressed, including harvesting the heat emanating from the deposited polymer to locally increase the substrate temperature, as well as positioning the metallic parts to avoid undesired collisions during the print job. Furthermore, to better understand the behavior of the encased metal under load, pullout tests were conducted on commercially available M6 and M8 steel nuts that were enclosed in a 3D-printed composite block. Results revealed that the length of the edge shared by the enclosure and metal significantly impacted the pullout strength.

Keywords: fused filament fabrication; laser powder bed fusion; metal–polymer hybrid joining; 3D-printing; additive manufacturing; technology demonstrators; Ti-6Al-4V; polyamide; composites

1. Introduction

Desktop Fused Filament Fabrication (FFF) 3D-printers have become an essential tool for individuals, businesses and industries. These devices offer a cost-effective and accessible way to create 3D models, as well as prototypes and even finished products. With the availability of a wide range of filament materials (such as ABS, PLA, Nylon and PEEK), it is possible to create objects with tailor-made properties, from rigid and durable to flexible and lightweight. FFF printers also offer a level of customization and design freedom that was previously impossible, enabling users to create complex geometries and intricate details that would be difficult to achieve with traditional manufacturing methods. Additionally, FFF printers are highly versatile and can be used in a variety of industries, including aerospace, automotive, healthcare and education. The affordability and accessibility of commercially available FFF printers have democratized the world of manufacturing, making it easier than ever for individuals and businesses to turn their ideas into reality.

In addition to polymers, the use of advanced materials such as composites and metal-infused filaments can further enhance the capabilities of FFF printers, enabling the production of multi-material parts with somewhat intricate shapes. Based on such potential, the AddJoining technique was conceived\(^{[1,2]}\). This is an FFF-based approach used to 3D-print polymer models onto metallic parts in such a way that they together comprise a metal–polymer hybrid part, joined without the use of adhesives, fasteners or friction. The schematics of the AddJoining approach is presented in Figure 1.
While several different approaches have been utilized to improve metal–polymer joint strength, little to no attention has been devoted to the manufacturing of larger and more complex parts using the proposed technique. In most cases, the tested substrate geometries were mostly flat and with limited dimensions, being therefore trivially manufactured from the machine/toolpath standpoint even in 3-axis desktop FFF printers. Naturally, this does not necessarily reflect real-life applications for which this technique might be applied further down its developmental cycle. Situations where the metallic substrate has features protruding out of the printing plane may be expected, which pose a challenge for the toolpath generation, as discussed below. Another challenge that may emerge in real-life scenarios is the heat generation and dissipation; this becomes particularly relevant when longer travel distances are involved, differing from the temperature dynamics experienced by coupon-sized parts.

To date, the AddJoining technique (whether named as such or not) has been studied at the coupon level with several material combinations and from different perspectives [2–12]. While several different approaches have been utilized to improve metal–polymer joint strength, little to no attention has been devoted to the manufacturing of larger and more complex parts using the proposed technique. In most cases, the tested substrate geometries were mostly flat and with limited dimensions, being therefore trivially manufactured from the machine/toolpath standpoint even in 3-axis desktop FFF printers. Naturally, this does not necessarily reflect real-life applications for which this technique might be applied further down its developmental cycle. Situations where the metallic substrate has features protruding out of the printing plane may be expected, which pose a challenge for the toolpath generation, as discussed below. Another challenge that may emerge in real-life scenarios is the heat generation and dissipation; this becomes particularly relevant when longer travel distances are involved, differing from the temperature dynamics experienced by coupon-sized parts.

At the same time, it is important to emphasize that one of the key advantages of FFF (and by consequence of the AddJoining technique) is the affordability in terms of machinery, which is directly correlated to the abundance and popularity of desktop 3-axis devices. The more traditional Cartesian design, with a 3-axis gantry system [13,14], uses three stepper motors to control the movement of the print head in the x and y directions, while the print platform (or bed) typically moves along z. The conjoint movement of print head and bed allows 3D models to be reproduced layer by layer, with each layer occupying a plane parallel to the build platform. This setup is reliable and relatively cost effective, being commonly used in both consumer-grade and industrial-grade printers [15]. While more-recent 5-axis setups can be considered more advanced technologically and therefore more capable of addressing the aforementioned challenges, they are also considerably more expensive and much less user-friendly, both in terms of slicing algorithms, toolpath generation and machine tailoring/modification.

Therefore, to preserve aspects that have made desktop 3D-printers extremely popular while still being able to manufacture 3D models over large and/or complex (i.e., non-flat) substrate geometries, it is necessary to introduce printing strategies that can work even

**Figure 1.** Schematics of the AddJoining technique: (a) a metallic substrate is clamped onto a heated bed; (b) a "coating layer", normally comprising an unreinforced polymer, is deposited directly onto the metal surface; (c) the first layer of the sliced model is deposited onto the coating layer; (d) the subsequent layers of the sliced model are 3D-printed following standard FFF principles. Adapted with permission from [3].
when only three axes are available. In fact, this is a relevant engineering field nowadays, which motivated studies in areas such as support structure design [16–21] and advanced slicing algorithms that can optimize the placement of material during printing [19–22], including over non-planar surfaces (e.g., convex, concave) [14,23–28].

However, other existing printing challenges have been relatively less addressed by the scientific community. For instance, the benefits of sequential printing of multiple parts within the same print job (instead of printing one layer of each model at a time) have not been explored, which can be partially attributed to difficulties that sequential printing entail, i.e., the risk of collision between print head and already-printed parts. Nonetheless, the apparent lack of scientific interest regarding this subject was no obstacle for the user community, which has developed tools to enable sequential printing. Cura (v5.3.1)—a popular slicer software developed and distributed by Ultimaker (Utrecht, The Netherlands)—has a built-in function that enables printing one part at a time; the slicing algorithm identifies the locations where each component was printed, restricting the movement of the print head across certain areas of the print bed. Other well-known slicers such as PrusaSlicer (Prusa Research, Partyzánská, Czech Republic) and Slic3r (open source project) also provide comparable functions with equal effectiveness.

Although not the goal of the present study (as elucidated later), this printing challenge in particular deserves to be mentioned in this context, since its core technical issue may also be present in the AddJoining technique, depending on the metallic substrate to be used. Geometries containing protruding features inevitably will pose a threat in terms of crashing, which demands special attention concerning printing strategies, as mentioned earlier. Despite similarities, however, printing over and around a protruding feature is an issue in and of itself and therefore cannot be tackled simply by using the same approach as for sequential printing. When printing one part at a time, spreading each part over large distances from each other is always possible; this is not the case if the print head must constantly and necessarily avoid one or more protrusions present on a given metallic substrate when depositing polymer over metal. Printing strategies in this scenario may vary depending on the specific geometries involved, necessitating a case-by-case approach.

Additionally, another printing challenge that is relevant not only for 3-axis systems but also for other systems pertains to the temperature dynamics when scaling up 3D models. Similar to most Additive Manufacturing (AM) processes, FFF processes can undergo significant temperature variations depending on the dimensions and geometry of the 3D model, since they impact both the hot end path and the total time spent on the heated bed [29,30]. This is particularly important for the metal–polymer joining, where adhesion is highly sensitive to the substrate temperature during the process [3,8,10]. At the coupon level, dimensions are relatively small, which may cause a heat build-up effect that, together with heated bed and/or heated chamber, increases substrate temperature even further. In fact, this additional heat build-up provided by the hot end itself can be considered relevant for the temperature profile and even beneficial for the joint strength, as observed before [3,12]. However, whether such an effect can be carried over to the manufacturing of larger parts is still unknown.

To address these two printing challenges (i.e., collision avoidance for complex substrates and heat retention for larger parts), the aim of the present study is to demonstrate the upscaling of the AddJoining technique for a combination of Ti-6Al-4V substrates and PA-CF 3D-printed parts. This has been accomplished by designing and successfully manufacturing two metal–polymer demonstrator parts, with each part highlighting key aspects and addressing specific challenges mentioned earlier. To upscale the temperature dynamics observed at the coupon level, a “direct assembly” strategy was adopted to circumvent protruding features on the substrate, and a “surround and enclose” strategy was used.

The present publication can be considered a direct continuation of the work reported in [3,12], both dealing with the optimization of AddJoining parameters for the said material combination (using rolled and 3D-printed substrates, respectively). Therefore, details
concerning parameter selection, joint microstructure, mechanical properties and micromechanical fracture mechanisms will be mostly omitted.

Finally, since both pieces of work (as well as all those cited in AddJoining publications) have employed the “direct assembly” strategy, there are plenty of data concerning mechanical behavior of metal–polymer joints in this situation. On the other hand, limited information on the effectiveness of the “surround and enclose” strategy is available. While this can be assessed in several different ways, the current study employed a simple pullout test using embedded metallic screws on 3D-printed PA-CF blocks. This approach aims to establish an initial understanding of the subject, serving as a reference for this and future studies alike.

2. Materials and Methods

2.1. Manufacturing of Demonstrators: Design and Printing Strategy

In order to evaluate the upscaling capabilities of the AddJoining approach, two technology demonstrators were proposed, designed and manufactured. Both demonstrators were based on a generic omega stringer joined to a flat panel (or skin), which is a fairly common structural detail found on many vehicular applications [31,32]. A schematic drawing of the planned demonstrator profile is shown in Figure 2. For Demonstrator 1, a rolled/sandblasted Ti-6Al-4V sheet was used as the panel, onto which the omega stringer was 3D-printed by AddJoining; this strategy will be referred to as “direct assembly”. For Demonstrator 2, the Ti-6Al-4V omega stringer was produced by laser powder bed fusion (LPBF), whereas the panel was subsequently 3D-printed using the AddJoining approach; this strategy will be referred to as “surround and enclose”. A summary of the specificities for each demonstrator is available in Table 1. Specific geometry details and dimensions for each demonstrator are presented in the following sub-sections.

![Figure 2. Generic profile of the planned demonstrators.](image)

### Table 1. Description of substrate characteristics regarding materials and additional features, based on Figure 2.

<table>
<thead>
<tr>
<th>Demo Type</th>
<th>Printing Strategy</th>
<th>Stringer</th>
<th>Panel</th>
<th>Enclosure</th>
<th>Filling of Space under Stringer</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Direct assembly</td>
<td>Coating layer: PA6/66</td>
<td>Rolled, sandblasted</td>
<td>No</td>
<td>Honeycomb structure (normal to panel)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Subsequent layers: PA-CF</td>
<td>Ti-6Al-4V</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Surround and enclose</td>
<td>LPBF Ti-6Al-4V</td>
<td>PA-CF</td>
<td>Yes</td>
<td>None</td>
</tr>
</tbody>
</table>

The “direct assembly” strategy implemented for Demonstrator 1 used the same approach as reported by most AddJoining studies [2–12], whereby the ensuing joint strength was strictly a function of the bond strength of both the metal/coating layer and coating layer/subsequent layer interfaces. Demonstrator 2, however, applied a different approach, whereby (1) a portion of the polymer/composite is 3D-printed by FFF, (2) the process is paused, and the metal part accommodated onto the 3D-printed portion (which is still on the print bed) and then (3) the rest of the polymer/metal part is printed around the metal.
As a result, the metal part is partially enclosed by the polymer/composite layers, which provides an additional strengthening effect for the joint.

To manufacture the polymer component of the demonstrators, an unmodified Ultimaker S5 FFF printer (Utrecht, The Netherlands) was used. This device operates with a 3-axis gantry system and a dual-nozzle extrusion head, where two different filaments can be loaded simultaneously. The print bed consisted of a 2 mm aluminum sheet (365 \( \times \) 278 \( \times \) 2 mm), which was protected by a 3M masking tape (Hutchinson, KS, USA) on the regions where the polymer would be printed.

Two different filament materials have been used for the production of the demonstrators (see Table 1). For the coating layer (i.e., layer deposited directly over the metallic substrate), an unreinforced Polyamide 6/66 filament produced by Ultimaker, (Utrecht, The Netherlands) was used, which was extruded through a nozzle with a diameter of 0.4 mm. The subsequent layers of the demonstrators were printed using a polyamide-based filament reinforced with 6.5% (volume) of short carbon fibers (PA-CF), produced by BASF (Emmen, Netherlands). This filament was extruded through a nozzle of 0.6 mm. In both cases, a nozzle priming stage was carried out immediately before the print job, for which a total of around 10 g of material was extruded. Further details on the material properties of those filaments are available in [3,29], respectively.

2.1.1. Direct Assembly Strategy

As mentioned above, this technology demonstrator consisted of a stringer of 3D-printed PA-CF manufactured over a Ti-6Al-4V panel. The specific geometries of the stringer are shown in Figure 3. Its design was based on stringers that are traditionally applied in many vehicular structural components, including in aircraft [31,33]. Furthermore, internal honeycombs were added to the stringer; in theory, such patterns would be used as a means to further improve the stiffness of the component [32]. In this case, however, they also highlight the capabilities of the AM-based approach, since such a pattern cannot be trivially realized by other polymer processing techniques such as injection molding. As for the metallic panel (or skin), it consisted of a rolled 100 mm \( \times \) 90 mm Ti-6Al-4V sheet with a thickness of 2 mm. A sandblasting surface pre-treatment was performed on the panel using Corundum (\( \text{Al}_2\text{O}_3 \)) particles (Strahlimittel24, Bindlach, Germany), with parameters shown in Table 2.

![Geometries of PA-CF stringer to be manufactured onto a 100 mm \( \times \) 90 mm \( \times \) 2 mm rolled, sandblasted Ti-6Al-4V sheet (panel). (a) Cross-sectional dimensions; (b) isometric view of the demonstrator; (c) detailed view of the internal honeycomb structures. Z denotes the printing direction. Dimensions in mm.](image-url)
Table 2. Sandblasting parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particles</td>
<td>Corundum (Al₂O₃)</td>
</tr>
<tr>
<td>Pressure</td>
<td>4.5 bar</td>
</tr>
<tr>
<td>Particle size (average)</td>
<td>35 µm</td>
</tr>
<tr>
<td>Incidence Angle</td>
<td>90°</td>
</tr>
<tr>
<td>Distance nozzle—substrate</td>
<td>100 mm</td>
</tr>
<tr>
<td>Nozzle diameter</td>
<td>3 mm</td>
</tr>
</tbody>
</table>

Following the design stage, the 3D model was converted into .stl file format and then imported into Ultimaker Cura 5.3.1 slicer software (Utrecht, The Netherlands), where the printing strategy as a whole was defined. Firstly, instead of using a dedicated sample holder for fixing the metal, four 2 mm thick L-shaped parts were 3D-printed prior to the AddJoining process itself. By placing these small structures appropriately, the rolled Ti-6Al-4V substrate could be fixed in between, providing a stable base for the assembly of the composite stringer. However, it is important to emphasize that these additional support parts were only a requirement based on the experimental setup at hand; for a larger process chain, these aspects would be addressed with proper holders and fixers that would not need to be 3D-printed each time.

The stringer itself consisted of a coating layer (PA6/66) deposited directly onto the rolled Ti-6Al-4V sheet, with subsequent PA-CF layers, comprising the 3D model itself, 3D-printed over the said coating. Process variables were selected based on the knowledge gathered during the previous optimization activities [3,12,29], being summarized in Table 3.

Table 3. Process variables used in the production of the technology Demonstrator 1 (direct assembly).

<table>
<thead>
<tr>
<th>Process Variables</th>
<th>Coating Layer (PA 6/66)</th>
<th>3D Model (PA-CF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Printing bed temperature</td>
<td>140 °C</td>
<td>120 °C</td>
</tr>
<tr>
<td>Printing speed</td>
<td>5 mm/s</td>
<td>80 mm/s</td>
</tr>
<tr>
<td>Layer height</td>
<td>0.4 mm</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Nozzle diameter</td>
<td>0.4 mm</td>
<td>0.6 mm</td>
</tr>
<tr>
<td>Extrusion temperature</td>
<td>280 °C</td>
<td>280 °C</td>
</tr>
<tr>
<td>Road width</td>
<td>0.4 mm</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Distance between roads</td>
<td>0.4 mm</td>
<td>0.4 mm</td>
</tr>
</tbody>
</table>

2.1.2. Surround and Enclose Strategy

As briefly explained earlier, this method consists of surrounding the metallic component with extruded polymer/composite in such a way that the 3D-printed model is printed not only over the metallic part but also around it. Eventually, the metallic component is partially or totally enclosed by the 3D-printed polymer/composite, with the joint strength being in this case a function of the enclosure itself, and not of the interfacial bond strength, as was previously the case.

Demonstrator 2 was designed in such a way that it would roughly mirror Demonstrator 1, that is, the stringer would be metallic and the panel polymeric. Thus, in this case, the metal substrate (stringer) was 3D-printed by LPBF, mostly replicating dimensions used on the PA-CF stringer from Demonstrator 1 (see Figure 4). This was performed on an EOS 280 printer, using a laser power of 280 W, as well as a layer thickness of 30 µm, a hatching distance of 140 µm and a printing speed of 1200 mm/s [34]. Commercially available Ti-6Al-4V powder (D50 = 33.6 µm) was used as a feedstock, with characteristics such as particle size distribution and chemical composition reported in [34]. The stringer was 3D-printed with a leaning angle of 90°, meaning that the building direction was the one indicated by the arrow in Figure 4b. The PA-CF panel (subsequently manufactured via AddJoining) consisted of a 94 mm × 84 mm × 2 mm flat model to be 3D-printed below the stringer, as shown in Figure 5.
The strength of the interfacial bond on Demonstrator 1 ("direct assembly") could be reasonably inferred from the results of mechanical tests at the coupon level reported in [3]. However, these results could hardly describe a situation such as the one found on Demonstrator 2. Therefore, in order to collect more information on how the enclosing mechanism works, an additional set of experiments was performed, whereby blocks of PA-CF (30 mm × 30 mm × 13 mm) were 3D-printed with pre-designed insert cavities. Commercially available M6 and M8 steel nuts were inserted into these cavities and then enclosed with a 2 mm thick PA-CF cap (see Figure 6a). Geometry and dimensions of steel nuts are presented in Figure 6b and Table 4, respectively.

Table 4. Values of dimensions shown in Figure 6b.

<table>
<thead>
<tr>
<th>Type</th>
<th>d (mm)</th>
<th>e (mm)</th>
<th>s (mm)</th>
<th>m (mm)</th>
<th>A (mm²)</th>
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<tbody>
<tr>
<td>M6</td>
<td>6.0</td>
<td>11.1</td>
<td>10.0</td>
<td>3.2</td>
<td>50.3</td>
</tr>
<tr>
<td>M8</td>
<td>8.0</td>
<td>14.4</td>
<td>13.0</td>
<td>4.0</td>
<td>82.5</td>
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</table>

2.2. Pullout Tests

The strength of the interfacial bond on Demonstrator 1 ("direct assembly") could be reasonably inferred from the results of mechanical tests at the coupon level reported in [3]. However, these results could hardly describe a situation such as the one found on Demonstrator 2. Therefore, in order to collect more information on how the enclosing mechanism works, an additional set of experiments was performed, whereby blocks of PA-CF (30 mm × 30 mm × 13 mm) were 3D-printed with pre-designed insert cavities. Commercially available M6 and M8 steel nuts were inserted into these cavities and then enclosed with a 2 mm thick PA-CF cap (see Figure 6a). Geometry and dimensions of steel nuts are presented in Figure 6b and Table 4, respectively.
In order to assess the load-bearing capacity of the enclosed metallic inserts, a pulling-out test was proposed, in which a screw would be fastened to the steel nut and pulled, while the PA-CF block would be fixed in place. To execute this plan, an adapted setup (as shown in Figure 7) was implemented on a Zwick Roell universal test rig (Ulm, Germany). The test speed was 1 mm/s. The main outcome of the test was the first force peak (herein termed “maximum pullout force”), which indicates that a crack between PA-CF block and PA-CF cap nucleated and started to grow.

For fracture analysis, specimens tested for pullout strength were cut longitudinally and analyzed using a Zeiss SteREO Discovery.V20 stereomicroscope (Oberkochen, Germany) and a Tescan Mira-3 scanning microscope (Brno, Czech Republic) under secondary electron (SE) modus.

### Table 4. Values of dimensions shown in Figure 6b.

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</table>

![Figure 6](image_url)  
**Figure 6.** (a) Sketch of the PA-CF block used for the experiments with enclosed metallic inserts. Z denotes the printing direction. Dimensions as follows: D = 30 mm; h = 13 mm; t = 2 mm; (b) Generic shape of the steel nuts inserted into the cavities shown in (a). Blue ring A denotes the area on which PA-CF is directly printed. Dimensions available in Table 4.

![Figure 7](image_url)  
**Figure 7.** Experimental setup for the pullout experiments, (a) side view, (b) top view. Black arrows indicate load direction; d = 20 mm.

### 2.3. Microscopy

For fracture analysis, specimens tested for pullout strength were cut longitudinally and analyzed using a Zeiss SteREO Discovery.V20 stereomicroscope (Oberkochen, Germany) and a Tescan Mira-3 scanning microscope (Brno, Czech Republic) under secondary electron (SE) modus.
3. Results and Discussion

3.1. Direct Assembly Strategy: Execution and Results

Aside from process variables, another important aspect of the printing strategy was the nozzle path during the coating layer deposition. As shown in [3,12,29], the path followed by the nozzle has a significant impact on the temperature of the surrounding area. When the nozzle remains in close proximity to a specific substrate area for an extended period, it results in increased temperature in that region. As a consequence, the extruded polymer exhibits decreased viscosity after deposition [9], thereby improving wettability; this was indeed the reason why the process was not feasible for substrate temperatures lower than 140 °C, as previously reported in [3].

By exploiting this particularity, one is capable of locally increasing the substrate temperature beyond the preset bed temperature. For the manufacturing of this demonstrator, instead of depositing the coating layer onto the 100 mm × 90 mm Ti-6Al-4V surface at once, the surface was segmented into 20 strips, each with dimensions of 5 mm × 90 mm. On each strip, the nozzle would oscillate back and forth with a 5 mm amplitude (named local path for convenience) as it moved from one edge of the substrate to the other (global path, 90 mm per strip). A visual representation of this moving pattern is shown in Figure 8.

![Visual representation of the nozzle path implemented on the coating layer deposition for technology Demonstrator 1. (a) Red arrows represent the global nozzle path. (b) In detail, black arrows represent the local oscillating path.](image)

The 5 mm amplitude of the local path was selected after a comparison between the temperature profiles reported in [3,12]. For the former, an oscillation width of 14 mm was adopted, with a printing speed of 5 mm/s. This combination led to the creation of a toolpath that accumulated sufficient heat to locally increase the substrate temperature to 189 °C [3], 49 °C above the preset bed temperature (T_{bed}). However, by decreasing the oscillation width to 5 mm while keeping the same printing speed [12], the peak substrate temperature reached 218 °C, which is even above the measured melting temperature (T_{m}) of the PA6/66 (193 °C [3]). A visualization of the effect of oscillation width on the substrate temperature based on data collected from [3,12] can be seen in Figure 9. This local temperature excess ensured that the polymer has a sufficiently low viscosity to penetrate the surface irregularities with more efficiency.
With this strategy set, the process began by printing four L-shaped supports to hold the metal substrate in place. Immediately after, the process was paused and the Ti-6Al-4V panel was placed between the supports (Figure 10a). To ensure a homogeneous temperature on the panel, the process remained paused for 5 min. Next, the process resumed with the coating layer deposited according to the strategy described earlier. The result was a wavy, non-homogeneous visual appearance, as shown in Figure 10b. This was a clear sign of temperature excess, which was an advantage in this case, as discussed above. Moreover, according to [3], a rougher/wavier coating layer is beneficial to the joint strength, since it helps with the integration between the coating layer itself and the subsequent layers, which otherwise can be considered as weak a link as the metal–polymer interface itself.

The input printing speed of 5 mm/s (see Table 3) was related only to the local path (black arrows, Figure 8b); the speed of the global path (red arrows, Figure 8a) was not a direct input, being instead a function of other process variables. Thus, based on these, the resulting global path speed was 0.4 mm/s, meaning that the coating layer took 75 min to fully cover the Ti-6Al-4V panel. However, it is important to mention that, for the proposed substrate dimensions, the completion time was only a function of the process variables listed in Table 3, and not of the way the coating layer was subdivided. In fact, a single strip with a 100 mm amplitude (i.e., local path = global path) would also require 75 min to be deposited (with all other variables kept constant), although with no added benefit related to the local temperature increase.

After the deposition of the coating layer, the PA-CF stringer was 3D-printed following standard FFF principles, with the final demonstrator shown in Figure 11. The whole manufacturing process, from coating layer to the final skin-stringer, was completed in 2.6 h, with the coating layer deposition taking approximately 48% of the completion time. Aside from material used on the initial nozzle priming (a couple of grams), there was no material loss. The part weighted 134 g, with the stringer itself comprising 40% of the whole manufacturing process, from coating layer to the final skin-stringer, was completed in 2.6 h, with the coating layer deposition taking approximately 48% of the completion time. Aside
from material used on the initial nozzle priming (a couple of grams), there was no material loss. The part weighted 134 g, with the stringer itself comprising 40% of it.

**Figure 11.** (a) Overview of the technology Demonstrator 1 in its final form; (b) side view highlighting the metal–polymer interface.

**Joint Characteristics and Expected Mechanical Performance**

As mentioned in the Introduction, the present work is based on results from two previous studies carried out and published by this research group, in which Ti-6Al-4V/PA-CF joints were produced, optimized, tested and evaluated according to different aspects at the coupon level. In one of these studies [3], a combination of rolled, sandblasted Ti-6Al-4V, PA6/66 and PA-CF was used to produce metal–polymer joints that were later tested under single-lap shear. This is identical to the material combination used in the presented demonstrator, which was also 3D-printed with the same machine, process parameters and printing strategy (“direct assembly”). Therefore, it is reasonable to anticipate that factors such as interfacial characteristics, and subsequently the mechanical properties of the joints, would be consistent from the coupon level to the demonstrator level.

With respect to the metal–polymer interface, it was possible to observe that the polymer was able to penetrate into relatively deep indentations left by the sandblasting pre-treatment (Figure 12a); however, it was also possible to observe that some entrapped air bubbles were still present at the interface. Nevertheless, such an interfacial configuration led to an ultimate lap shear strength of 23.9 ± 2.0 MPa, when using the same process parameters as listed in Table 3 [3].

**Figure 12.** Comparison of metal–polymer interface microstructures between (a) rolled, sandblasted Ti-6Al-4V/PA-CF and (b) LPBF-printed Ti-6Al-4V/PA-CF combinations. Continuous arrows indicate instances where the polymer was able to penetrate surface cavities; dashed arrows indicate air bubbles. Process parameters: see Table 3.

In spite of the satisfactory performance in the single-lap shear test (ASTM D1002-10), joints such as the one in Demonstrator 1 tend to perform poorly under flexural loads, as
observed by [3] using an adapted three-point bending test (ISO 14679:1997). This test is used to determine the force (or energy) necessary to detach a 25 mm × 5 mm × 4 mm polymer (or adhesive) block attached to a metal substrate using a three-point setup [35,36]. The results in [3] suggested that, for a 5 mm/s printing speed and a 0.25 mm coating layer height, the force required for the interfacial failure was 120.9 ± 20.5 N, which represents an energy absorption of 22.3 ± 6.7 J (details on force–energy conversion provided by [12,36,37]).

Later, a study using LPBF Ti-6Al-4V substrates [12] indicated that, for the same Addjoining parameters, the energy absorption reached 148.6 ± 66.7 J (note: this specific value was not mentioned in the paper but was used to calculate the prediction model). An overview of the three-point bending test results from both sandblasted [3] and LPBF [12] substrates is shown in Figure 13.

**Figure 13.** Summary of results from three-point bending tests (ISO 14679:1997) on Ti-6Al-4V/PA-CF hybrid joints with different substrate roughness, as collated from previous published studies (sandblasted [3] and LPBF [12]). Coating layer height and printing speed maintained constant at 0.25 mm and 5 mm/s, respectively.

It is possible to conclude that while under shear loads a relatively low substrate roughness is sufficient to achieve satisfactory performance, this is not the case when the joint is submitted to flexural loads. In these circumstances, a rougher metal surface is required, since it provides intricate cavities that can serve as anchoring spots for the penetrating molten polymer during the process. This is clearly visible when comparing Figure 12a,b, where the latter provided much deeper cavities that effectively acted as ink bottle pits [38], providing a better micromechanical interlocking effect in comparison to the shallow and relatively simplistic surface irregularities resulting from the sandblasting pre-treatment. Thus, when implementing the “direct assembly” approach, it is recommended to give particular consideration to the overall surface of the substrate. This can be achieved by either enhancing its roughness or incorporating engineered surface structures, specifically designed to enhance the interlocking between the metal and polymer components [6,8].

### 3.2. **Surround and Enclose Strategy: Execution and Results**

Due to the limitations imposed by the 3-axis system, several adaptations had to be made in order to realize the demonstrator as presented in Figure 5. For example, whenever a layer is being 3D-printed on traditional 3-axis FFF devices, there must be no section of the substrate above the nozzle level (considering conventional layer-by-layer slicing). Otherwise, there is a risk of collision between the out-of-plane section and the print head, which can cause damage to both. Even if this is considered within the Gcode (i.e., the file with the set of commands used by the machine during a print job), the minimum distance...
between the out-of-plane section and the nozzle depends on the size of the print head, which can be several hundred millimeters in many cases. This is illustrated by Figure 14a.

![Figure 14](image)

Figure 14. Approaches to enclose metallic parts with protruding sections (example) using a 3-axis FFF printer. (a) Placing the metal part onto a pre-printed polymer section with the protrusion facing upwards (i.e., above nozzle level) may cause a collision with the print head; (b) printing the enclosure first using removable support structures results in a collision-free path.

This is especially relevant for the proposed omega stringer, since during the enclosure printing, the print head may have collided with the trapezoidal section of the stringer if this section was placed above the nozzle level. A solution to this problem would be printing the enclosure first, at a height equal to the height of the stringer, which then could be placed in such a way that the print head would travel freely, with no risk of collision. This situation is illustrated (in a generic fashion) by Figure 14b. In this case, the enclosures can be suspended by the use of support structures.

Finally, the last concern regarding print strategy was the gap below the trapezoidal section. When using the Figure 14b approach, a significant portion of the PA-CF part would be 3D-printed in a suspended state, without proper support as a result of the gap, which obviously was considered unfeasible. A solution to this issue was the use of a temporary platform: a 2 mm aluminum sheet covered with a layer of polyimide (PI) tape (commercially available as “Kapton”). This platform could be easily removed once the job was concluded. An illustration of this method is shown in Figure 15.

While implementing this printing strategy, the process was briefly halted after the enclosures were printed to allow for the placement of the omega stringer and temporary aluminum/PI support in their respective positions (see Figure 15). Figure 16 shows the results of Demonstrator 2 as printed, while it was still sitting on the printing bed. The 3D-printed support structure was easily removed by hand afterwards, since its bonding with the enclosure was minimal.
Figure 15. Use of a temporary platform (aluminum sheet covered with PI layer) for suspended regions such as the ones below the gap of the trapezoidal section of the LPBF stringer.

The complete part took 6 h to be finished, including the 3D-printing of the omega stringer by LPBF (4 h), the 3D-printing of the support structures and enclosures (30 min) and the pause for the placement of the stringer (5 min). It weighed 176 g, of which 130 g resulted from the Ti-6Al-4V omega stringer itself. An image of the final part is shown in Figure 17.

Figure 16. Technology Demonstrator 2 at the end of the print job. Z denotes the printing direction.

(a) Overview of the technology Demonstrator 2 in its final form; (b) side view highlighting the enclosure.

Figure 17. (a) Overview of the technology Demonstrator 2 in its final form; (b) side view highlighting the enclosure.
3.2.1. Pullout Test Results

Typical Force × Displacement curves for both nut sizes can be seen in Figure 18. For either nut size, curves consistently presented a higher, sharper initial peak (represented by asterisks in the image) followed by a lower, broader one, after which the force decreased until the test was manually stopped.

![Force vs Displacement](image)

**Figure 18.** Representative Force × Displacement curves from pullout tests performed on M6 and M8 steel nuts embedded into a PA-CF 3D-printed cube. Asterisks indicate the peak resulting from the initial crack nucleation.

The identified peaks represented different stages of the test. The first peak indicates the moment at which a crack between the enclosure and the base block is formed, effectively determining that the enclosure has failed. This crack formed along the edge between enclosure, base block and nut (asterisks in Figure 19); the extension of the edge was equal to six times the length of one of the sides of the nut (indicated by “d” in Figure 6b) and therefore was proportional to the size of the nut itself.

![Cross-section of a tested specimen](image)

**Figure 19.** Cross-section of a tested specimen after the pullout test. “E” indicates the enclosure, while “B” indicates the base block, with the white dashed line indicating the transition between both. Asterisks indicate crack nucleation sites, while white arrows show the crack propagation direction. Nut size: M6.

Once the crack had formed along the entire length of the mentioned edge, it was able to propagate radially in an outward direction (white arrows in Figure 19), causing delamination between enclosure and base block. During this stage, a force decrease was observed. Quickly thereafter, the force began to rise again; at this stage, the crack had encountered the clamping ring (see Figure 7), which prevented further delamination at the enclosure/base block interface. In this case, the load applied by the testing rig was transferred via the steel nut (already loose within the fractured cavity) to the enclosure itself, eventually causing a trans-laminar crack [39] to emerge across the enclosure layers. As the nut was raised in relation to the base block, the load transferred by the nut to the enclosure
layers gradually shifted its direction (with respect to the enclosure layers), which caused the propagating crack to change its path. This is visible in Figure 20. Eventually, the force began to decrease again, as the nut found itself in a position where it no longer could transfer enough load to the specimen to tear the enclosure entirely. At this point, the steel nut was barely slipping along the displaced enclosure, which ultimately would have resulted in the complete separation of metal and polymer had the test not been manually stopped.

![Image](a) Top view of a tested specimen, where the imprint of the clamping ring is indicated; (b) cross-section view of a tested specimen, where the region (c) is indicated; (c) SE-SEM image of the said region, where a crack across the enclosure is observed. Arrow indicates the crack path. “E” indicates the enclosure, while “B” indicates the base block. Nut size: M6.

In terms of force values, by considering the first force peak as the specimen strength (“maximum pullout force”), it was possible to conclude that the size of the embedded nut played a role in the pullout resistance. In this case, the larger nut is the embedded part, and it will also be the required force to remove it from the enclosure. This is shown in Figure 21. The larger M8 nuts required an average of 2.2 kN to be pulled out of the PA-CF block, a 46% higher force in comparison to the smaller M6 nuts.

![Graph](Averag maximum pullout force for specimens with M6 and M8 steel nuts.)

As discussed earlier, during the pullout test, the initial crack is formed along the edge shared between enclosure, base block and nut, with the length of this edge being proportional to the size of the embedded part. Supposing that the crack can only propagate away from the nut once the entirety of this edge has failed, it is also reasonable to assume...
that longer edges will require higher forces to fail. Moreover, based on these observations, one could also assume that the extent of the interfacial area between enclosure and base block also plays a role in the energy absorption as the nut is pulled out of the enclosure. However, this has not been evaluated within the present study.

Undoubtedly, the loading conditions present on a pullout specimen are not the same as the ones that would occur in Demonstrator 2 if one were to pull the stringer out of the polymer case. However, the pullout test results indicate at the very least that the length of the enclosure/metal edges has an important influence on the strength of the hybrid part under these circumstances. Therefore, it is a useful tool at the specimen level that can be later employed to optimize the strength of the enclosure, supporting the design stage of the hybrid component.

3.2.2. Other Potential Uses and Outlook

The “surround and enclose” strategy may be ideal for the embedding of other metallic inserts within the 3D-printed polymer. These include not only nuts but also bolts, springs, sensors, circuits, LED lamps and magnets, the last produced as a proof of concept within this study and shown in Figure 22. In this example, a neodymium disc magnet was embedded into a hexagonal-shaped PA-CF part by employing the “surround and enclose” strategy. With only two 0.2 mm thick layers on each side of the magnet, it was still possible to observe the magnetic properties of the disc, although expectedly not as strong as it would be with no enclosure. Nevertheless, this proof of concept highlights the versatility of this printing strategy.

![Figure 22. Example of a neodymium magnet embedded within a PA-CF hexagon produced by the “surround and enclose” strategy.](image)

In any case, it is important to stress, once again, that the mentioned adaptations are solely a result of the use of a standard desktop 3-axis 3D-printer. Carrying out such methods within a production line may be worthwhile only if every step of the process (placement of metal part, placement of temporary substrates, etc.) is performed in an automatized fashion (i.e., using robot arms or other similar solutions). However, a much simpler alternative for the manufacturing of parts with similar geometries would be the use of a 5-axis 3D-printer, whereby the substrate part and the print head could move conjointly without the risk of undesired collisions. Nonetheless, the methods described in this section are relatively straightforward and therefore may be useful for prototyping, production of tools on-the-fly and other similar activities, especially considering the abundance of 3-axis 3D-printers used specifically for such purposes.
4. Conclusions

Using a desktop 3-axis Fused Filament Fabrication 3D-printer, metal–polymer hybrid parts have been successfully produced using the FFF-based AddJoining approach. A material combination of Ti-6Al-4V (both rolled and 3D-printed by laser powder bed fusion), polyamide 6/66 and short-carbon reinforced polyamide was employed in the technology demonstrators. Two different printing strategies were proposed and implemented: “direct assembly”, where a polymer model is 3D-printed directly onto a metallic substrate; and “surround and enclose”, where the polymer is 3D-printed around the metallic substrate in order to encase it (partially or fully) within the polymer part.

Mainly, two different aspects have been focused on when planning the printing strategies. For the directly assembled demonstrator, slicing the coating layer into several strips allowed for a greater heat build-up effect and consequently better metal–polymer adhesion, which had been also observed at the coupon level in past studies. For the surrounded-and-enclosed demonstrator, the challenge was to avoid collisions between the metal part and the print head, which was solved by printing the enclosure first, with the aid of support structures.

Additionally, to understand how the “surround and enclose” strategy works against pullout loads, coupons comprising steel nuts of different sizes (M6, M8) embedded into 3D-printed PA-CF were produced and tested. In this case, M8 nuts withstood an average force of 2.2 kN before the PA-CF enclosure failed. Moreover, it was possible to conclude that the pullout force is dependent on the length of the edge shared between metallic insert and enclosure. Overall, this work offers a detailed case study to support the fabrication of metal–polymer hybrid structures using a 3-axis desktop Fused Filament Fabrication 3D-printer.

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