Replicability Assessment of a 3D-Printed Mold with Advanced Polymers and Chemical Smoothing

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Abstract

Fused Deposition Modeling (FDM) 3D printing is the most widespread technology in additive manufacturing worldwide acknowledging its low cost, finished component applications, and the production process of other parts. The aim of this study is to perform a process for checking the reproducibility capabilities of an FDM-created part by means of state of the art, 3D scanning technology and dedicated software for analysis. One of the main challenges that FDM processes have found to become a trustful manufacturing process in the industry, is the high variability of the outcome, given the printing parameters choice due to the wide variety of material choices, and different suppliers. Additionally, there is the variability of the FDM manufacturing elements, that translates into a different interlayer bond quality, same of which could punish the capability of the printed element to sustain mechanical tests with accuracy. This procedure is a step further into reaching a proper method for FDM manufacturing that takes into account these challenges and help to turn FDM manufacturing into a mainstream, trustworthy manufacturing process for engineering prototyping.

Keywords
3D printing, Replicability, manufacturing, chemical smoothing

1. Introduction
The need to fabricate a light-weight carbon fiber cover to protect exposed components on motorbikes during a race has arisen. Elements of this kind prevent internal parts of the vehicle to break or malfunction due to ambient elements like debris and rocks, as well as contacting other riders. The fuel cap is found dangerously unprotected in the Husqvarna TC 85 motorbike, so the racing team involved in the project found necessary to protect it. Therefore, a mold to laminate this protector is needed to be produced. This mold has to reach target surface quality and dimensional tolerances. The need to obtain cost-effective part, capable to be reproduced in small lots. It is possible to produce molds with FDM technology (Garg et al., 2017), (Singh et al., 2017). Nevertheless, a few challenges to achieve this would be the probable obtained high surface roughness of the 3D part ought to be transferred completely to the final component. Other issues like printing parameters, tooling and material characteristics make very challenging to guarantee that FDM 3D printing processes are capable to portray successive parts with the same quality, so small lots of parts could be produced with confidence.The aim of this study is to propose a method to check the reproducibility capabilities of FDM-created parts by means of state of the art, 3D scanning technology and dedicated software for scanning data analysis.

2. Objectives
To perform a reproducibility capability assessment of an FDM-created part by 3D scanning technology and dedicated software.

3. Literature Review
Fused Deposition Modelling, or FDM has been the pioneer, and most widespread form of 3D printing since the 1990s, patented as a moldless, fabrication method for solid objects (US Patent No.5,738,817). In the present times it is among

the most popular additive manufacturing techniques, mainly because of its versatility and wide choice of thermoplastic-sourced materials (Guessasma et al., 2021). This method of manufacturing rules out a continuous placing of successive material layers, by heating and extruding a filament (Shahrubudin et al., 2019), thus enabling the possibility of building a three-dimensional solid objects with complex shapes, outlined in results of SAVU et al., (2019), Mahamood et al. (2019), and Brian et al., (2014). Other results suggested that FDM can build fully functional parts of product (Tofail et al., 2018). Likewise with outlines from Ait-Mansour et al. (2020). Furthermore, a potential cost-effective solution for small-scale components can be found in the metal-fused filament fabrication (FFF) process, since regular desktop FFF printers could be used to create metal-sourced objects.

3.1 3D printing challenges

However, 3D printing processes had dealt with challenges since their creation, the main drawback of FDM printing would be associated with the overall surface quality that for FDM is lower than that obtained with other technologies such as SLM, Stereolithography (SLA) (Kim et al., 2018), and multi jet fusion from HP (Frizziero, Donnici, et al., 2018a). Further literature findings suggested that surface instabilities, in the form of spikes and peaks created in the component during modelling could derive in poor printed surfaces (Bacciaglia et al., 2021). Additional to the main problem of correctly predicting residual stresses (Casavola et al., 2017) and deformations of printed components once extruded has so far limited the use of FDM printing for structural components, thus requiring numerous trials before obtaining the finished component with the desired quality level.

3.2 Replicability assessment

Research findings delivered the need deploy quality functions to rework innovative problems (Donnici et al., 2018), (Frizziero, Donnici, et al., 2018b). However, the great amount of research found about FDM printing have concentrated in individual exercises to understand the FDM processing, from tooling, parameter setup or filament characterization. Few researchers have assessed the need to achieve part replicability. Proposals have been done like the optimization of printers for accurate replication (Chung et al., 2018) or by quantifying the effect of the process parameters for geometric precision resulting in replicability (Schneidler et al., 2021) so parts could be produced rapidly and at low cost. These studies ruled out specific printing parameters that showed the best results, ought to be true to a single combination of part geometry, 3D printer, type of material, and printing conditions; but lacked to establish a procedure valid for general FDM processing at all circumstances. Therefore, a need to establish tools and procedures for comparison to determine the replication of the process has to be performed. Research findings on this matter are limited though, with valid examples found from applying digital light processing technologies to verify linear measurements performed in dental models made with FDM, produced via intraoral scanning (Maia et al., 2021), other results submitted by Mileti et al. (2021) were focused on the evaluation of the interlay variation of static performance of conductive Polylactic Acid (PLA); in which strain sensors were fitted in printed elements, and gave a generalist approach to deal with this problematic.

Nevertheless, replicability assessment could be obtained by establishing an efficient manufacturing process that would depend on multiple factors, which have to be measured in various iterations in order to arrive to the optimal solution, A novel remote sensing technique by (Jin et al., 2020) for characterizing 3D printed structures was developed by non-destructive ultrasonic imaging of a commonly make it a promising diagnostic tool for an in situ inspection method of optimizing FDM printing and quality control of 3D printed objects. Likewise, the study of (Siva Rama Krishna et al., 2020) demonstrated the need to accurate make elements with FDM with the same, repeated characteristics. A first research on replicability of dental implants with acceptable accuracy (Muta et al., 2020). Thereafter, this study aims to introduce a complete digital methodology to assess the capacity of the used printing technique, parameters, materials and equipment to create technically equal elements, ought to increase the robustness on the manufacturing of FDM 3D-printing process.

4. Methods

4.1. Mold printed with FDM process

This study was mainly focused on validating both the efficiency of the printing and post-printing processes. This by building a custom mold made through FDM and smoothing processes for polymer-matrix composites. Current moldless technologies do not allow the production of carbon fiber components starting from a fabric, being constrained to a single, continuous fiber, allowing designers just to make reinforcements (Heidari-Rarani et al., 2019). Nowadays mold design have been optimized to assess issues that can affect the development of a product (Frizziero, Francia, et al., 2018).

The starting point was the CAD drawing of the fuel tap guard. The software used is PTC Creo, and the overall dimensions were acquired directly on the fuel tank by means of a caliper. Once the protection geometry was created, a Boolean approach was chosen for the construction of the mold. The CAD file of the protection was modified with the addition of material and draft angles to obtain the correct geometry for the slot on the mold. Finally, the addition of fittings made it possible to avoid ripples in the fabric that could rise to defects in the final component. The overall process is summarized in Figure 1.

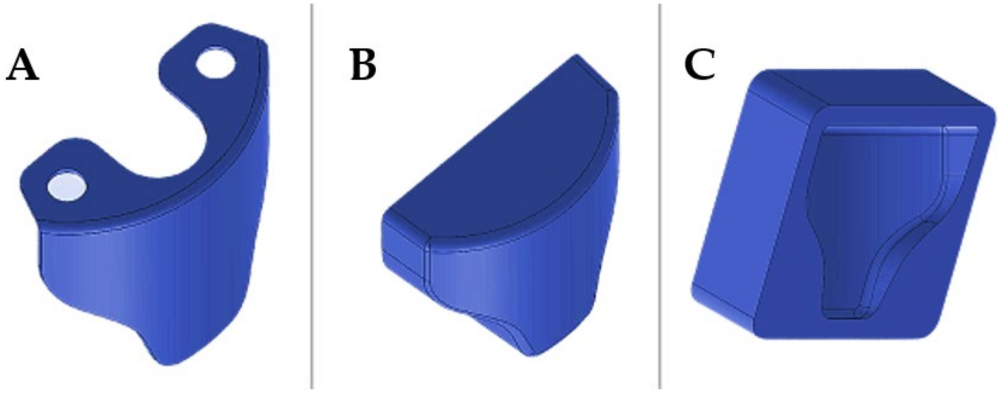

Figure 1. Steps followed during the design of the mold cad model, starting from: A) the actual part, B) making the solid block, C) Cavity extruded, surface-optimized Mold

Material wise, Polyvinyl butyral (PVB) FDM filament (Polymaker Inc., China) was chosen for this application. This polymer is usually used in the creation of multilayer safety glass (Iwasaki et al., 2007) in the automotive sector due to its high transparency but is not popular in FDM printing. Moreover, there are only two PVB filament suppliers available, and the cost of this product is higher respect to cheaper filaments like PLA, but anyways lower than Nylon and other engineering materials. Its printability is excellent compared to PLA and its mechanical properties are similar (Liu et al., 2012). Additionally, by having a low glass temperature (Tg) property, this denotes limited deformations during printing, like in PLA. Lastly, it is soluble in a specific solvent, like most thermoplastic materials, with compounds like IPA alcohol.

4.2. Printing Strategy and Settings

The printing strategy adopted for this component could also be generalized to other parts with similar characteristics. Table 1 shows the printing parameters used to create the component. The first key point is the orientation of the part with respect to the build platform. Although it is a relatively simple component, there are four possible part orientations to the print bed, as shown in Figure 2. The software used for slicing was Cura v4.9.1.

Table 1. Applied Slicing Printing Parameters in Cura.

Parameter	Value	Unit
Infill Density	15	%
Layer Height	0.22	mm
Line width	0.4	mm
Print Speed	80	mm/s
Printing Temperature	205	°C
Adaptative Layers Max. Space	0.02	mm
Bottom Layers	3	-
Build Plate Temperature	65	°C
Fan Speed	70	%

Flow	100	%
Infill Patten	Gyroid	-
Regular Fan Speed at Height	0.2	mm
Retraction Distance	4	mm
Support Overhang Angle	60	°
Support Structure	Tree	-
Top Layers	3	-
Travel Speed	250	mm/s
Wall Line Count	3	-
Z seam position	Back Left	-

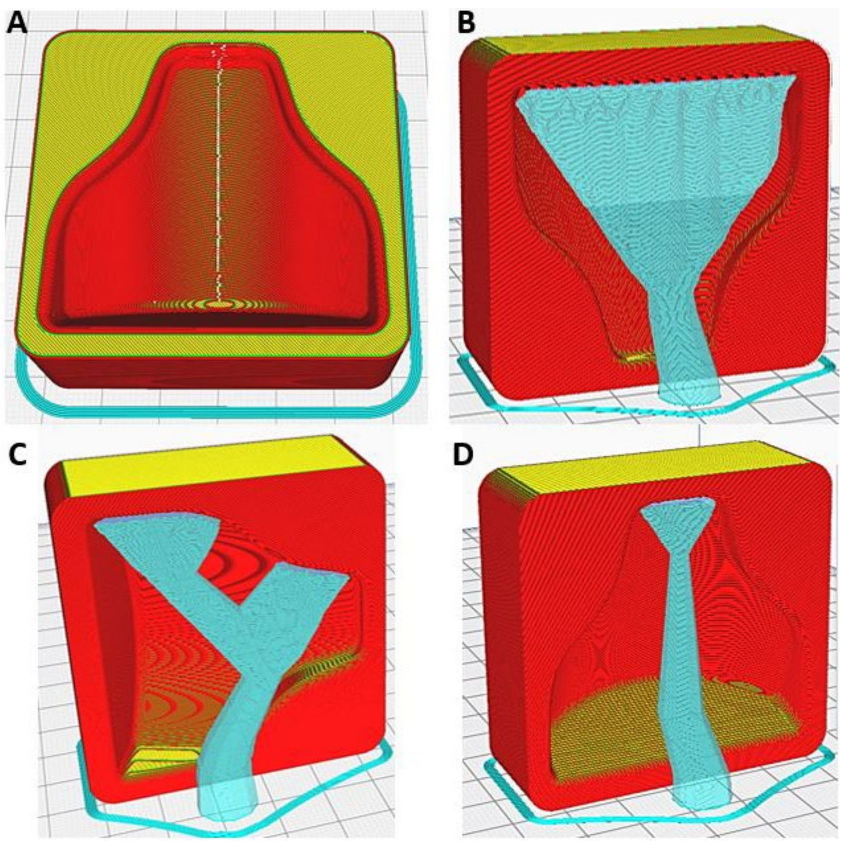

Figure 2. Part orientation with supports in the buildplate.

4.3. Chemical Surface Smoothing

Nevertheless, the well-known printed surface roughness found in FDM-sourced parts could be solved with other processes like the addition of a filler, followed by manual sandblasting to improve the surface finish. This technique could be applied to components with a relatively simple geometry with low tolerance values, but either way it would still require an important manual intervention. Thermoplastic polymers would dissolve with some solvent compounds. Solvent bonding differs from adhesive bonding since the solvent does not become permanently adhered to the adhered substrate and this softening usually occurs well below the glass well below the glass Transition Temperature (Tg) and therefore overall component integrity was maintained. This process can also be used to smooth the surface of thermoplastic components (Singh et al., 2017). This is superfluous for parts made with injection molding as little surface roughness could be achieved, but instead it could become a process to improve the surface characteristics of a component made by FDM (Singh et al., 2017). This process is called chemical smoothing and it allows a localized reaction on the surface of the component only, keeping the main structure unchanged. Once reaching the desired smoothing quality, the component must be cooled in open air or under forced ventilation to promote the evaporation of the solvent from the surface. In this research, the chosen machine for the vapor smoothing is the Polymaker Polishear (Polymaker Inc., China), designed specifically for Polyvinyl butyral (PVB) polymer smoothing with Isopropyl Alcohol (IPA). For safety reasons it is therefore necessary to have a suitable device for filtering the fumes. Overall, PVB found to be a tradeoff of other FDM filaments like PLA and ABS, obtaining the good printability of the former and the solubility of the latter in readily available solvents. In Figure 3 it is possible to see the effect of smoothing in an image taken using an optical microscope at 20× magnification.

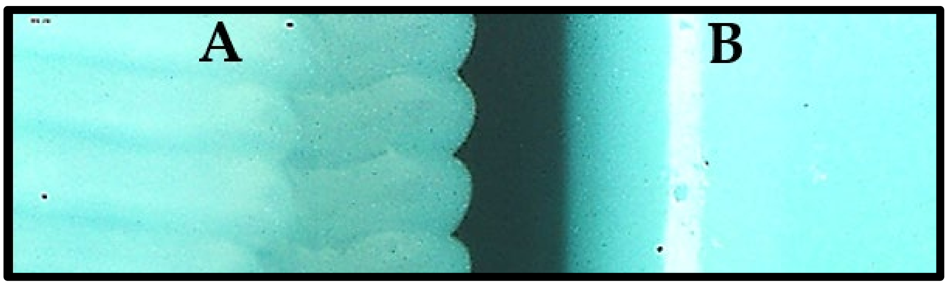

Figure 3. Effect of vapor smoothing, (A) the surface as printed, (B) same surface after chemical smoothing.

4.4. Replicability assessment

In order to verify the reproducibility of the process, two molds were printed with the same printing parameters (thus the same gcode) and both subjected to the smoothing process. Both were left to dry for 24 hours at an ambient temperature of 22 degrees before a 3D scan was performed on both elements and compared its values.

5. Data Collection

5.1. Dimensional Verification of a 3D-Printed Mold with an Optical 3D Scanner

The replicability assessment needs robust technology support, this study considered a Faro 3D scanner to check the fidelity of the printed model compared to the designed CAD file. In order to evaluate the reproducibility of this process, two molds with the same gcode were printed. Therefore, Geomagic software was used to compare with the theoretical, CAD file could be appreciated in Figure 4 and the initial cloud points matching with readings taken to the printed specimens was good altogether, as an absolute range of 0.05 mm was obtained in most of the mold.

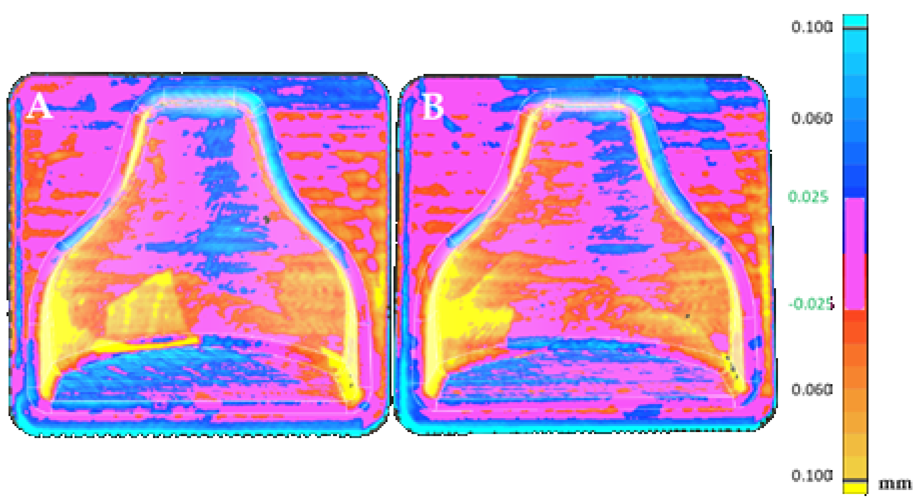

Figure 4. Comparison between the CAD model and first mold (A) and CAD model and second mold (B).

Furthermore, Figure 5 shows the comparison between the two molds point-clouds with each other. It could be seen that the reproducibility of printing with this specific material was very high. In fact, the two molds could be superimposed, as can be seen from the almost complete green color of the image.

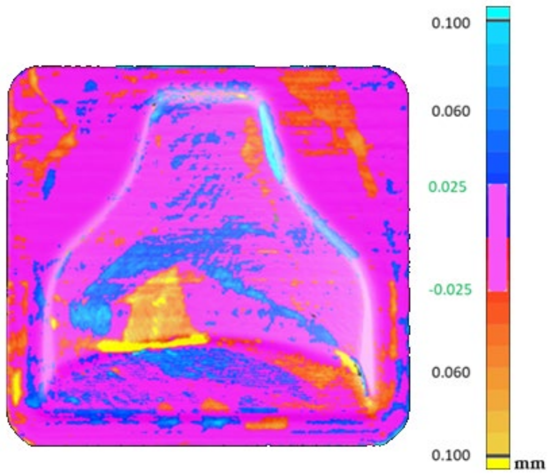

Figure 5. Comparison between the two molds after printing.

6. Results and Discussion

6.1 Numerical Results and Validation

After the first dimensional verification, both molds were subjected to a chemical smoothing process, as described in Section 3.3. Afterwards, dimensional verification with respect to the CAD file gave the results visible in Figure 6. As expected, the chemical smoothing process reduced the peaks of inaccuracies and filled the valleys, reducing the overall external dimensions of the component. Once again, the verification was carried out on both molds printed to evaluate the repeatability of the process, and a comparison was made with respect to the CAD file values and with respect to the scanning performed before the smoothing process.

From Figure 6 it could be deduced that overall, the dimensional tolerance of the component after smoothing reached an absolute value of 0.1 mm, with both molds completely colored green. Figure 7 shows that the treatment was uniform; positive or negative values also differed in the way in which the software superimposed the two scans and did not indicate removal or addition of material. Therefore, they must be understood in an absolute manner. In fact, the software tried to minimize the distance between the points of one mesh and those of the other, obtaining the result shown.

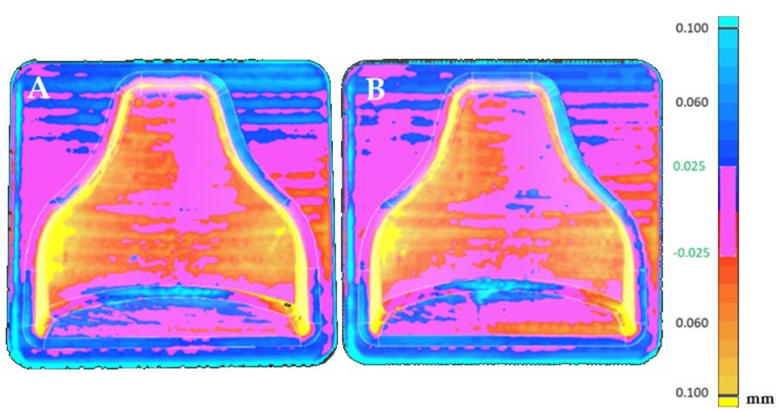

Figure 6. Comparison between the CAD model and first mold after chemical smoothing (A) and cad model and second mold after chemical smoothing (B).

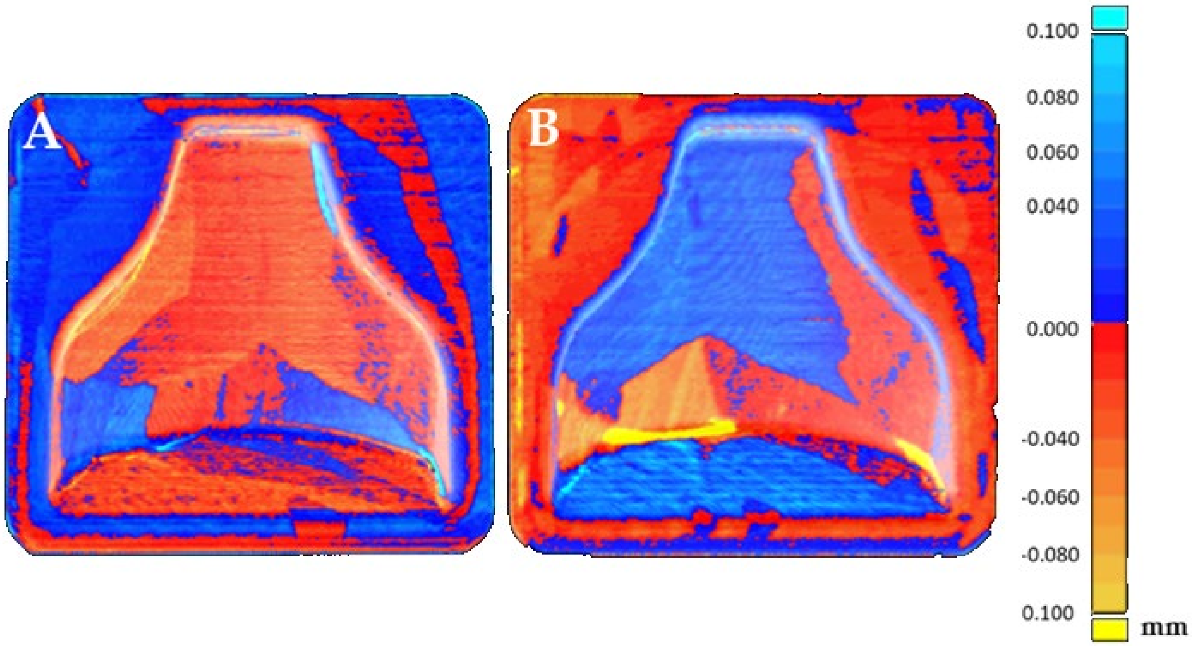

Figure 7. Comparison between the scan of mold 1 pre and post smoothing (A) and comparison of mold 2 pre and post smoothing (B).

Afterwards, the reproducibility of the process could be evaluated in In Figure 8a. In fact, it can be seen that the two post-treatment molds differed in an absolute value by less than 0.1 mm, with the likely analysis almost completely colored green. Figure 8b shows the areas that were slightly positive and those that were negative, but overall, a 85% match within the 0.050 mm absolute value was obtained, making it possible to guarantee narrow tolerances.

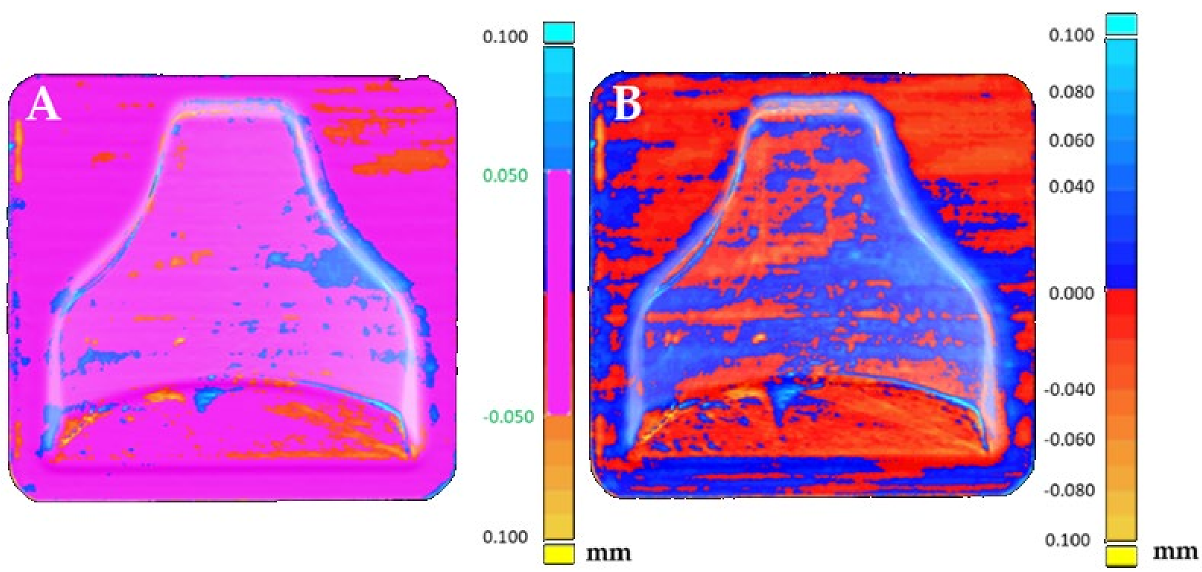

Figure 8. Comparison between the two molds after smoothing.

7. Conclusion

A proper method to assess the reproducibility of an FDM-constructed polymeric component that includes a post-manufacturing chemical surface smoothing process has been verified to show a correlation in the order of hundredths of a millimeter. This process, envisioned with the help of an optical 3D scanner together with a powerful data analysis software like Geomagic that, provided the proper visualization tools to find out the overall surface tolerance values

that each part obtained after the printing procedure. Additionally, this tool provided the ability of compare multiple point clouds, enabling to find out the replicability veracity of two parts manufactured separately under the same 3D printing procedure and posterior treatment to assure required tolerance requirements and surface quality.
This procedure would be used to guarantee prototyping quality for lot production. This constitutes an important step in turning FDM printing method an acceptable and rather cost-effective method for engineering quality part manufacturing.

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