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Effect of Acetone Vapor Smoothing Process on Surface Finish and Geometric Accuracy of Fused Deposition Modeling ABS Parts

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Abstract

FDM is a widely used additive manufacturing process, however, it has some limitations, such as surface finish, due to the staircase effect caused by the layer-by-layer deposition. Studies have been conducted on surface finish of ABS parts with the use of acetone, but the process parameters and the resulting effects have not been fully investigated in the literature. Therefore, the aim of this study was to investigate the effects of acetone vapor smoothing process on surface finish and geometric accuracy of fused deposition modeling ABS parts. Specimens with different geometries were created and printed using two directions in different scales. The parts were exposed to acetone vapor for 20, 30 and 40 minutes. 3D deviation maps, roughness and microscopic analyses were conducted. The staircase effect was reduced at the expense of some geometric deviations, which varied according to the exposure time and part orientation. The smoothing process applied to the flat surfaces proved to be quite effective in reducing roughness by 90%, however, this reduction led to an undesirable rounding of the sharp edges. The results obtained in this study are consistent with those found in the literature and may help improve the quality of the ABS printed parts.

Keywords

Additive Manufacturing, 3D Printing, FDM, Staircase Effect, Acetone Vapor Polishing

1. Introduction

Additive manufacturing technology has become increasingly common in different areas since it enables material waste reduction and design freedom. Fused

Deposition Modeling (FDM) is the most popular 3D printing process, which typically uses polymeric filament as raw material. However, the FDM process has some limitations, such as surface finish, due to the staircase effect caused by the layer-by-layer deposition [1] [2].

In the FDM process, acrylonitrile butadiene styrene (ABS) is the most commonly used material. Some studies have particularly focused on the surface finish of ABS parts using solvents. Among the polar solvents, dimethylketone (acetone) is frequently used in the surface smoothing process because it is a safe and inexpensive organic compound. Acetone vapor at room temperature (18˚C to 22˚C), which is an easy-to-use method for surface smoothing of FDM parts, is highly recommended.

In the research conducted by Garg *et al.* [3], the parts were printed with different orientations and later exposed to acetone vapor (paper towel soaked with 30 ml of acetone and placed at side walls of a 1.3 L air tight container) for 40 minutes. There was a significant reduction of the surface roughness with minimal variation in the dimensional accuracy of the parts. Lalehpour *et al.* [4] tested different combinations and determined that the best ABS smoothing setup was 3 cycles with 15 seconds. The maximum roughness reduction was obtained in printed parts with thinner layers (0.010 inches) at a 40˚ angle. Singh *et al.* [5] also tested some combinations while analyzing the best surface finish for a hip implant and established that the ideal printing parameters were at a 90˚ degree angle and the exposure of the parts to acetone vapor in 3 cycles with 6 seconds. Neff *et al.* [6] reported that a 45-minute treatment with acetone vapor (napkins soaked with 5 ml of acetone and placed around the perimeter of a 1 L container) has significantly reduced surface roughness and porosity in all tested parts. However, it had also impacted the mechanical performance and the dimensional accuracy that varied according to thickness. Maciąg *et al.* [7] examined the surface of samples after 30, 60, 90 and 120 minutes of smoothing. Most favorable parameters for the sample surface were those obtained when in contact with acetone vapor for 60 minutes. In turn, Romero *et al.* [8] used acetone vapor (100 ml in a container with an elevated grid) for 15 min, 30 min and 45 min to smooth the surface of the ABS parts, and the best result was obtained with 45-minute exposure. Popescu *et al.* [9] observed that the porosity of medical ABS instruments produced by FDM was reduced after 45-minute exposure to acetone vapor.

Butanone (acetone) acts as a solvent in the butadiene (from ABS) since it has the same organic structure. This causes the polymer chains to slide past each other, filling the air voids between neighboring layers and reducing the staircase effect. As a result, there is an increase in dimensional deviation as well as some shrinkage can be observed in the treated parts [3].

In this regard, it is important to control the ABS smoothing parameters with acetone vapor, not only to reduce the staircase effect caused by the FDM process, but also to minimize the geometric deviation of the parts. Therefore, the aim of this study was to investigate the effect of acetone vapor smoothing process on surface finishing and geometric accuracy of fused deposition modeling ABS parts. This approach can be applied to enhance the surface quality as well as to achieve a desirable dimensional accuracy for the FDM parts.

2. Materials and Methods

In the present study, the specimens had different geometries, as follows: flat, inclined (pyramid) and curve (sphere) both concave and convex. The parts were produced in triplicate using FDM technology (uPrint SE, Stratasys, USA). ABS (ABS Plus 430XL Ivory, Stratasys, USA) samples were printed with 0.254 mm layer height. The specimens were printed in both horizontal and vertical directions (**Figure 1(a)**)—with different scales. The peaks and valleys were 2, 3 and 4 mm (**Figure 1(b)**).

The specimens were individually packed in an airtight polypropylene container with 300 ml capacity and at controlled temperature (22˚C). Absorbent papers soaked in 5 ml of acetone 99.5% (Próton Química, Brazil) were placed in the container. Different exposure times to acetone vapor were tested: 20, 30 and 40 minutes. The specimens remained in a controlled environment for 24 hours for drying.

A stereo microscope (SZX16, Olympus, Japan) was used for a visual analysis. Later, a Scanning Electron Microscope—SEM (TM3000, Hitachi, Japan) was used to provide more detailed surface information.

A roughness tester (Surftest SJ 401, Mitutoyo, Japan) was used, according to the ISO 4287 standard, to verify the average roughness (Ra) of the parts. The flat part in the center of each sample was measured 5 times perpendicular to the print direction, before and after smoothing with acetone vapor.

For the 3D geometric deviation analysis, the parts were digitized (before and after exposure to acetone vapor) with a 3D laser scanner (Digimill 3D, Tecnodrill, Brazil), 75 mm lens (0.01 mm z-precision) and 0.05 mm xy resolution. The data obtained were evaluated using the Geomagic Qualify software.

3. Results and Discussion

The visual analysis with the stereo microscope (**Figure 2**) showed smoothing of the staircase effect and an increased brightness of the part, particularly after 30

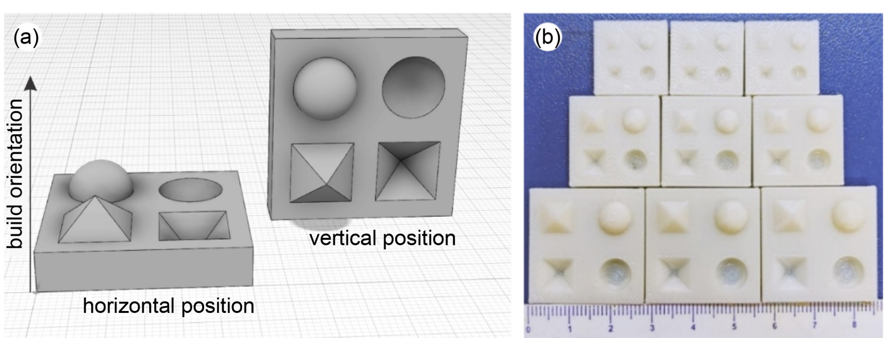

Figure 1. Production of specimens.

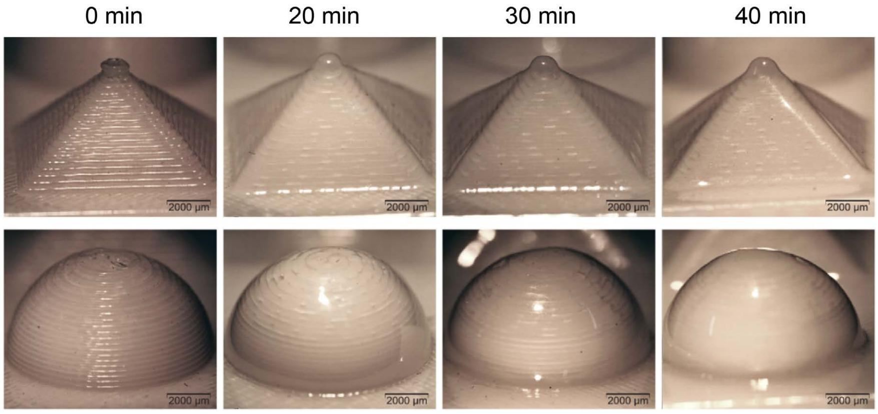

Figure 2. Visual analysis of the parts before and after exposure to acetone vapor.

and 40 minutes of exposure to acetone vapor. Some deformations at the apex and edges of the pyramid could be observed. In addition, the edges became rounded at the intersection between the geometries and the base plane, which were more critical in the 40-minute specimen. This behavior was observed in all specimens.

The average roughness of the flat surfaces of the parts prior to exposure to acetone vapor was 4.87 µm. After exposure, the Ra value was 0.47 µm with no significant difference among 20, 30, 40 min. These substantial reductions in the roughness value and the reaching of a plateau are in line with those reported in previous studies [3] [4] [6] [7] [8].

3.1. Parts Printed with Horizontal Orientation

The SEM images of the printed parts with peaks and valleys of 2 mm (**Figure 3**) showed smooth surfaces and rounded edges after 20-minute exposure. In the convex parts, the pyramid showed a conical shape after 40-minute exposure and its edges were well-rounded. In the semispheres, the height was slightly reduced after 40-minute exposure. In contrast, smoothing was lighter in the concave parts, and a little staircase effect was observed after 40-minute exposure.

The corners of the printed parts with peaks and valleys of 3 mm (**Figure 4**), showed smooth surfaces and rounded edges after the short exposure to acetone vapor. On the side surfaces of the parts, the greater difference in smoothing occurred after 30-minute exposure. The concave geometries were smoother near the edges and less smooth in the deeper layers, indicating that the vapor was not able to reach all the grooves.

The same behavior was observed in the parts with peaks and valleys of 4 mm (**Figure 5**). Again, the SEM images show smooth surfaces and rounded edges. By increasing the size of the part, the same rounding effect becomes less evident as the side planes of the triangular geometries are proportionally larger. Similar to the concave 3 mm geometries, the vapor was not able to reach all the grooves. However, when the part size was increased, both depth and width of the concave geometries increased and smoothing was more evident, and apparently, the

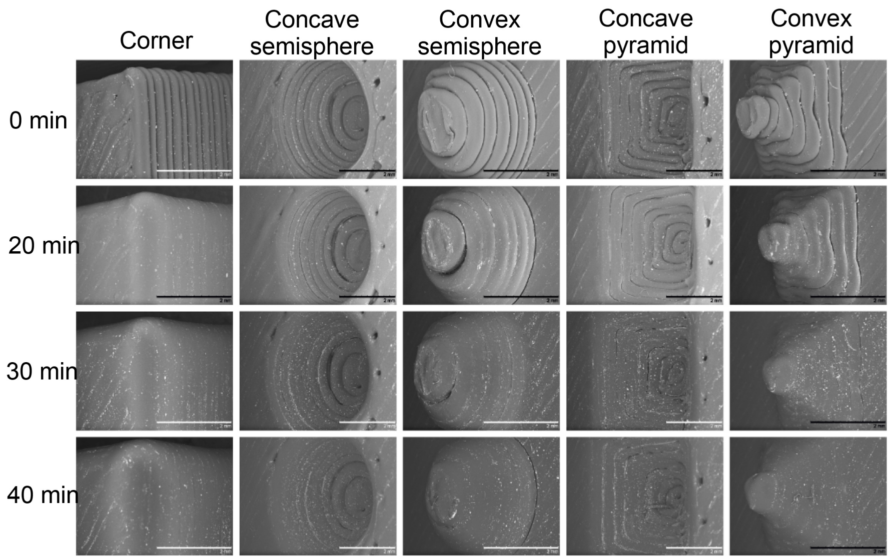

Figure 3. SEM images of the parts printed horizontally with peaks and valleys of 2 mm before and after exposure to acetone vapor.

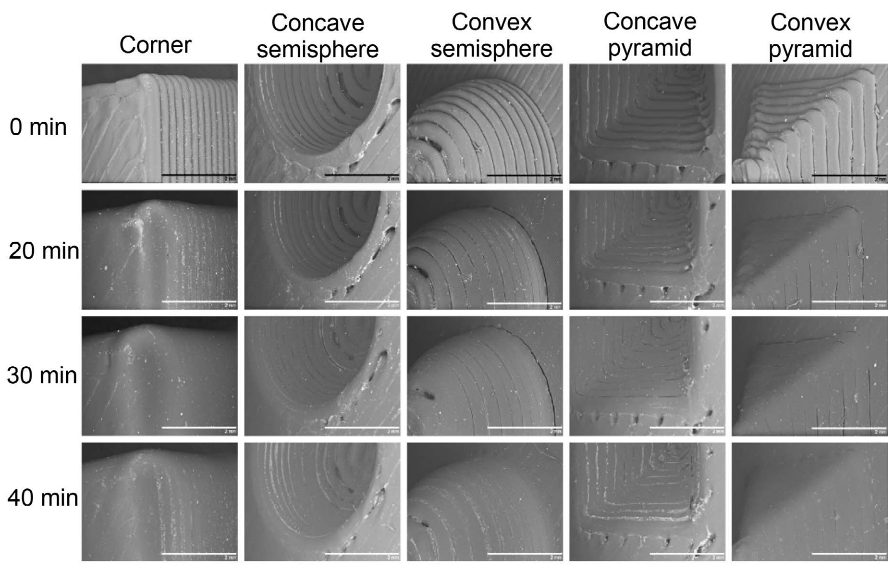

Figure 4. SEM images of the parts printed horizontally with peaks and valleys of 3 mm before and after exposure to acetone vapor.

width was the most influential factor.

3.2. Parts Printed with Vertical Orientation

The SEM images of the parts printed vertically exhibited a distinct surface finish, with a reduced staircase effect before exposure to acetone vapor. Notably, the pyramids presented smoother peaks and more defined edges. As these shapes were more representative for the results, the analyses focused only on the triangular geometries.

The SEM images of the printed parts with peaks and valleys of 2 mm (**Figure 6**) revealed better smoothing results when exposed to acetone vapor at 30 and 40

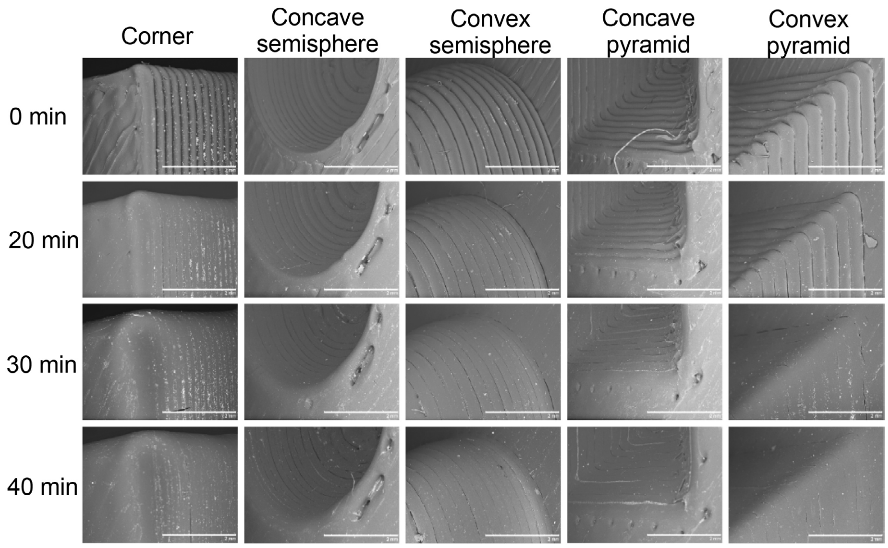

Figure 5. SEM images of the parts printed horizontally with peaks and valleys of 4 mm before and after exposure to acetone vapor.

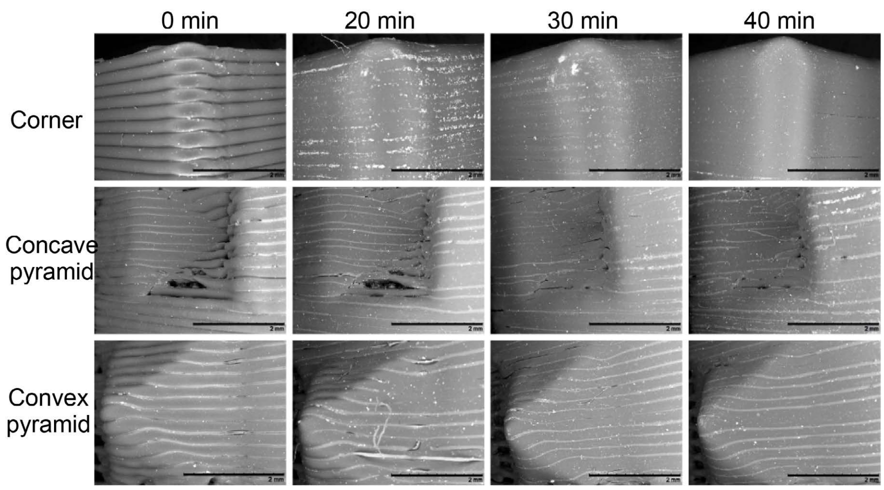

Figure 6. SEM images of the parts vertically printed with peaks and valleys of 2 mm before and after exposure to acetone vapor.

min. Although their edges were rounded, the pyramids revealed minimal geometric deformations when compared to those printed horizontally. Even so, the smoothing results were better for the concave pyramid.

In the parts with peaks and valleys of 3 mm (**Figure 7**), the rounded edges can still be observed, however, with less evident effects due to a greater number of printed layers.

The same results were also observed in the printed parts with peaks and valleys of 4 mm (**Figure 8**). It should be noted that the concave geometry has provided better results with 40-minute exposure to acetone vapor.

3.3. Geometric Deviation Analysis

To rule out the intrinsic errors of the 3D printing process, the CAD model (STL

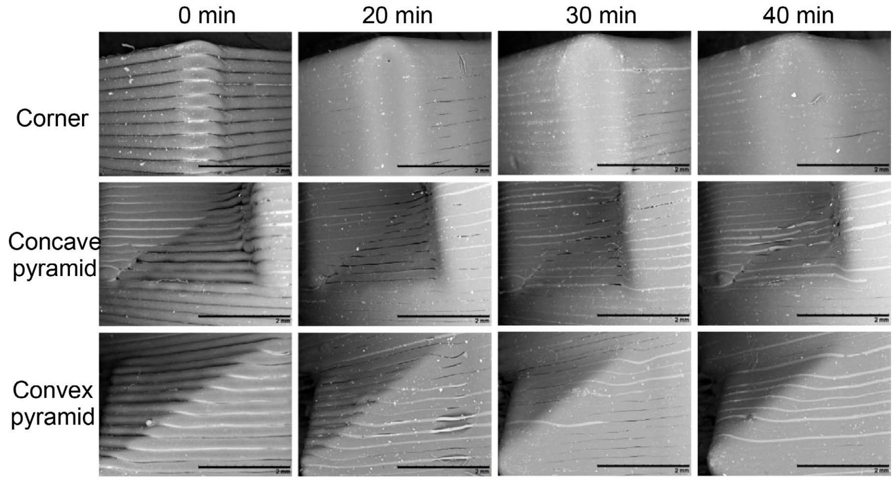

Figure 7. SEM images of the parts printed vertically with original peaks and valleys of 3 mm and after exposure to acetone vapor.

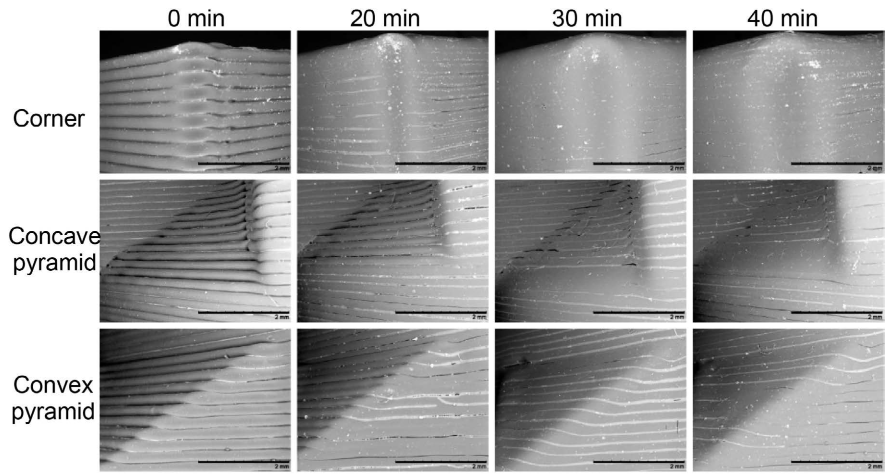

Figure 8. SEM images of the parts printed vertically with original 4 mm peaks and valleys and after exposure to acetone vapor.

file) was not used as a reference, but rather the untreated part, which was directly produced by FDM. Therefore, the data obtained with 3D scanning before and after the smoothing process with acetone vapor were used to create the 3D deviation maps (**Figure 9**).

The green areas were those where the deviations occurred below 0.05 mm (used scanning resolution). Some geometric deviations can be observed in places where colors change to blue, yellow, and red. Although the technique allowed a statistical calculation of the points, the smoothed areas were smaller compared to the rest of the green model, causing the values of dimensional deviations to be diluted, with no significantly different means. For this reason, the qualitative analysis of the images was performed. In general, it was possible to observe that the geometric deviations were compatible with the SEM visual analysis.

Clearly, some rounded edges of the pyramids (convex) could be observed, implying a 0.1 mm reduction in geometry (in yellow). Also, some material seemed

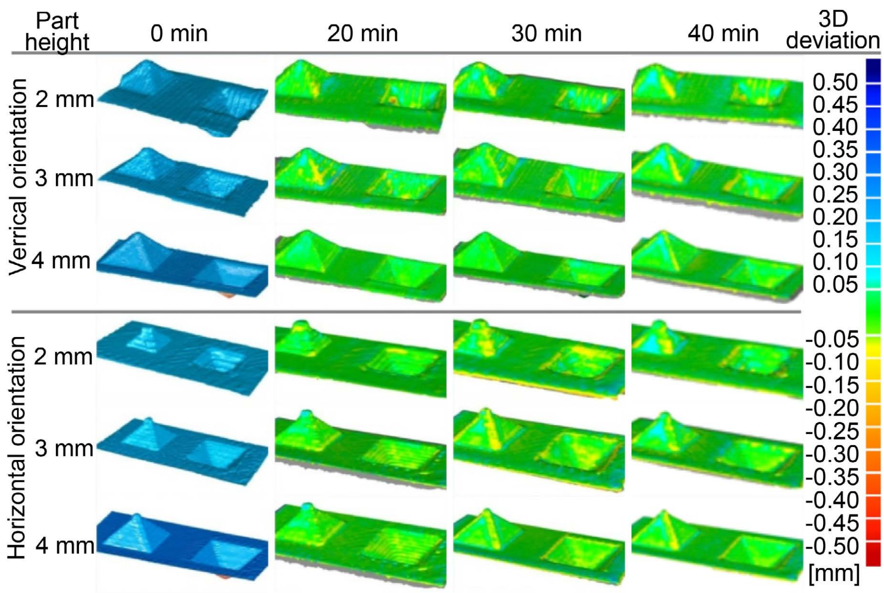

Figure 9. 3D deviation maps between printed parts before and after exposure to acetone vapor.

to flow to the base of the pyramids, and in some cases, forming a fillet of 0.1 to 0.2 mm (in blue). These effects were most noticeable in smaller samples and with longer exposure time to acetone vapor. A slight swelling of some flat areas and faces of some pyramids (in blue) were also visible. A good example of these effects was the 2 mm/40min sample printed horizontally, which has become virtually conical. As for concave shapes, it was possible to observe the rounded edges with reduced geometry (in yellow) and also some deformations on the inner sides.

In general, it was possible to notice that the samples printed vertically have showed better finishing results and smaller geometric deviations, which are consistent with the findings of Garg *et al.* [3]. Based on the results presented in this study, a 30-minute exposure should be used, considering that the longer the exposure to acetone vapor, the greater the geometric deviation observed in the parts.

Apparently, the geometric deviation was more significant in smaller samples. Thus, more critical results were obtained for 2 mm samples, intermediate for 3 mm samples and optimal for 4 mm samples.

4. Conclusions

In the present study, the acetone vapor smoothing process was applied to printed ABS parts to investigate and compare surface finishes and geometric deviations. This smoothing process proved to be efficient since it provided visually smooth and shiny surfaces. The reduction of staircase effect was achieved, however, at the expense of variable geometric deviations, according to the tested parameters.

The smoothing process of the flat surfaces was efficient in reducing roughness by 90%, however, this reduction led to an undesirable rounding of the edges (0.2 mm deviations). The best results were obtained with 4 mm parts printed vertically and exposed to acetone vapor for a time of 30 minutes.

It should be highlighted that previous, and current studies on acetone vapor smoothing process have used many different materials and methods. A significant difference is the ABS itself, which is not always specified and is available in various grades. To our best knowledge, very few authors have determined the amount, purity and concentration of acetone, the method to be used to generate vapor, or the container volume where the sample should be placed. These key factors have shown how challenging it is to reproduce and compare the results. Nevertheless, the results obtained in the present study are consistent with those found in the literature and may help improve the quality of the ABS printed parts.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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