Study for the selection of 3D printing parameters for the design of TPU products

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Abstract: The design and development of elastic products for additive manufacturing has the particularity that the manufacturing parameters can affect the aesthetic and functional properties due to the flexible nature of the material. Therefore, the selection of each of them should not be analysed separately. For this reason, in this work, different printing parameters were explored sequentially, observing their influence on the final finish obtained with the aim of adjusting the appropriate values to provide valid prototypes and products. Layer height, wall thickness, followability, extrusion temperature, shrinkage and printing speeds were studied. As a result, the parameters that offer the best results, with respect to the quality of finish, in 3D printing of TPU for application to the design of elastic products were determined.

Keywords: Product design, TPU, FFF, 3D printing, Manufacturing properties.

1. Introduction

Design and development of new products represents a high investment for the industry, since it requires a long production process. In order to reduce the time in the development phases, the incorporation of additive manufacturing (AM) technologies is extended to several sectors of the industry [1-3]. The additive technology of Fused Filament Fabrication (FFF) is based on a procedure of a filling material, which is deposited layer by layer, following a determined code with which the digital model is reproduced and being separated in a determined number of layers [2,4]. This makes it an interesting process to obtain elements fairly quickly, whatever the stage of the product design and development process. Its main application is the prototypes generation since it reduces the risk of overcosts and a way to optimize the times during the development phase. However, for this to be feasible, the prototypes must reliably represent the final product and thus the success of the final product design will be greater [5]. In the case of products with elastic properties, manufactured in elastomeric materials becomes more relevant because the elastic end properties usually directly affect the functionality, that is why in this field also the properties are studied and new TPU materials appear [6].

Moreover, today AM not only allows the generation of evaluation prototypes, but also functional end products and improved designs, thanks to the versatility that this technology allows [7]. Not only in rigid materials, but also in elastic materials for various purposes [8]. Therefore, its application can also be focused on obtaining customised elements thanks to the flexibility that FFF allows, and it also has other applications in the field of industrial design such as the redesign of components and product optimisation...
All this means that, in recent years, additive manufacturing has been a research focus for industries such as footwear, automotive and medical, among others [4].

In general, in the design and development of products, when manufactured by FFF, the results obtained depend to a large extent on the parameters used [10]. The effects of these parameters have been studied for materials considered as rigid, such as PLA and ABS [11,12]. Several investigations have extensively analysed the combinations of parameters affecting surface finish and dimensional accuracy in rigid plastics [13,14].

However, in the case of elastic materials, such as TPU, although it is well established in the market, it is only in recent years that its application and therefore its study has begun to spread. This recent acceptance of this type of material is due, in part, to the improvement of extruders to be able to support this type of material [15]. However, apart from the recommendations of the filament manufacturers [16], no evidence has been found on the study of the optimum parameters that affect the surface and dimensional finish of the product. For this reason, a study of 3D printing conditions and parameters was carried out to improve the finishing conditions of the product printed with TPU material [17].

The main defects affecting the final finish of the TPU product, as with PLA material, are: lack of adhesion between layers, lack of precision and surface finish [18,19]. Therefore, efforts were focused on reducing interlayer defects and excess or lack of filler material [20]. In addition, the extrusion temperature was studied to improve the surface finish and the finishes were evaluated by tactile-visual analysis, in accordance with the aesthetic aspects of the product [21,22].

It is important to highlight that the aim of this work is to review the parameters for obtaining early prototypes of product designs whose function will be to submit them to validation with users. For this reason, it is considered convenient that the analysis of the surface finish is carried out at the level of appearance, without entering into micro-geometric evaluations. Therefore, the analysis carried out is based on the Likert scale, taking into account several factors that affect the aesthetic finish of the printed object [22-24].

For all the above described, this research was carried out in this work was to study the appropriate manufacturing parameters for specimens made of flexible material, due to the complexity that this material entails [17].

2. Experimental procedure

The study was started by making a series of test prints, based on the parameters offered by the manufacturer [16]. However, the range of parameters with which the TPU material can be printed is wide, and these can be defined for the given geometrical conditions of the product to be printed [10].

For this reason, a specimen was designed in the form of a 20 mm³ cube that includes flat faces, rounding and cavities, figure 1. This model includes different geometries and surface changes in order to identify the faces, where differences in finish can be evaluated.

\begin{figure}[ht]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Test model designed to obtain the optimum manufacturing parameters for the TPU: (a) The cube dimensions (X, Y, Z) correspond to 20 mm, the rounding (R) is 1.75 mm, the depth (d) and diameter (Ø) of the holes are 2 mm and 4mm respectively, (b) example of the printed specimens.}
\end{figure}
A total of 20 specimens were printed in a Witbox one printer, with cold bed, using polyether-polyurethane elastomer, trade name Filaflex® 82A, in which a combination of parameters was studied according to the process specified in figure 2. It should be added that this printer works with a cold bed. In addition, a 0.2mm diameter micro extrusion nozzle made of wear-resistant copper was used.

Each model was manufactured individually, adjusting the variables of layer height, wall thickness, extrusion temperature, flow, extrusion speed and tensile speed, until a set of parameters was obtained that would limit the manufacturing defects in the model as much as possible. The percentage of filler used has been constant, 20% to reduce the printing time of each model.

It should be added that these variables were studied progressively until those printing defects that could invalidate the products printed with the previous parameters studied were reduced.

This process was carried out by previously studying the layer height and wall thickness simultaneously, keeping the extrusion temperature and speed constant. Heights of 0.06 mm, 0.1mm and 0.15 mm; and wall thicknesses of 0.8mm and 1 mm were studied.

The extrusion temperature was then evaluated along with the flow, using the parameters selected in the previous evaluation, as it was observed that the temperature needed to be raised due to insufficient flowability of the material through the extruder. The temperatures studied correspond to 220, 230, 240 and 245°C. Flow variations corresponded to 130, 120, 110 and 100%.

The best results from each of the study phases were obtained by a visual tactical analysis. This analysis was sufficient due to the fact that most of the parameters had visible defects that made the sample of poor quality. This analysis was carried out using a 5-point Likert scale, with number 1 being a poor finish and number 5 an optimum finish, and taking into account several properties directly related to the prototype's finish from the point of view of perception: printing defects such as burrs, quality of detail, irregular surface finish and poor definition in the holes of the faces, according to [24, 25].

Finally, the study of the speed and retraction of the material was carried out, keeping the rest of the parameters constant, which were those selected in the previous phases. Three print speeds were studied: 40 mm/s, 30 mm/s, 20 mm/s and 15 mm/s. In turn, these were combined with the retraction speeds of 40 mm/s, 30 mm/s and 25 mm/s. Selected the retraction speed, 3 samples were printed for each speed to make a dimensional and visual-tactical analysis was carried out. it was measured rounding, cylinder diameters and depth, and wall thickness. The specimens were cut to carry out the last measurement. Measurements were taken with a digital microscope with 1000x optical zoom with static resolution of 640x480mm and manual adjustment from 0 to 40 mm, and also checked with a precision digital caliper.

3. Results
Once the experimental work has been carried out, the results corresponding to the study of the parameters are presented by means of a visual tactical analysis and a dimensional analysis with respect to the printing speed.

3.1. Sequential study of parameters
At the beginning of the study, print evaluations were made with the factory recommended values for that material and the printer became clogged and the layers did not adhere to each other due to the resulting voids between them. The modification of the layer height and wall thickness parameters was then analysed.

Of the six specimen types tested in the first phase, printing defects were observed in all specimens
except for the specimen that was produced with a layer height of 0.1 mm and a wall thickness of 1 mm, figure 4 (e). On the other hand, with the combination of layer height 0.06 mm and wall thickness of 0.8 mm, surface defects occurred with excess material adhering to the outer wall and deforming the geometry, as well as printing errors between the layers, figure 4 (a). For this reason, it was not possible to obtain a valid specimen with these parameters. This could be due to the fluidity used, but this parameter will be analysed later. Then, the layer height was increased to 1 mm, better printing results were obtained, but there were still interlayer faults, although less pronounced, figure 4 (b).

When a layer height of 0.15 mm was applied, defects continued to occur although the finish was very similar to the previous height, figure 4 (c). As mentioned above, the best result was obtained with a height of 0.1 mm, where no cavities were observed between the layers, but with a wall thickness of 0.8 mm, the finish was rough and with excess material at the surface changes, figure 4 (d). Thus, by increasing the wall thickness to 1 mm, it was observed that the quality of the finish improved, figure 4 (e). Therefore, it is clear from these results that the wall thickness has a greater influence on the final finish than the layer height.

Once the specimens had been analysed and the data collected, a 5-point likert scale was made according to the level of finish according to aesthetic parameters mentioned in methodology, with number 1 being a poor finish and number 5 an optimum finish. It was observed that the finish quality improves by using layer height around 0.1 mm, figure 4. As for the wall thickness, if it is reduced to less than 1 mm, the finish quality decreases. It is assumed that the higher the wall thickness, the better the results will be due to the stability of the wall with respect to the height. However, it must be taken into account that the elastic properties are reduced the thicker the wall thickness is.

The results obtained in the second phase of the study show that, in general terms, the quality of the finish increases the lower the percentage of fluidity and the higher the temperature. This is because, due to the elasticity of the material, defects occur as a result of insufficient flowability of the material. However, this flowability is not associated to the percentage of flow but to the extrusion temperature. Therefore, it was observed that the optimum printing conditions of the elastic material is the increase of temperature reducing the percentage of flow, figure 5. However, if the temperature is increased by 5 degrees, although the results are similar, the quality is reduced, with small surface defects appearing that do not occur with the other parameters studied.

Finally, as a result of the study of printing speeds and shrinkage, it was observed that adjusting both values improved the results. Likewise, the filament tension was reduced, thus favouring the printing quality. In general terms, reducing the retraction speed improves the finishing quality proportionally. With 25 mm/s being the retraction speed at which good quality was achieved in the study. Using this shrinkage speed, it was observed that the printing speed modified the final result on the printed product. From the speeds studied, it was observed that the lower the speed, the higher the quality of the finish, figure 6. However, it was observed that the validity for 15 mm/s and 20 mm/s is practically the same. Therefore, it is considered that the best speed is 20 mm/s, as it reduces printing time while obtaining the
same results. It is also the minimum recommended by the manufacturer. Although a speed of 30 mm/s is also possible to obtain a good finish.

Then, once the study was carried out, the manufacturing parameters considered optimal were obtained, table 1, for obtaining good print finishes for TPU material. In such a way that they can be applied to the design of elastic products.

![Figure 4](image1.png)

**Figure 4.** Contour graphic showing visually the relation of wall thickness quality to layer height.

![Figure 5](image2.png)

**Figure 5.** Contour graphic showing finish according to temperature in °C and percentage of flow.

![Figure 6](image3.png)

**Figure 6.** Finishing quality according to the ratio of printing and retraction speed.
Table 1. Optimal manufacturing process parameters defined for Filaflex® 82A TPU filament.

| Parameter            | Recommended value | Optimized value |
|----------------------|-------------------|-----------------|
| Layer height [mm]    | 0.08 – 0.3        | 0.1             |
| Wall thickness [mm]  | -                 | 1               |
| Printing speed [mm/s]| 15-100            | 20              |
| Flow [%]             | -                 | 100             |
| Extrusion temperature [ºC]| 210 - 250      | 240             |
| Retraction speed [mm/s]| 25 - 160        | 25              |

3.2. Dimensional assessment according to speed

In the tactical-visual evaluation carried out on the specimens, with different printing speeds, it was observed that the quality of the finish improves as the printing speed is reduced. However, at a speed of 20 mm/s, it has the same finish as 15 mm/s, so with a speed of 20 mm/s it is possible to reduce printing time and energy. Discarding 15 mm/s, the dimensional evaluation was carried out with the rest of the speeds, using a digital microscope, as specified in the methodology.

Analysing the results, which are detailed in figure 7, it was observed that the overall dimensions of the specimen and the wall thickness vary with respect to the speed. The length is reduced with respect to the speed. Thus, it was observed that the lower the speed the length decreases approximately 0.2 mm with respect to the higher speed in the 3 axes of measurement, been slightly minor in Z axis. This may be due to the fact that as the material is exposed for a longer time without the adhesion of the layer, it shrinks causing a slight dimensional reduction. However, the edge rounding present reliable average dimensions with respect to the CAD geometry, R1.75 mm, without reflecting variations in the results with respect to speed. Therefore, small variations due to manufacturing tolerances are negligible for small edge rounding.

On the other hand, in the dimensions corresponding to the changes in geometry on the surface, specifically the depth and diameter of the holes, it was observed that the mean values obtained vary by a maximum of 0.1 mm and 0.6 mm respectively, table 2. The variations recorded in the different speeds cannot be directly related to this manufacturing parameter, as the different measurements recorded are similar and it is considered that they may be the result of the manufacturing tolerances of the machine itself.

With regard to the wall thickness, it does not present notable variations with respect to the printing speed, with a slight reduction in the speed of 20 mm/s, which may have a direct relationship with the results of the total measurements of the test piece, figure 7.

![Figure 7](image-url)
In general, it can be seen that within the small variations, the most accurate measurements correspond to the 40 mm/s speed even though the visual tactile finish is lower.

Table 2. Dimensional assessment results according to the print speed: rounding of corners, R, in mm, diameter of holes, ∅, in mm, depth of the holes in mm and wall thickness of specimens in mm.

| ∅ (mm) | Depth (mm) | Wall thickness (mm) |
|--------|------------|---------------------|
| CAD | 4 | 2 | 1 |
| 20 mm/s | M=3.98, σ=0.04 | M=2.0, σ=0.11 | M=0.88, σ=0.02 |
| 30 mm/s | M=3.96, σ=0.03 | M=2.1, σ=0.13 | M=0.89, σ=0.01 |

4. Conclusions

By evaluating the parameters in sequence, it was possible to obtain a combination of parameters that offers better finishing quality on elastic products. With the speeds of 20 and 30, good finishes were obtained, but as the quality increases with lower speeds, the speed of 20 mm/s, the minimum recommended by the material supplier, is recommended. On the other hand, the extrusion temperature that provides the best finishes corresponds to 240°C, 5°C higher than the maximum recommended value. Likewise, the result obtained for the percentage of fluidity is 100% flow. Finally, the visual tactical analysis shows that the best results correspond to the combination of 0.1 mm layer height and 1 mm wall thickness. On the other hand, the dimensions according to the velocities present small variations that can be considered negligible for the correct functioning of an elastic product made of TPU.

Regarding the application potential of TPU for additive manufacturing, it is considered to be of great value due to its elastic properties and its ease of adaptation, especially for highly ergonomic products. However, the limitations still existing in FFF technology with flexible materials keep open a research field to work on topological properties in order to increase the performance of additive manufacturing with TPU and the final quality of these products. This could potentially increase the applicability in all kinds of sectors and products.

In short, the data obtained is considered to be of great value for further application to elastic or flexible products. In this way, the geometry of the product can be customised with respect to its specific function and the quality of the finish of elastic products manufactured by additive manufacturing can be improved.

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