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ORIGINAL ARTICLE

Quality Investigation of 3D Printer Filament Using Laboratory X-Ray Tomography

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Abstract

Consumer 3D printers produce varying qualities of prints due to various factors such as nozzle temperature, layer thickness, line spacing, among others. Until now, very little attention has been given to the filament quality and how this could affect the print quality. In this work, the effect of filament quality on the final build quality was investigated, with a range of different filaments on the same printer. The results indicate that, although the filaments vary significantly in terms of porosity and inclusions, the prints are reasonably unaffected by these factors and dimensionally very accurate. This indicates that filament quality is not of major concern for consumer-level 3D printing. However, the presence of large inclusions could lead to nozzle blockages (and failed prints), and the presence of porosity will lead to weaker parts, which is of interest for more advanced applications.

Keywords: X-ray tomography, additive manufacturing, 3D printing, non-destructive testing

Introduction

There has been tremendous growth in the uptake of consumer-level 3D printers over the last few years with a current total market value of $2B.[1] Consumer 3D printers can produce varying qualities of prints due to various factors such as nozzle temperature, layer thickness, line spacing, software encoding, among many others.[2] Some manufacturers claim the print quality of their printers are superior, while some try to enforce the use of their own brand of filament with their printers, claiming this is necessary to produce the best print quality. Total failure of prints can occur due to an extruder nozzle blockage, changes in environmental conditions, or even due to imperfect gripping of filament by the printer jaws.[3]

Besides the interest in reducing the failure rate and the user's aesthetic satisfaction of obtaining a well-printed object, some 3D printed parts are also destined for mechanical use and as such dimensional accuracy is important, as well as material strength. Low-cost tensile and other materials testing has been proposed and demonstrated,[4] while mechanical properties of parts produced have been the subject of numerous investigations. The ultimate tensile strength of PLA printed parts was investigated as a function of process parameters,[2] tensile strength of both ABS and PLA printed parts was investigated as printed on different systems,[5] and the effect of PLA filament color on the material properties of 3D printed materials was investigated.[6] The effect of additives to the filament used has been investigated, apparently increasing the tensile strength of ABS parts in one case.[7]

Much attention is given to software and hardware methods of improving print quality and to lower the failure rate. However, until now, very little attention has been given to the filament quality of off-the-shelf filaments and this could be mainly due to the lack of simple methods for quality testing of filaments. Currently the best methods are visual inspection or learning by trial and error which filaments work best for a particular machine. In this work, the effect of filament quality on the final build quality was investigated using laboratory X-ray tomography, also known as micro-computed tomography (microCT). A range of different filaments were analyzed by X-ray microCT. These filaments were then used for printing test objects, which were compared in terms of the resulting 3D print quality.

Laboratory X-ray tomography or microCT makes use of X-rays to generate high-resolution 3D images of objects, from which accurate dimensional measurements or advanced 3D analysis can be made, such as porosity or inclusion analysis. This method is gaining popularity in materials

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TABLE 1. FILAMENT ANALYSIS BY HIGH-RESOLUTION CT

Filament type	*Diameter*	*Circularity*	*Normalized circumference*	*Porosity larger than 10 μm diameter (%)*
#1–UP! white ABS	1.719	0.81	6.99	2.7
#2–Cube blue ABS	1.696	0.85	6.81	1.6
#3–Cube yellow ABS	1.715	0.85	6.80	0.2
#4–Cube white ABS	1.670	0.87	6.72	0.1
#5–Zortrax red ABS	1.746	0.87	6.71	0.0
#6–Skertech black ABS	1.740	0.77	7.17	0.0
#7–eSUN Grey PLA	1.740	0.89	6.66	0.1

CT, computed tomography.

sciences,[8] geosciences,[9] food sciences,[10] and industrial applications,[11] among others. Its major advantage is its ability to visualize and quantify internal features of objects in three dimensions, nondestructively. This is especially useful when sectioning of samples could potentially damage the features of interest on the sectioned surface. For example, sectioning a 3D printer filament would smear out the porosity. X-ray tomography is therefore ideal for quality inspection of 3D printer filaments, both for nondestructive quality inspection of full cartridges for major defects as well as for high-resolution analysis of porosity and inclusions in small offcut sections.

Materials and Methods

X-ray tomography was done at the Stellenbosch University CT Scan facility,[12] using a General Electric VTomex L240 (microCT) as well as a General Electric Nanotom S (nanoCT). These systems have varying resolutions depending on sample size, magnification, and X-ray parameters chosen. The methods described could be applied on any type of microCT instrument. X-ray projection images are recorded using parameters as described below, at many angles as the sample rotates. The X-ray projection images can be used for a fast quality inspection, although these images are limited by lack of depth information. A full 3D rotation of the object and recording of many angular projection images are followed by reconstruction of the data into a 3D data set, using Datos reconstruction software. The resulting 3D data are analyzed by Volume Graphics VGStudio Max 2.2.

Whole cartridges of ABS and PLA filament of 1.75 mm diameter were microCT scanned at an isotropic voxel size of 160 μm, allowing a simple visual quality assessment. These whole-cartridge scans were done with the following settings: 200 kV, 150 μA, and 500 ms per image without averaging, with 3000 images recorded during one rotation. Beam filtration was used to minimize artifacts from dense metal parts inside some cartridges, with 1 mm copper filters used. These scans are good for qualitative analysis and making relatively fast decisions on filament quality ($\sim$30 min for the scan). This type of scan is best for finding large inclusions or porosity (>0.3 mm).

In an attempt at quantitative analysis, higher resolution scans of 7 mm offcut sections were made at 5 μm voxel size. These scans were done on the nanoCT instrument, with 60 kV,

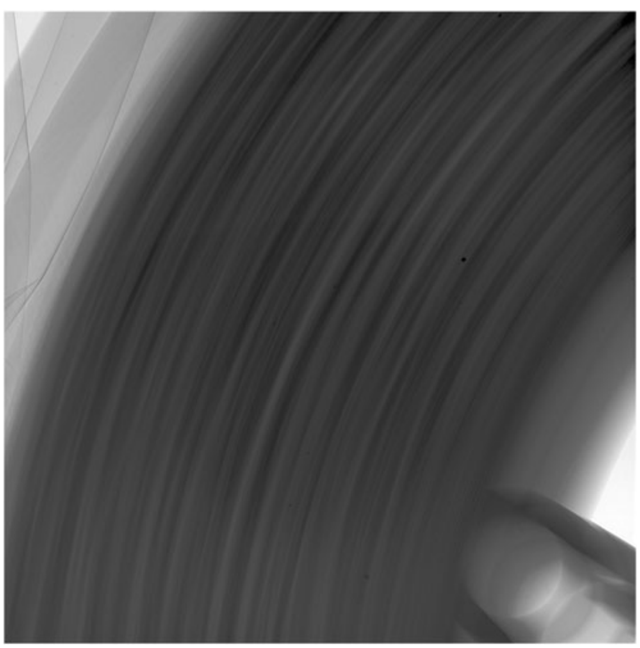

FIG. 1. 2D X-ray image of a section of an entire filament roll containing inclusions shown by the small *black dots*. Inclusions in filament could cause extruder nozzle blockages.

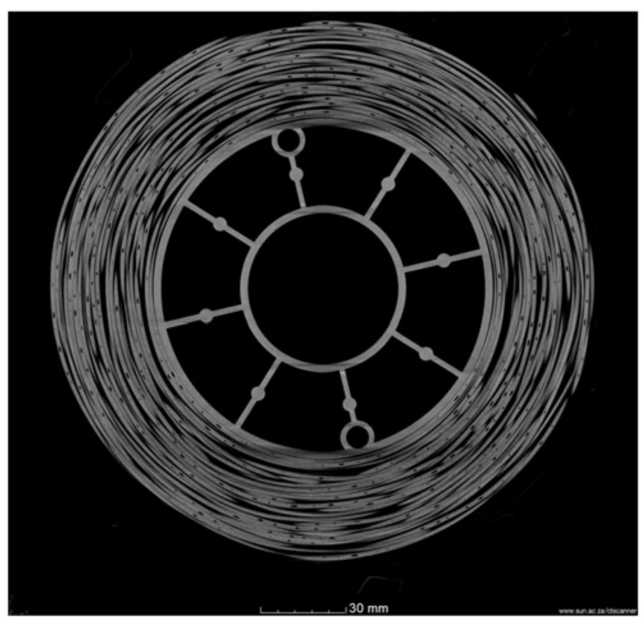

FIG. 2. Example of an X-ray CT slice image of a full roll of ABS filament (sample #1), showing internal porosity as *black dots*. A 2D X-ray did not show up the pores as above, as the contrast is not good enough in 2D X-ray, hence the requirement for a CT scan. CT, computed tomography.

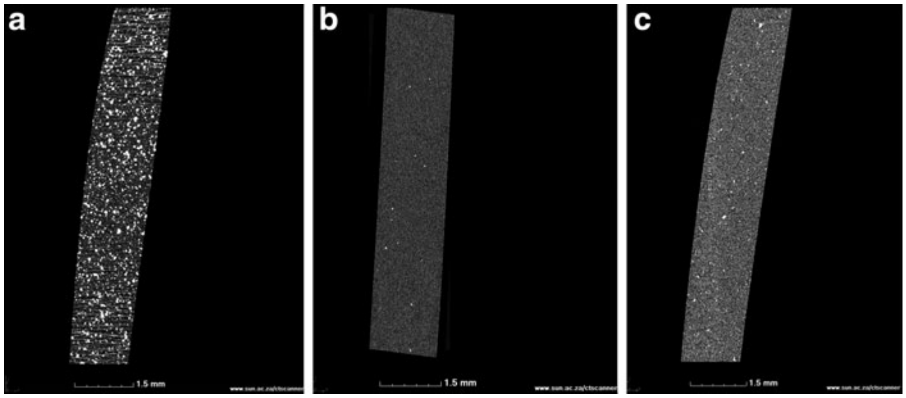

FIG. 3. High-resolution CT slice images of sections of ABS filament (#2, 3, 4) from the same manufacturer, differently colored filaments showing different amounts of bright inclusions **(a-c)**.

200 μA, and 500 ms per image with averaging of two and skipping of the first image at each new step position, with 1100 images recorded during one rotation. Although the field of view is small (5 mm), it provides a very high resolution view, clearly resolving all features of interest. The scan time is also reasonable at ~30 min. 3D prints of a typical model, the 3D Hubs ''Marvin'' quality indicator, were made using the exact same model, software and 3D printer–the UP! Mini, using seven different filaments of which five are from different manufacturers (numbered #1–7 and detailed in Table 1). The scans of these models were done at 60 kV, 200 μA, and 500 ms per image with no averaging and with a voxel size of 30 μm. These printed models were assessed qualitatively by visual inspection and quantitatively by X-ray CT. Finally, a section of extruded material was scanned at very high resolution (1.5 μm voxel size) on the nanoCT instrument, using the mode 1 option, which ensures the X-ray spot size is smaller than 2 μm. Scan settings were 40 kV, 325 μA, and 2 s per image acquisition time and averaging of two and skipping of the first image at each new position, with a total of 2000 step positions in a rotation. The scan time was ~4 h in this case.

Results and Discussions

Whole cartridges or rolls of filament can be inspected by 2D X-ray inspection as well as 3D CT scans, for porosity and inclusions. An example of a 2D X-ray of a roll of filament shows in a close-up view the presence of a small quantity of inclusions in Figure 1. This X-ray image was recorded in the microCT instrument with settings as described above for the whole-cartridge scans, but the sample was repositioned for a close-up view of the observed inclusions, for the purpose of this demonstration. This method of quality inspection is very fast and can be used for routine testing or screening, and is especially suited to detection of large inclusions.

Whole-cartridge full CT scans at 160 μm voxel resolution reveals more details and could visually provide qualitative evaluation of filaments in terms of major porosity or inclusions present, and the rough distribution of those features. Figure 2 shows an example of such a scan where the CT slice images clearly show internal porosity (black spots). This method could be used to assess homogeneity of filaments or to inspect new filament suppliers for quality (or to ensure no major inclusions are present, which could block a nozzle).

Since an entire roll can only be scanned at a 160 μm voxel size due to its size, shorter sections were scanned at high resolution (5 μm) to investigate in more detail the internal features of a series of filaments from various suppliers. A surprising variation was found in terms of porosity and inclusions present, among various suppliers and even from the same manufacturer. A selection of three ABS filament colors from the same manufacturer is shown in CT slice images in Figure 3. The bright spots indicate dense inclusions, of varying concentrations. The microCT method can be calibrated for density determination or for compositional estimation, as was demonstrated for example in Ref.[13] but the process is not simple and requires some assumptions as to the type of material expected. The inclusions observed can therefore not be classified as metallic or not from the microCT data alone. However, metal inclusions typically produce X-ray streak artifacts (not shown); so a qualitative estimate of metallic nature of inclusion can be made simply.

A significant variation was also found between different manufacturers, with a selection of two different manufacturers (different from that in Fig. 3) whose ABS filaments are shown in Figure 4. These two examples show a filament with porosity and one without (two suppliers were clear of porosity and inclusions). The porous filament is the same as the one shown in Figure 2 and here also, some small dense inclusions are seen (white spots).

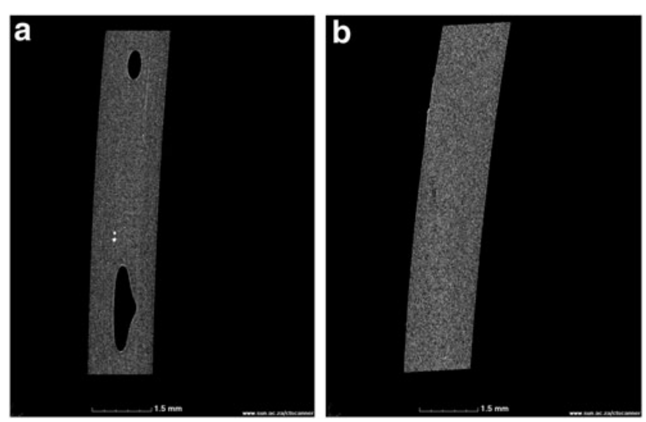

FIG. 4. High-resolution CT slice images of ABS filaments of different manufacturers (#1, 5)—examples of filament containing large porosity **(a)** and one without **(b)**.

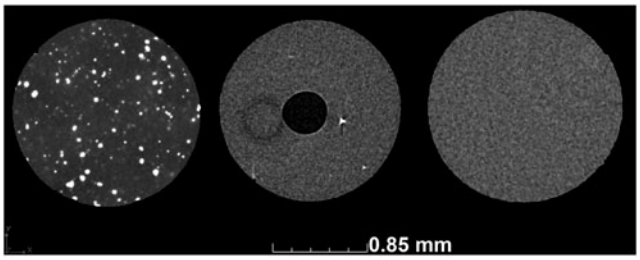

FIG. 5. *Top view* CT slice images of filament sections (#2, 1, 5) at high resolution. From these images, circularity and normalized circumference (roughness) can easily be determined.

The internal features can be visually assessed and quantitative values can be determined if necessary, with volumetric analysis for example of porosity. However, a simpler method is to use the ''top view'' slice images as shown in Figure 5, which can be analyzed in 2D using freely available software. The values that could be of interest in quantification of filament quality include the actual diameter (as opposed to the specification of 1.75 mm), the circularity, and the normalized circumference (which is an indirect measure of the surface roughness of the filament). The circularity is of interest as a noncircular cross-section could possibly result in difficulty with the gripping and feeding to the nozzle, while the normalized circumference or roughness might also affect the gripping. These values are determined for the seven filaments tested and presented in Table 1 as demonstration of the quantitative nature of the method. The porosity was also determined volumetrically in the offcut section and is given as total porosity >10 μm, that is, two voxels wide in one dimension.

The values obtained from filament analysis indicate good circularity and normalized circumference within a small range without any filament being significantly better than others. All filaments tested were narrower than the specified 1.75 mm diameter. The sample #6 has the largest circumference value indicating a rough surface, as well as the lowest circularity value indicating deviance from circular shape. Sample #4 was the narrowest and thus the lowest specification in terms of diameter.

Test objects were printed using all these filaments on the same printer and under identical conditions (same position on build plate, etc.). All test objects were printed successfully and were visually of excellent quality. The test objects were subsequently CT scanned at high resolution with CT slice images showing the internal structure in Figure 6, for samples printed from filaments #1, 2, and 5.

To analyze the dimensional accuracy of the test objects, a CAD variance analysis was done on the three selected examples in Figure 6, with the same method as demonstrated in Ref.[14] The resulting 3D variance analyses are shown in Figure 7 with values summarized in Table 2).

The dimensional accuracy of the three test parts is good in each case (total offset of about 60 μm and 90% of the surface is within less than 0.3 mm total), and in comparison with the CAD file, the volumes are slightly smaller (due to the small negative offset). The surface areas are larger, as expected, due to the nonsmooth surface of the actual prints. The total surface area does not differ much between the three prints indicating similar surface roughness between the prints. On visual inspection, these three samples compared very well to each other. The same is true of the other five printed test objects, which printed very well but were not subjected to CT analysis.

Although the porous filament printed an accurate model, the presence of porosity is important and could result in weaker parts. Closer inspection of the analysis reveals that the porous filament produced the largest 99% variance value of the test object, which means it also has the largest deviation from the CAD file of the three models.

To further investigate the effect of porous filament on extrusion, a small section of extruded filament was analyzed by nanoCT scanning (CT scanning with an instrument capable of submicron resolution). The resulting image in Figure 8 shows clearly the pore in the extruded filament being significantly large, relative to the diameter of the extruded material, and causing irregular extruded diameters.

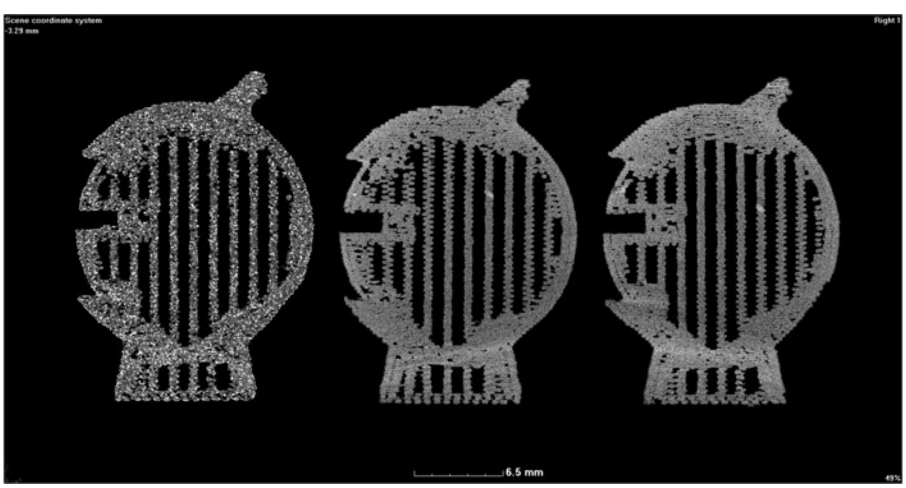

FIG. 6. High-resolution CT slice images of test objects printed with the same three filaments as analyzed in previous figure—examples of filament with inclusions (#2), with porosity (#1), and with neither (#5).

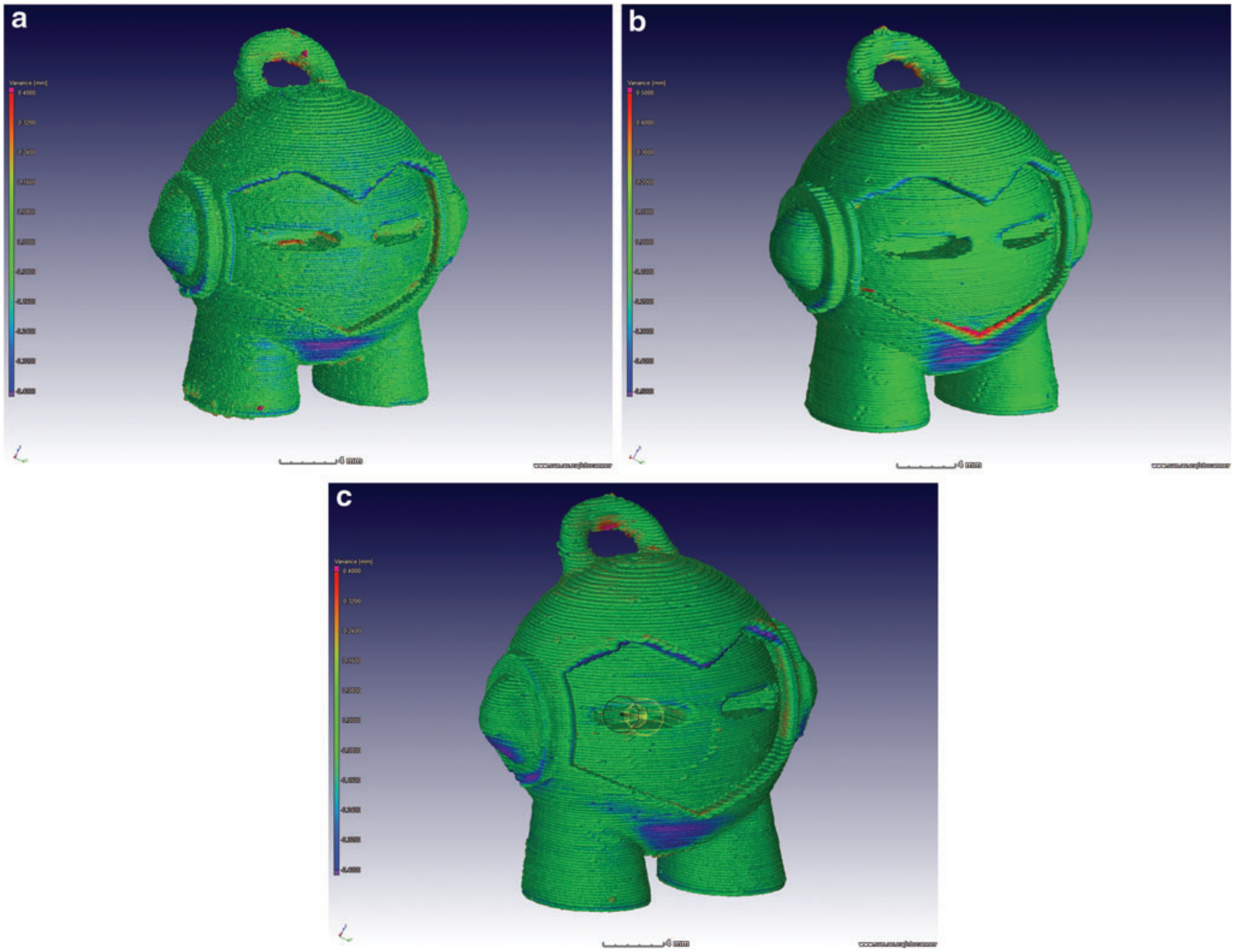

FIG. 7. 3D CAD variance analysis shows filament with inclusions (#2 **[a]**), with porosity (#1 **[b]**), and without either (#5 **[c]**). All three show good dimensional accuracy compared to the design CAD file. Color images available online at www.liebertpub.com/3dp

Conclusions

It was shown that X-ray computed tomography provides a detailed view of the internal structure of 3D printer filament, showing significant variations between different colors and manufacturers. A full cartridge scan is shown to be sufficient to monitor the presence of major porosity and inclusions. A much faster 2D X-ray inspection method was also demonstrated to identify inclusions, with the same instrument. Detailed analysis of small sections allows a more quantitative analysis as demonstrated for the presence of inclusions, porosity, and dimensional measurements of the actual diameter, circularity, and effective surface roughness by a normalized perimeter measurement. A suggested protocol for quality control is therefore to scan an entire roll to qualitatively look for major defects and variations across the filament, while one offcut section scanned at high resolution provides quantitative measures as described above. This combination will provide a holistic analysis for quality control purposes. Alternatively, in the case of X-ray microCT benchtop instruments, which cannot handle entire rolls, more offcut sections can be analyzed. It is envisaged that this method of filament characterization will be useful for filament manufacturers to optimize their production processes, while advanced users may want to validate the quality of their filament from new suppliers.

Table 2. 3D Test Object Analysis by High-Resolution CT

Sample	*90% CAD variance (μm)*	*99% CAD variance (μm)*	*CAD offset (μm)*	*Surface (mm^2)*	*Volume (mm^3)*
CAD model	—	—	—	1883.65	4650
#1	293	536	–60	2393.24	4481.89
#2	182	430	–70	2822.53	4501.58
#5	257	498	–60	2553.51	4521.05

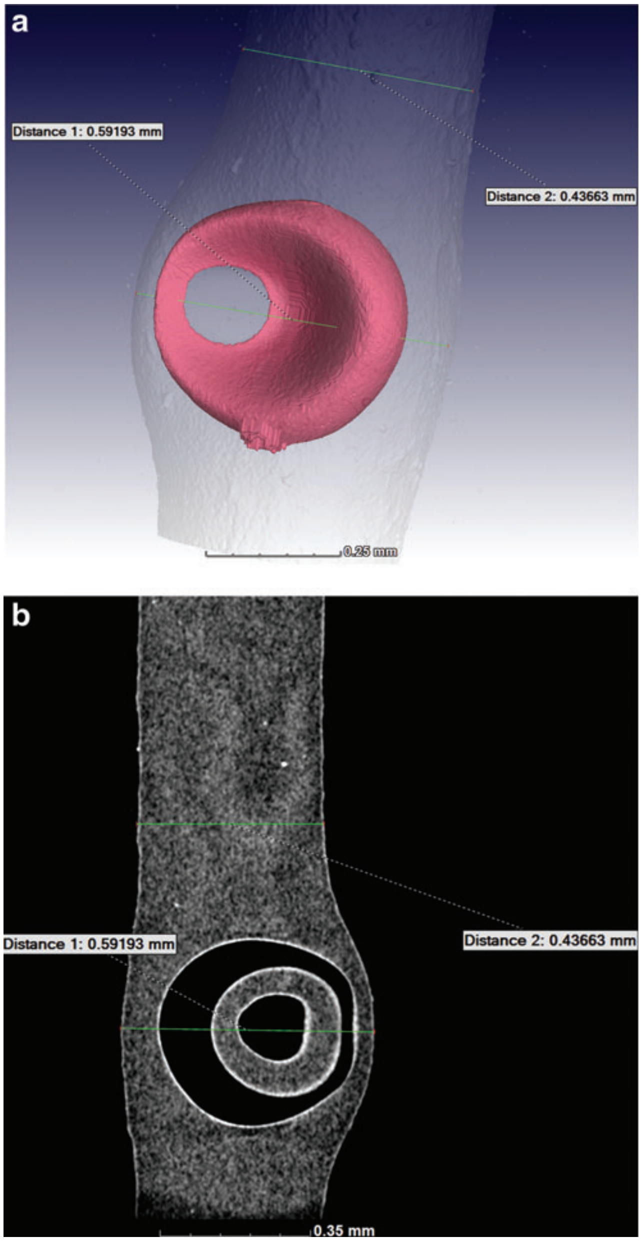

FIG. 8. **(a)** 3D image shows large irregular-shaped pore in *pink* and extruded material semitransparent. **(b)** NanoCT analysis of extruded porous filament at 1.5 μm voxel size, showing dimensional measurements of extruded diameter across pore region and nonpore region. Color images available online at www.liebertpub.com/3dp

In this case study, significant variations were observed in filament quality from different manufacturers, but all printed test objects were of high dimensional accuracy and visually acceptable. This indicates that filament quality is not a strong factor influencing the build quality. However, the presence of large inclusions is expected to affect the possible blockage of a nozzle, or large pores will result in weaker built parts. An extruded section of filament of the porous type was analyzed at high resolution, clearly showing the transfer of pores into the extruded sections as well and covering up to 75% of the width of the filament in this case.

Author Disclosure Statement

No competing financial interests exist.

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