Defectology Characterization of FDM Drilled Parts

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Abstract: Since its emergence, the industry has made great efforts to implement additive manufacturing processes in its production systems. However, to achieve this use, the precision of the parts must also be guaranteed. But it is not yet possible to achieve the characteristics required in certain industrial sectors like the aeronautical where highly rigorous requirements are related to the assembled parts. In this way, alternatives arise, such as the use of machining to obtain the precision required. This concept has been applied for some time to metal parts obtained through additive manufacturing, but not so much to polymer parts. For this reason, given that it is expected that polymeric parts will be used in aeronautical structures, these will have to be machined to obtain the required geometric characteristics. Therefore, in this article, a parametric study of the quality of the holes made in parts obtained by Fused Deposition Modelling (FDM) will be carried out.

Keywords: FDM, Additive manufacturing, Drilling, Roughness.

1. Introduction

Additive Manufacturing (AM) is currently a technology that offers a transformative approach to industrial reality and a business opportunity [1]. This can be seen in an increasing number of examples where the advantages of these processes are being exploited. So much so that there are already several success projects for complex metallic products. [2]. However, metal parts are not the only successful examples, and the shipbuilding industry has already focused on taking advantage of the characteristics offered by polymeric parts [3,4]. Polymeric additive manufacturing (PAM) has a large market share [5], therefore, it is understood that polymeric additive manufacturing is not destined to disappear due to the incorporation of metal. There is a large number of applications where PAM could contribute to the environmental performance of the transport sector due to its low weight and good physicochemical characteristics, without involving a great effort in product redesign [6].

For the aerospace industry, PAM could be interesting for non-structural parts such as tooling, jigs or even for shimming type fillers. In these last elements, there is a problem associated with its current application in liquid [7-9] because of the loss of properties under certain conditions. This liquid shim, so common in this sector, could be replaced by a solid shim obtained by PAM for this specific purpose. This would represent a great technological breakthrough in the sector and especially a great contribution to its environmental improvement considering the toxic component of the materials currently used, but it would require compliance with the complex standards of the sector [10]. This is not the only example, reinforced PETG is also being studied for its incorporation in certain types of parts where it can compete with other traditional materials [11].
However, due to the lack of quality in the final parts, it is becoming increasingly common to find examples where additive manufacturing is either post-processed [12] or complemented with machining. This trend to hybridize both technologies is not new and in metal AM there are already cases of commercial equipment that successfully hybridize the two technologies, managing to lift a metal part and then machining it to finish it [13]. This is state of the art in the case of WAAM (Welding Arc Additive Manufacturing) but there are many earlier applications in other processes such as lasers [14].

But this is not the case in polymeric additive manufacturing where there is still no such clear evidence of technology hybridization or combination of deposition with machining. However, there are plenty of examples of material removal to improve part quality, such as the use of abrasives as a post-processing technique [15]. Nevertheless, there are not so many cases of machining in conventional removal processes such as pressuring or drilling, only some examples such as milling of ABS parts for roughness improvement [16].

This may be explained by the lack of study that exists in the machining of polymers in general, perhaps because until now for this type of parts, this need was very low. Nonetheless, if this type of polymeric parts are successfully implemented in the aerospace industry, they will require at some point a drilling process with aeronautical requirements and even their stack drilling with a metal [17].

Hence, the aim of this work is to make a first approach to the feasibility of drilling parts obtained with PAM and specifically with Fused Deposition Modelling (FDM) as this is one of the most widely used polymeric processes nowadays. PETG has been selected as one of the most interesting materials in terms of its mechanical properties. In the same way, it is intended to study how a basic parameter such as the layer thickness can influence the geometric characteristics of the subsequent machining.

2. Experimental Methodology

In order to carry out the proposed study, a series of flat square samples with a side of 60 mm and a thickness of 5 mm were fabricated. These parts will be manufactured on standard commercial FDM equipment configured with a 0.4 mm diameter nozzle. As mentioned above, the material selected is PETG, which was supplied by the manufacturer eSun in 1.75 ± 0.03 mm diameter filament.

For the fabrication of these samples, a series of constant parameters were used, such as an extrusion speed of 30 mm/s, an overlap of 55%, a construction surface temperature set at 60º, 100% filling and 5 perimeters. Also, a straight 45º pattern will be selected so that all holes will have the same conditions. As a variable parameter for the fabrication, the layer thickness has been selected, where 0.15, 0.2 and 0.3 mm have been set as thicknesses to be studied. However, as a special case, an additional extreme thickness of 1 mm has been chosen. To obtain these samples, the extrusion speed was reduced to 10 mm/s and the extrusion width was increased by 200%. Creep was kept constant at 95% in all cases.

Repetier Host® software was used to process the samples. To facilitate sample clamping and rapid anchoring, four holes were located at the corners of the sample. In this way, the samples were anchored to a pre-drilled sacrificial block made of Sika Industry's Prolab 65 technical resin. Figure 1 shows the sample outline and its slicing.

Once the samples have been manufactured, they will be drilled. As can be seen in figure 1, 5 holes of 8 mm diameter per sample will be made. This diameter has been selected because it is a diameter close to those used by the aerospace industry in some of its programs [14]. A general-purpose drill, recommended for machining HSS-Co polymers of the Latz brand, was selected for drilling the holes. A constant rotational speed of 1000 rpm and a variable feed rate of 150, 300 and 600 mm/min were chosen as cutting parameters. Other reprocess, as reaming was not used, because this modify the original roughness and hide the real behaviour of the drilling process.

Once machined, images of the holes, tool and chip were taken using stereo optical microscopy (Nikon SMZ 800). The images obtained were used to analyze the chip geometry, the tool wear elements and the defects that appeared in the holes. Additionally, the roughness obtained has been analyzed using the Mahr Perthometer PGK 120 contact roughness profilometer, obtaining the arithmetic mean roughness (Ra) of each hole. For this purpose, measurements were taken using a 0.8 mm cut-off and 6 scanning sections in feed drilling direction, perpendicular to the layer deposition.
3. Results
Once the holes have been analyzed, it can be seen that there are defects in practically all the holes drilled, although their severity varies according to the cutting parameters (figure 2).

|   | 150 mm/min | 300 mm/min | 600 mm/min |
|---|------------|------------|------------|
| 0.15 mm | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| 0.20 mm | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| 0.30 mm | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |
| 1 mm | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |

Figure 2. Images of holes drilled.
Figure 3. (a) Defect associated with softening of the material at 300 mm/min and 0.2 mm layer thickness. (b) Delamination of the upper layer of the sample at 600 mm/min and 0.3 mm layer thickness.

It can be seen how the increase of the feed rate causes the appearance of more defects, as well as the intensification of the existing ones. However, there does not seem to be a relationship with the layer thickness selected in each case.

These defects could be separated into two types. The first defects are related to the nature of the material itself. These include certain effects that appear due to the softening of the material, such as the appearance of burrs or the accumulation of adhered chips. This burr is superficial, appear only in the first layer of the hole and no affect to the roughness measure because the thickness of the sample is higher than the evaluation length. Also this burrs does not affect to the diameter measure because the image processing software select only the original diameter, discriminating the burr.

The second ones are related to the manufacturing process of the samples. The layer composition of the specimens causes certain filaments to occasionally separate and/or break. As the parameters increase, these local breaks increase, even delaminating part of the first layer. An example of the two types of materials is shown in figure 3.

Figure 4. Diameter evolution with the layer thickness for the studied feed rates.

However, these defects do not seem to influence the hole geometry, as this trend is not observed when studying the hole diameter (figure 4). On the contrary, increasing speed seems to stabilize the
diameter. So much so, that it is at higher forward speeds that more holes are observed within traditional tolerances established by the aeronautical industry [14].

There is also, however, an appreciable dispersion variation of the data that seems to be greater with increasing layer thickness. This may be due to the fact that the defects mentioned above, associated with thread breakage, when they occur in samples with higher thicknesses, cause a greater deviation of the diameter because there is a greater quantity of them (Figure 5). Moreover, an increase in this thickness can favour cutting since it causes a chip of a more constant thickness. The chips obtained during the cutting of specimens of lower layer thicknesses tend to open up and separate into layers. This fragmentation causes particles of the chip to adhere to the walls of the holes causing some of the defects already mentioned. In the same way, others would be deposited on the tool making it difficult for the chip to flow. The fragments deposited on the tool, in many cases remain mechanically adhered and are not eliminated after cleaning with compressed air (figure 6).

As with other adhesive fillers, the removal of these particles causes progressive damage to certain parts of the tool. Thus, breaks appear along the cutting edge creating a characteristic chipping, as well as the appearance of an adhered bale on the detachment face, which can be seen by the change in coloration in the area closest to the cutting edge (figure 7).

![Figure 5](image1.png)  ![Figure 6](image2.png)

**Figure 5.** (a) Effect of chip fragmentation at 300 mm/min and 0.2 mm layer thickness. (b) Effect of chip formation at 300 mm/min and 1 mm layer thickness.

![Figure 6](image3.png)  ![Figure 6](image4.png)

**Figure 6.** (a) Condition of the tool without cleaning after 45 holes. (b) Condition of the tool after 45 holes cleaned with compressed air.
This behaviour, together with the defects already mentioned, mainly fibre breakage, causes the calibrated diameter to differ from the nominal diameter, forming an ovalization that affects all the holes (figure 8). This defect, although generic, is not constant. So much so that no general trends can be observed, although large dispersions can be observed. Despite this diverse general behavior, the best results seem to be shown at high layer thicknesses. In addition, despite the fact that there is no clear trend with the feed rate, it seems that increasing the feed rate does not benefit this effect.

Moreover, the same stabilization seen in diameter with increasing layer thickness also appears in roughness. For all the lower speeds there seems to be a tendency to stabilization with increasing layer thickness. This does not occur at the higher speed due to the appearance of defects. In addition, most of the holes present high roughnesses, above the reference value established in the aeronautical requirements (figure 9). This may be due to the appearance of delaminations and layer separations. The effect of delaminations means that in samples with fewer layers where delaminations are less likely to occur, the grades are more stable at low speeds. However, when the speed increases, the thrust force

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**Figure 7.** (a) Effect of chipping along the cutting edge of the tool. (b) Particles deposited on the cutting edge of the tool and change of coloration in the area closest to the cutting edge.

**Figure 8.** Evolution of hole ovalization.

**Figure 9.** Hole ovalization variation with layer thickness and feed rate.
increases and these delaminations, when they occur, are very important, further increased by the progression of the separation due to the high thickness of the separation. But this effect can also be caused in parts of lower layer thicknesses, where if it appears in a general way it can worsen the quality significantly. This effect therefore makes it tremendously important to improve the aggregation of the layers, since, as shown in Figure 8, this delamination can appear every two layers, which could be linked to a change in the filling pattern.

![Figure 9. Evolution of roughness with layer thickness for the forward speeds studied.](https://www.ge.com/additive/additive-manufacturing) accessed 2 March 2021

4. Conclusions
This article presents the first data on the machining of PETG parts obtained by FDM. These first data will allow to bring this process closer to the aerospace industry where there are high requirements that cannot be obtained directly by FDM.

The holes produced have different characteristics. Morphologically, they all have defects associated with softening of the material or breakage of the filaments that make up the parts. These defects are complex and difficult to eliminate and appear independently of the cutting parameters.

In addition, diameter deviations have been found, in all cases accompanied by a certain ovalization. This is due to the irregular cutting of the strands which causes a certain roundness defect. In the same way, many holes present a roughness superior to that admitted by the aeronautical sector.

However, some holes present worse roughness as a consequence of the previous problems that generate delaminations. Furthermore, the drilling process improves considerably the roughness of the parts.

With these data, it can be assured that the FDM machining process is not a simple process and that it requires a standardization effort to make it industrially profitable.

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