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Influence of Integrated Pressing during Fused Filament Fabrication on Tensile Strength and Porosity

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ABSTRACT

Additive manufacturing or 3D printing is a technology that built 3D objects by adding material layer-by-layer. There are tremendous studies have been conducted regarding this new emerging technology to transform the printed part from being a prototyping tool to a manufacturing process that can create durable and functional goods, and comparable to the traditional manufacturing processes. Therefore, this study proposes a new method of Fused Filament Fabrication (FFF) by integrating with mechanical pressing where a roller is used to improve the strength and porosity of the printed part during processing. This study focuses on the low-range RepRap 3D printer. Mendel RepRap was used to print the samples, and the material of Acrylonitrile-butadiene-styrene (ABS) was used for this study. The samples printed from both techniques, normal FFF and FFF with pressing were compared with respect to their tensile strength and porosity. The strength of the samples was tested using an Instron machine, and the images of the samples were captured using Scanning Electron Microscope (SEM). Later, Image J software was used to analyze and calculate the percentage of the porosity. Based on the results, the percentage of porosity for the normal FFF is about 20~21% while FFF with pressing shows the smaller value that ranges from 12~15%. Meanwhile, the tensile strength of the FFF with pressing gave a greater value which is up to 38.34 Mpa.

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Introduction

Additive Manufacturing (AM) or 3D printing technology started in the 1980s and gradually being adapted into the manufacturing industry, engineering design, arts and architecture to create prototypes and models. Apart from that, this technology is also utilized in the medical field due to its ability to customize nearly anything that can be modelled as a 3D design with almost no limitation in creating a body parts for human or even animals. For example, this advanced technology has successfully made prosthetic limbs and bones through a bioprinter [1]. 3D printing is not only available for heavy and large industries, but it also can be used as a personal fabrication in fulfilling the dreams of some enthusiasts. Therefore, many 3D object repositories now provide access for free 3D models for download-and-print such as Thingiverse, where a wide variety of the 3D model can be downloaded and printed directly like toys, machine spare parts, musical instruments, smartphone cases, mini statutes and much more.

The 3D printing technology enables the 3D object to be built up directly by depositing material layer-by-layer based on the computational-aided design (CAD) data without the need of part- specific tooling. There are a few types of 3D printing such as fused filament fabrication (FFF) selective laser sintering, electron-beam melting and laminated object manufacturing, solid ground curing, polyjet and etc. [2]. These processes can be differentiated from how the layers are deposited in order to create parts and the types of materials used. Therefore, this study focuses on the influence of integrated pressing during FFF on the tensile strength and porosity of parts.

FFF is a technique where the thermoplastic wire is fed through the printhead using the drivewheels and being heated up by the liquifier to become semi-molten. The nozzle and the platform move according to the G-code that has been developed through CAD data so that the deposited material is built-up layer-by-layer as illustrated in the Figure 1 [3].

Basically, most of low-range open source 3D printers applied FFF due to low-cost and large open source community to support their development. Unfortunately, the mechanical properties of the part printed using such 3D printers are less superior compared to the high-range 3D printers and well-established manufacturing techniques such as sand casting, injection molding, machining and etc. Many studies were conducted to analyze the performance of 3D printed material, for example, a study conducted by Bakar et al. (2010), they had analyzed the FFF performance by applying different process parameters and concluded that the circular shape is less accurate for a very small radial distance [4].

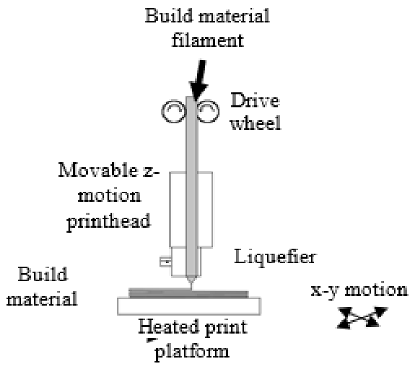

Figure 1**:** The schematic diagram of normal FFF [3]

Therefore, a few researches have been conducted to overcome this problem either through process optimization, process improvement and others. Anitha et al. has determined the effect of layer thickness, road width and deposition speed of the FFF process by using Taguchi method and found that the layer thickness is the most dominant process parameter that affecting the surface roughness [5]. The surface finish of the printed is also better with a small number of layer thickness. Besides, chemical treatment also has been utilized for a better surface finish. Dimethyl ketone and water solution were used which significantly improved the surface roughness yet reduced in tensile strength [6]. In addition, one of the process improvements has been proposed by Ren X. et al. in 2016, which is called 3D gel-printing. This technique is based on methaerylate-2-hydroxy ethyl (HEMA) gelation system where the organic monomer undergoes through the radical polymerization, forming a micro polymeric network to hold the particles together. This resulting the surface roughness increases from 3.5±0.5 µm to 3.8±0.9 µm and the tensile strength increases from 16.1±2.2 MPa to 488±15MPa [7].

In order to improve the mechanical properties of the printed part, this research has introduced a new method of FFF by integrating with mechanical pressing. This will enhance the mechanical properties of the printed part by reducing the porosity percentage and concurrently increase the tensile strength. Based on Jason et al who had conducted an experiment using Sintered Laser Printing technique found that the tensile strength of the samples increases from 4.9±0.4 MPa to 10.4±0.4 Mpa [8]. This is because the strength of the printed part is significantly affected by the percentage of the porosity [9]-[11].

Methodology

Material used for this study was acrylonitrile butadiene styrene (ABS) and printed according to ASTM D638 standard [12] using open source RepRap Mendel 3D printer. Figure 2 shows the schematic diagram of the printhead where the modification was made by assembling the rollers to the nozzle. The roller is made up from the chrome steel with 1 cm diameter and 0.8 cm width.

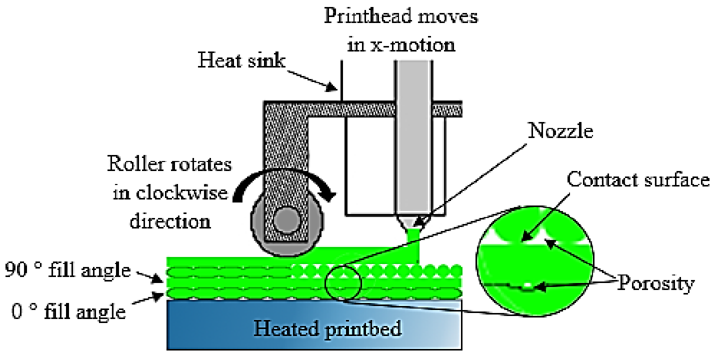

Figure 2: The schematic diagram of FFF with mechanical pressing

There are two rollers that move in the direction of the nozzle are attached to the heat sink of the printhead. When the semi-molten filament is deposited from the nozzle, the rollers moves towards on the deposited material and pressed it concurrently. The position of the roller is at the same level of the nozzle.

In order to study the effect of mechanical pressing, the samples were printed from both techniques, normal FFF and FFF with pressing. The setting of printed component is a basic line pattern and at 90° fill angle. The parameters that varied in this study were fill density, layer height and pattern spacing. This is shown in Table 1.

Table 1: The parameter varied in the study.

Parameter	**Fill density (%)**	**Layer height (mm)**	**Pattern spacing (mm)**
Value	20	0.1	1
	40	0.2	2
	60	0.3	3
	80	0.4	4
	100	0.5	5

Then, the tensile strength of the samples was tested using an Instron machine (Model: INSTRON 5585H Series Floor Model Testing System). The images were captured using Scanning Electron Microscope (SEM) (Model: Zeiss Axiovert 200 Matt) and the Image J software was used to analyze and calculate the percentage of porosity in the samples. Lastly, the data between normal FFF and FFF with pressing were compared and analyzed.

The porosity of the samples was determined by the captured images obtained from SEM. The cross- sectional area of the sample printed from the normal FFF as shown in Figure 3 has been prepared by sectioning the printed samples into 5 mm x 15 mm rectangular shapes. Later, the surface was polished so as to reveal its porosity and to observe the deposited filament material arrangement. The figure also shows circular shaped deposited filament which caused the small contact surface area between the layers. Therefore, the porous area of the printed part was greater in numbers. However, when the sample printed by the new FFF method which combined with the mechanical pressing as shown in Figure 4, the printed layer become flat as the pressure was applied by the roller onto the surface of each of the layers. This resulted in larger contact surface area and subsequently narrowing the presence of the porous area where the percentage of pososity has been calculated by using the Image J software. This image recognition software binarized the images captured by the SEM and calculated the value of the porosity percentage based on the Equation (1).

$$\varnothing_t = \frac{A_S - A_{Non-pore}}{A_S} \times 100 \qquad (1)$$

where

$\varnothing$: porosity

A_s : area of printed surface

$A_{Non-pore}$: area of non-porous surface

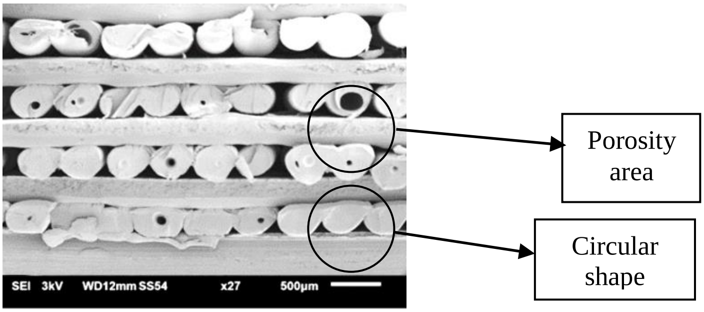

Figure 3**:** Images of the cross sectional view of sample printed by using Normal FFF for fill density of 100%

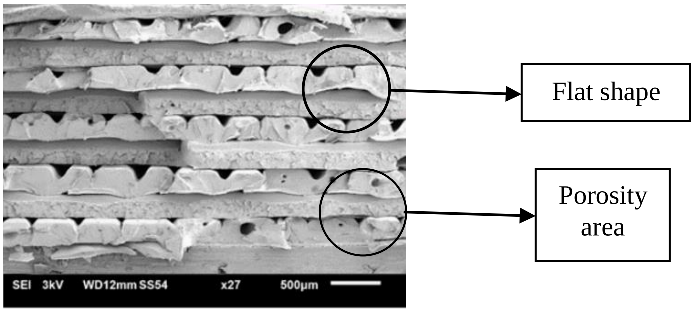

Figure 4: Images of the cross sectional view of samples printed by FFF with pressing for fill density of 100%.

Figure 5 shows the cross-sectional view of the samples printed by normal FFF and Figure 6, FFF with pressing, respectively. The layer height was varied while the other parameters such as fill density and pattern spacing were kept constant at 100% and 1 mm, respectively. The layer height is 0.1 mm. The sample printed by using FFF with pressing as shown in Figure 6. The figure indicates the particles are very close to one another which resulted in less porosity. This is due to the low value of layer height that caused the distance between the surface of the deposited material to be closer to the roller, and increases the roller width of the touching surfaces Thus, the roller rolled onto the surface of the deposited material and subsequently covers the area between the layers. The standard parameters of 100% fill density and 1.2 mm layer height were used. For Figure 7 and 8, the pattern spacing used is 1 mm while the fill density and layer height are 100% and 1.2 mm, respectively. It was observed that the layers are much closer to one another. Therefore, as the roller is applied onto the surface of the deposited material, the layer becomes closer to one another. As a result, major reduction in porosity and small overlap between the layer was observed.

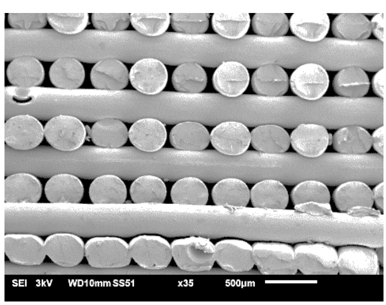

Figure 5: Image of the cross sectional view of samples printed by Normal FFF for layer height 0.1mm

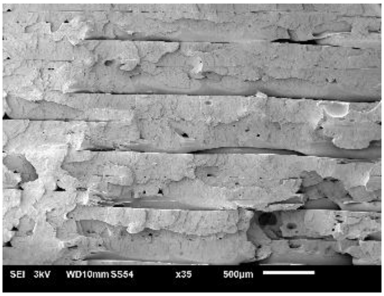

Figure 6: Images of the cross sectional view of samples printed by New FFF with additional pressing for layer height of 0.1 mm

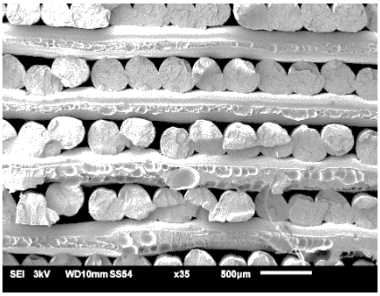

Figure 7: Images of the cross sectional views of samples printed by Normal FFF pressing for pattern spacing of 1 mm

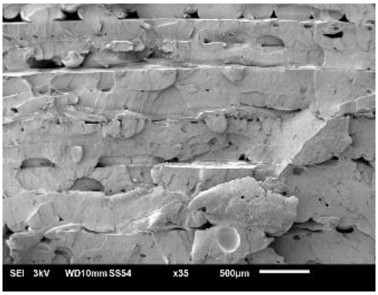

Figure 8**:** Images of the cross sectional views of samples printed by New FFF with additional pressing for pattern spacing of 1 mm

The images as shown in Figure 3, 4, 5, 6, 7 and 8 were uploaded in the image recognition software called Image J. This is to analyze and calculate the percentage of porosity in the samples printed by both techniques. Figures 9 shows the binarized image obtained from the software for the samples with the fill density of 100% printed by Normal FFF and Figure 10, by FFF with pressing, respectively.

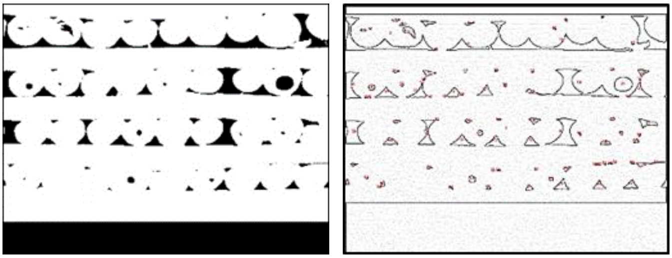

Figure 9: Binarized images for the sample printed by Normal FFF for fill density of 100%

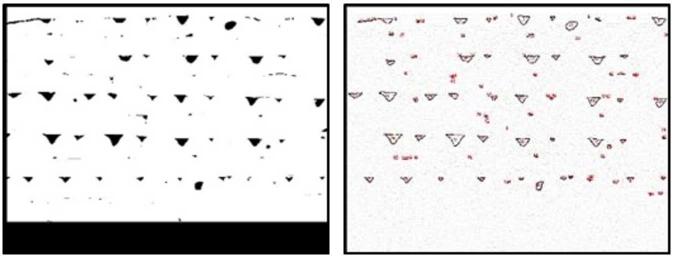

Figure 10: Binarized images for the samples printed by FFF with pressing for fill density of 100%

Figure 11 shows the binarized image from the sample of FFF with pressing and the calculated porosity is 12.04%, as shown in Figure 15. Meanwhile, the porosity was recorded to 21.68% of the sample printed by the normal FFF.

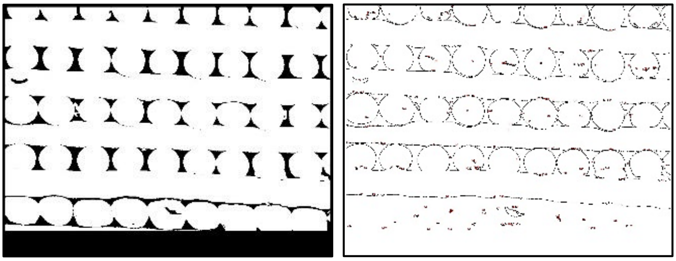

Figure 11: Binarized images of the samples printed by Normal FFF for layer height of 5 mm

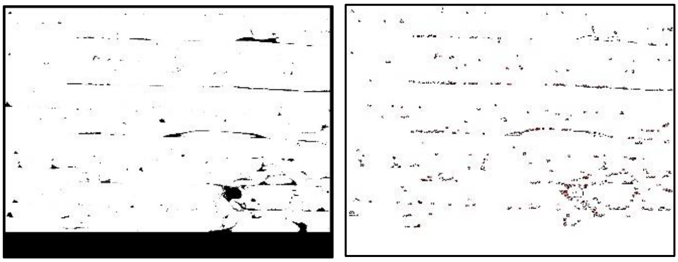

Figure 12: Binarized images of the samples printed by FFF with pressing for layer height of 5 mm

Figure 13 and 14 shows the binarized image of the pattern spacing of 1mm . Based on these images, the porosity percentages were calculated and presented in Figure 15 (c). It shows that the sample printed by FFF with pressing gives less porosity. It was recorded the porosity was 12.17% compared to that of the normal FFF with 20% porosity.

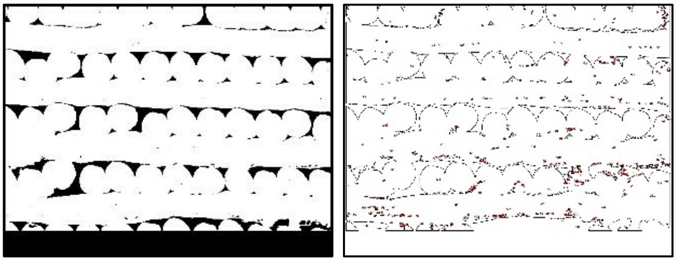

Figure 13: Binarized images of the samples printed by Normal FFF for pattern spacing of 1 mm

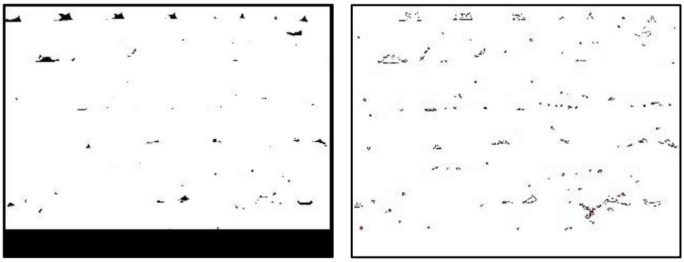

Figure 14: Binarized images of the samples printed by FFF with pressing for pattern spacing of 1 mm

Figure 15 shows the data on the porosity percentage where the normal FFF produce higher porosity percentage compared to the FFF by pressing, for all tested samples. At the same fill density as shown in Figure 15(a), the porosity is 21.22%for the normal FFF, while 15.33% for the FFF with pressing. For the influence of layer height, the normal FFF produced 21.68% porosity while the FFF with pressing only produced 12.04% porosity, as illustrated in Figure 15(b). This proves that the pressure applied to the new deposited material causes the empty space between the layers to be filled up and resulted in major reductions in porosity. Finally, at the same pattern spacing, less porosity can be obtained for FFF with pressing, as shown in Figure 15(c).

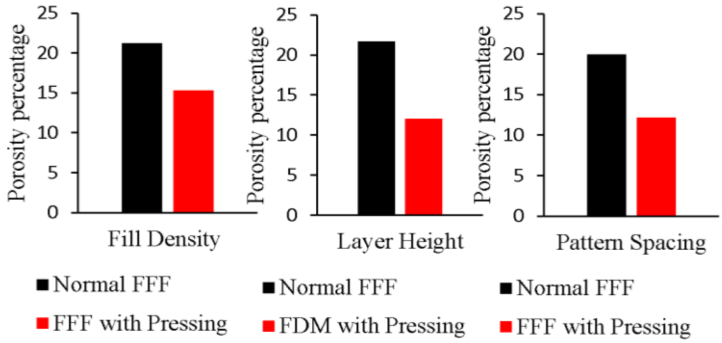

Figure 15: Porosity percentage of samples printed by normal FFF and FFF with pressing for (a) Fill density (b) Layer height and (c) Pattern spacing

Tensile strength

Basically, the tensile strength of the part printed by a low-cost and open source 3D printer is 28.5 MPa for ABS material while 56.6 MPa for PLA [13]. These values are also depends on the parameters used during processing. Tymrak et al. stated the layer height of 0.2 mm and 45° orientation improved the strength. Besides, the mid-grade commercial 3D printer has a tensile strength of 32 MPa [14]. Therefore, printed part having good strength can be produced if the process parameters are optimized.

Figures 16 shows the comparison between the tensile strength of the normal FFF and the new FFF with additional pressing, at different fill densities. From the graph, the tensile strength for normal FFF slightly increased from 28 MPa to 30 MPa while the tensile strength for the new FFF method ranges from 30 MPa to 36 MPa. The tensile strength shows a greater change between before and after applying the pressure. The fill density indicates the percentage of the material need to be filled for the solid part to build up. Therefore, when higher filled of material is used, it produced an excessive material to be filled up in the empty area when the roller rolled onto the surface of the deposited material, and cause the contact surface area to be wider and act as a strong bonding from one layer to another.

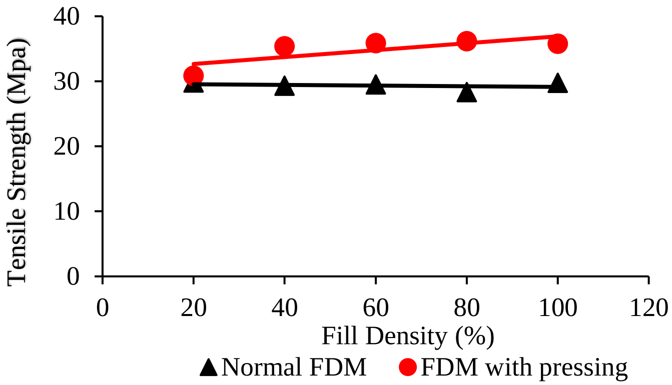

Figure 16: Tensile strength of the printed part with varying fill density.

Based on the Figure 17, the layer height for the normal FFF did not change significantly with the increase of layer height. However, it was found that by using the proposed technique of FFF with pressing, better tensile strength can be achieved.

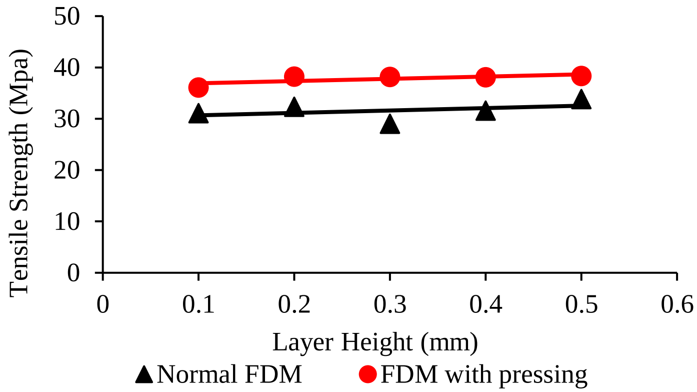

Figure 17: Tensile strength of the printed part with varying layer height

Figure 18 shows the tensile strength varying with pattern spacing. The greater the value of pattern spacing, the lower the tensile strength. When the space between the layer increases, no excessive material to be filled up to cover the empty space between the layers. However, the pressure applied by the roller compresses the surface of the deposited material causing the contact surface between the layers to be greater. Therefore, the highest tensile strength of 34 MPa was obtained from the pattern spacing. Although the value is not as much as fill density and layer height, such value is still comparable to the mid-grade commercial 3D printer.

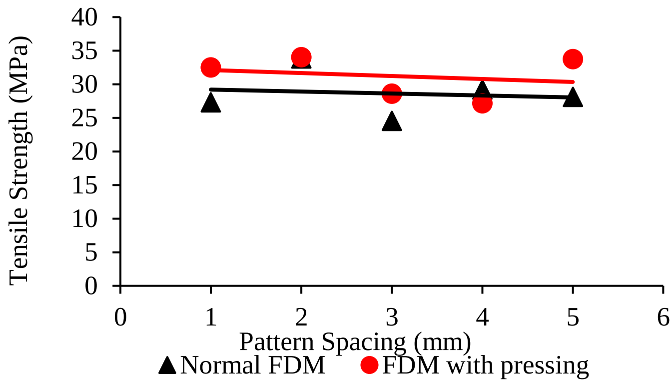

Figure 18: Tensile strength with varying pattern spacing .

Conclusion

Porosity percentage and tensile strength of 3D printed part between the normal FFF and FFF with pressing were determined at various setting. From the data analysis, the percentage of porosity for the normal FFF is about 20~21% while FFF with pressing shows the smaller value that ranges from 12~15%. Meanwhile, the tensile strength of the FFF with pressing gave a greater value which is up to 38.34 MPa. This is because when the roller is applied, the pressure on the surface of the sample is distributed and resulted in reduction in porosity. Thus, the contact surface area increases and leads to greater strength in the printed samples.

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