Engineering Manufacturing Letters, 1:1 (2022) 20-27
ISSN 2795-5168
DOI: 10.24840/2795-5168_001-001_0005

Received: 30 December, 2021
Accepted: 5 April, 2022
Published: 21 April, 2022

Effects of nozzle material and its lifespan on the quality of PLA parts manufactured by FFF 3D Printing

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Author Keywords

FFF, nozzle material, thermal conductivity, lifespan, PLA

Type: Rapid communication

Open Access
Peer Reviewed

Abstract

The calibrated nozzle is one of the main components of a Fused Filament Fabrication (FFF) 3D printer. However, few studies explore its lifespan, and the effects of the thermal conductivity of the material on which it is built in the 3D Printing process. These aspects were evaluated in this study through the analysis of mechanical properties (flexural test), porosity and density of Poly (lactic acid) (PLA) parts. Samples were manufactured with brass, hardened steel, and Vanadium™ nozzles, varying the building orientation and the raster angle parameters. A brass nozzle with a long printing history was used. The main finding showed that the lifespan of the brass nozzle was a significant factor in reducing the quality of printed parts compared to those obtained with low heat conduction nozzles (hardened steel and Vanadium™).

1. Introduction

Fused Filament Fabrication (FFF) process stands out as one of the most popular Additive Manufacturing (AM) technologies due to its ease of use and good cost-effectiveness. The FFF process is classified as an extrusion-based AM process, in which the raw material is a thermoplastic filament, which is gradually heated, extruded and deposited selectively by a calibrated nozzle. The material extrusion and deposition will be repeated throughout the entire layer stacking process, until obtaining the final object (Costa et al. 2021; Santana, Alves, and Sabino Netto 2017; Santana et al. 2018).

One of the main components of 3D printer in the FFF process is the nozzle, responsible for conducting thermal energy for the processing of the building material and for controlling the extrusion volume and resolution of the printing process, since it affects the dimensions and geometries of the extruded filaments. Thus, the nozzle plays a very important role in technological properties of printed parts and in the economic aspects of the FFF process (Li, Cheng, and Hu 2017; Jerez-Mesa et al. 2018; Wan Muhamad et al. 2020). Due to the importance of this component, scientific studies are dedicated to evaluating the effect of the nozzle diameter in terms of mechanical properties, porosity, surface roughness, dimensional quality, and density of printed parts (Triyono et al. 2020; Tezel and Kovan 2022). Other studies investigate the influence of nozzle diameter and output geometry on parameters related to material extrusion, such as pressure drop, extrusion time, geometric errors, and bed width stability (Sukindar et al. 2016; Gharehpapagh, Dolen, and Yaman 2019). There are also papers related to nozzle clogging (Tlegenov, Lu, and Hong 2019) and to its wear when using abrasive materials (Pitayachaval and Masnok 2017).

There are many studies on the behavior of the nozzle. It was observed, however, that few of them explore the influence of thermal conductivity of the nozzle's materials and its lifespan — when applied to printing with non-abrasive filaments, such as conventional one in Poly (lactic acid) (PLA) — in the final quality of the parts produced by FFF printers.

2. Materials and Methods

The analysis of the lifespan and the thermal conductivity of the materials of the nozzles was carried out indirectly from the evaluation of the quality of the printed parts, in terms of mechanical properties and porosity levels. Nozzles with 0.4mm, in brass, hardened steel and vanadium were selected. Brass nozzles are the most frequently available on 3D printers (are easily machinable and cheap and have good thermal performance) (Carolo 2020). However, they are susceptible to functional wear. This is the reason why they were selected for the study of the lifespan, considering the following criteria: (i) use a brass nozzle with a one-year printing history, (ii) compare the parts manufactured with this nozzle, with the ones produced with a new (not used before) brass nozzle and nozzles with low thermal conductivity (hardened steel and [1]Vanadium™), and (iii) use a thermoplastic with good printability; PLA filament (white, 1.75mm diameter) from PM™ supplier.

To study the effects of heat conduction from the nozzle on the formation of printed layers parallelepiped samples (127x12.7x3.2 mm) were fabricated for three-point flexural testing, based on the ASTM D790 (2010) standard, varying only two process parameters; raster angle and build orientation, under two experimental conditions. The first combination consisted of deposition of unidirectional filaments with lateral part orientation. This configuration, by having all the filaments aligned between and within the layers, provides better mechanical properties. However, in the lateral position, one of the largest dimensions of the specimen (12.7mm) is in the Z-stacking direction, causing a portion of the sample layers to move away from the heated bed of the 3D printer and have its formation energy dependent, mostly, from the temperature of the nozzle. In the second case, an "on the plane" build orientation was used, with the smallest part dimension (3.2 mm) in Z, together with a raster angle of 45°/-45°. In this situation, we sought to compensate for the thermal conductivity limitations of the nozzles through the thermal energy of the heated bed and the deposition of filaments with smaller vector lengths. The other printing parameters were kept fixed according to the studies

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[1] Vanadium™ is the trade name adopted by Slice Engineering™ to describe its product. The nozzle, according to the manufacturer, is made from an alloy of high-speed-steel with vanadium (Slice Engineering 2022).

by Castro (2021) and Santana et al. (2018), with emphasis on extrusion (215°/210°C) and bed (60°C) temperature, infill density (100%), and layer thickness (0.2 mm).

For each condition described, six samples were manufactured simultaneously in a Prusa MK3S 3D printer. Therefore, 12 parts were built for each of the four nozzles evaluated, generating a total of 48 elements analyzed. The samples were tested in a Mecmesin™ equipment with a 2.5kN load cell, support span of 61.5 mm, and a test speed of 5mm/min. Three-point flexural tests were carried out for each specimen to determine the maximum flexural strength (MFS) and the flexural modulus (FM).

Finally, the porosity (φ_{cube}) and density (ρ_{cube}) of the parts printed with the different nozzles were determined. Cubes with 20 mm sides were used as standard. Three parts were manufactured per nozzle, using the first printing configuration from the previous step. The dry mass and density of the cubes were measured on a Mettler™ H31AR scale with a resolution of ±0.1mg. The porosity values were based on the ratio between the apparent density of the cubes and the density of the material, as described in the studies by Al-Maharma, Patil, and Market (2020). The cube's apparent density was calculated by dividing its dry mass per its volume (measured with an Mitutoyo™ IP65 micrometer with ±0.001 mm resolution). To obtain the real density value of the PLA filament (1.26±0.01 g/cm^3), a Metter Toledo™ XS205 Dual Range scale was used. Both the cube and filament real density acquisitions were based on Archimedes' method, using distilled water as standard liquid and a test temperature of 22°C.

3. Discussion

Through Analysis of Variance (ANOVA, α=95%), it was found that in the "on the plane" condition, the use of different nozzles — in this case, brass (with a long printing history), hardened steel and vanadium — significantly affected the maximum flexural strength (MFS) (F (2,14) = 190.02, p = 0.00) and flexural modulus (FM) (F (2,14) = 62.52, p = 0.00). A Tukey test was performed to identify the differences between the means of the three levels of the "nozzle type" factor in the variation of MFS and FM — Figure 1(a) and Figure 1(b), respectively. Different letters in the yellow bars, Figure 1, indicate different means.

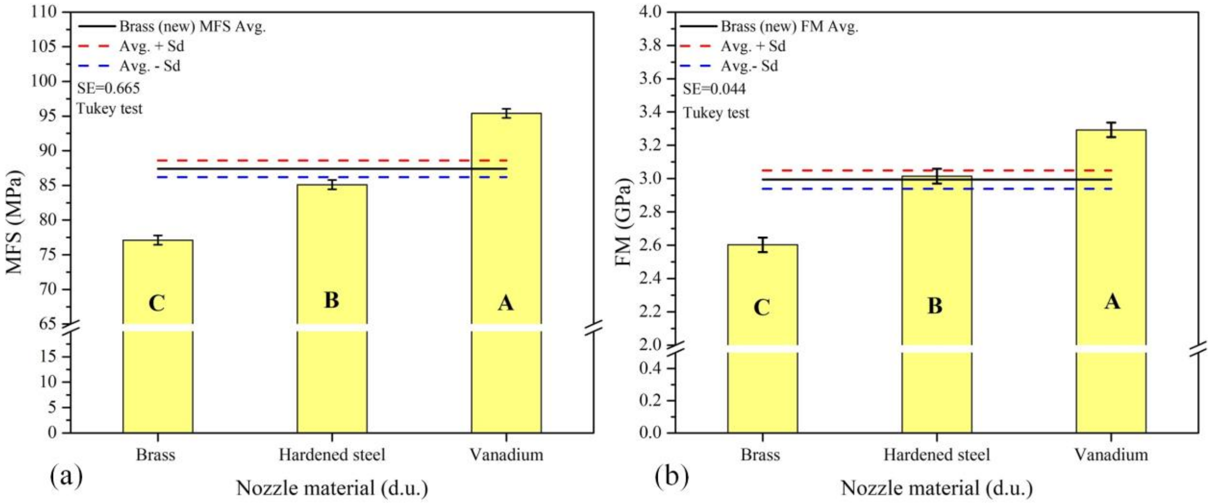

Figure 1: Average maximum flexural strength (a) and flexural modulus (b) for "on the plane" build orientation. (Note: standard error (SE)).

The basic principle of FFF structures formation is based on the supply of thermal energy for the extrusion of the building material and for the extruded filament to provide bonding to the previous layers. The higher and more stable this energy level, the more efficient the mechanisms responsible for the neck growth between the deposited filaments intra- and inter-layers and, consequently, the greater the mechanical strength of the printed parts. According to Ferretti et al. (2021), the heat transfer from the hot zone of the extrusion system to the material to be processed depends on the thermal resistance of the nozzle. Therefore, a nozzle with lower thermal resistance, or higher thermal conductivity, provides more energy for processing the thermoplastic.

Based on the concept described above, it would be more logical for the brass nozzle to promote the best results for MSF and FM, since it has a higher thermal conductivity —120 W/mK (Tichý et al. 2021) — than steel — 23 W/mK (Ferretti et al. 2021) — and vanadium steels — 28 W/mK, reference value for an AISI M2 steel with 1.75-2.20 (wt%) vanadium (Wilson 1975). However, the scenario observed in Figure 1 shows that the MFS (77.11 ± 1.47 MPa) and FM (2.60 ± 0.10 GPa) results obtained with the long-used brass nozzle are approximately 19% and 20% lower than those obtained with the Vanadium™ nozzle.

The performance loss verified in the brass nozzle may be related to the natural wear of the component, which may have caused damage to its geometry and initial dimensions (diameter and output channel size) from the previous printing runs. Such damage can be caused by the loss of material due to friction with the print bed or by pressures generated by the polymer mass inside the nozzle or in the contact between layers.

Structural changes in the nozzle can affect the material flow and the mechanisms of polymer deformation in the extrusion die, thus having consequences on the dimensional and shape continuity of the deposited filaments. Variations in the morphology of the deposited filaments lead to the formation of random voids in the union zones, as well as the formation of weak bonds between neighboring filaments.

In addition, a considerable concentration of residual material adhered to the external walls of the nozzle was observed, a behavior that, most likely, should occur on the internal surfaces of the extrusion channel over time. These residues, in the printing cycles, undergo a process of thermal degradation. The degraded material can be transferred to the parts during printing, promoting the formation of failure points in the joints between deposited filaments.

The Vanadium™ nozzle, according to its manufacturer, has a repellent surface coating that prevents the accumulation of plastic residue, leaving the nozzle cleaner (Slice Engineering 2022). This differential factor may have contributed to the better mechanical properties of the parts printed with this nozzle in the “on the plane” condition, compared to those obtained with the hardened steel nozzle (MSF= 85.10 ± 2.05 MPa; FM= 3.01 ± 0.14 GPa) and, including a new brass nozzle (MSF= 87.39 ± 1.23 MPa; FM= 2.98 ± 0.07 GPa) - Figure 1(a) and Figure 1(b), black line (average values) and blue and red lines (positive and negative standard deviation, respectively).

The “on the plane” condition also allows the heat conducted by the printer bed to act for a longer time on the manufactured layers, guaranteeing energy and mobility for the polymer in the sintering process of the bonding lines between filaments and for the PLA crystallization process to occur more slowly and effectively. Bed temperature has been proven to help overcome the thermal limitations of hardened steel and Vanadium™ nozzles. In addition, the use of a raster angle of 45°/-45° leads to the deposition of small vectors, that is, filaments with shorter path lengths within the layers due to the dimensions of the flexural samples. Such strategy decreases time between depositions and increases the thermal energy use by the extruded material from the nozzle and bed temperatures. In this favorable environment, the low thermal conductivity of the nozzle can be advantageous, because when printing blocks of six samples, there is less energy dissipation in the empty transitions between parts.

However, it should be noted that PLA is a polymer with low melting (when semi-crystalline) and glass transition temperatures (thermal reference in which the layers must be for adhesion formation between them). Additionally, the PLA used may still have good fluidity at low extrusion temperatures. This set of good thermal and rheological properties may have contributed to the good performance of the hardened steel and Vanadium™ nozzles in the "on the plane" condition.

The lateral building orientation requires a greater influence of the nozzle temperature to drive the bonds between and within the layers. This happens because of the distance, as the parts "grow" in Z axis, from the layers closest to the top of the printed model to the heat source generated by the heated bed. In this situation, due to the higher thermal conductivity, the brass nozzle should be more efficient than the hardened steel and Vanadium™ nozzles. This behavior is confirmed when analyzing the results of MFS and FM, Figure 2(a) and Figure 2(b), obtained with the new brass nozzle.

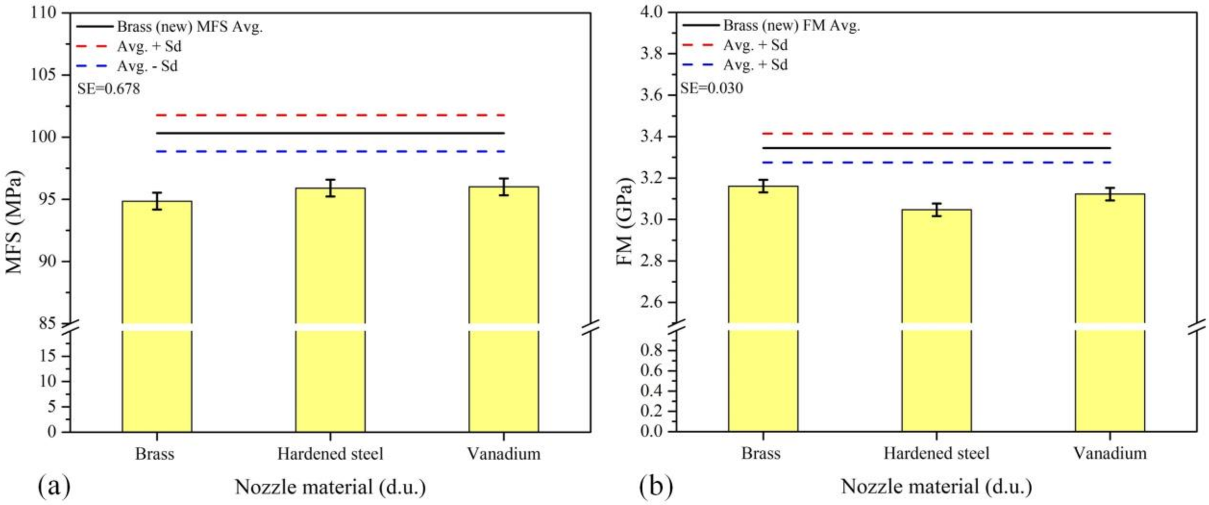

Figure 2: Average maximum flexural strength (MFS) (a) and flexural modulus (FM) (b) for lateral building orientation.

The maximum flexural strength (100.32± 1.45 MPa) of the parts built with the new brass nozzle was about 4% and 5% higher than the values generated by the samples in the Vanadium™ nozzles (96.01± 1.07 MPa) and hardened steel (95.91 ± 2.19 MPa). In the modulus (3.35±0.07 GPa), the percentage differences were 10% and 7% higher than the response of parts manufactured with hardened steel dies (3.05 ± 0.08 GPa) and Vanadium™ (3.12 ± 0.07 GPa).

Considering that the mechanical strength of FFF printed parts is related to meso-structural quality, any increase in the resistance to applied efforts and in the rigidity of the parts is the result of an improvement in the quality of the bonding between filaments, a reduction in the voids density and the proper processing of building material. As this is a study in which the printing parameters were kept fixed and the nozzle material was varied, it is possible to infer that in this condition the thermal conductivity of brass benefited the formation of the internal structure of the manufactured components.

The study with lateral building orientation also confirmed the functional wear of the brass nozzle with a long printing history. The analysis of variance (ANOVA, α=95%) show that the maximum flexural strength (F (2.14) =0.88, p=0.44) and flexural modulus (F (2.14) =3.67, p=0.06) were not affected by the nozzle material - Figure 2(a) and Figure 2(b) (yellow bars), respectively. There is statistical equality of the values of MFS (94.86±0.98 MPa) and FM (3.16 ± 0.05 GPa) between the parts made with the worn brass nozzle, the Vanadium™ nozzle, and the hardened steel nozzle ones. This situation opposes the scenario discussed in the previous comparison with the new brass nozzle responses, which were all superior than the ones found for the low thermal conductivity nozzles. Therefore, it is understood that functional wear can also affect the thermal energy deliver to the extruded/deposited.

The cubes for porosity measurement were built with 100% infill, that is, depositing as much material as possible to complete the volume of the part. It should be noted, however, that the parts in this filling configuration will not be massive, as natural voids of the layered structure will be present.

Parts made with a brass nozzle are even more porous (8.26 ± 0.22%) and less dense (1.17 ± 0.01 g/cm³) that those made with hardened steel (φ_{cube} = 6.32 ± 0.50% and ρ_{cube}= 1.17 ± 0.01 g/cm³) and vanadium (φ_{cube} = 5.43± 0.22% and ρ_{cube}= 1.21 ± 0.01 g/cm³) nozzles - Figure 3(a). Through this analysis, lower conductivity materials showed greater stability in the flow of deposited material, which allowed better-connected filaments and smaller voids between and within layers. With the new brass nozzle, Figure 3(b), the porosity (5.59 ± 0.10%) and density (1.21± 0.01 g/cm³) values were very close to those verified in the cubes produced with the Vanadium™ nozzle, indicating what may be the natural limit of void density for the porous structures constructed in this study. Therefore, the higher porosity and lower density verified in the parts produced with the long-use brass nozzle confirms the loss of its functional properties.

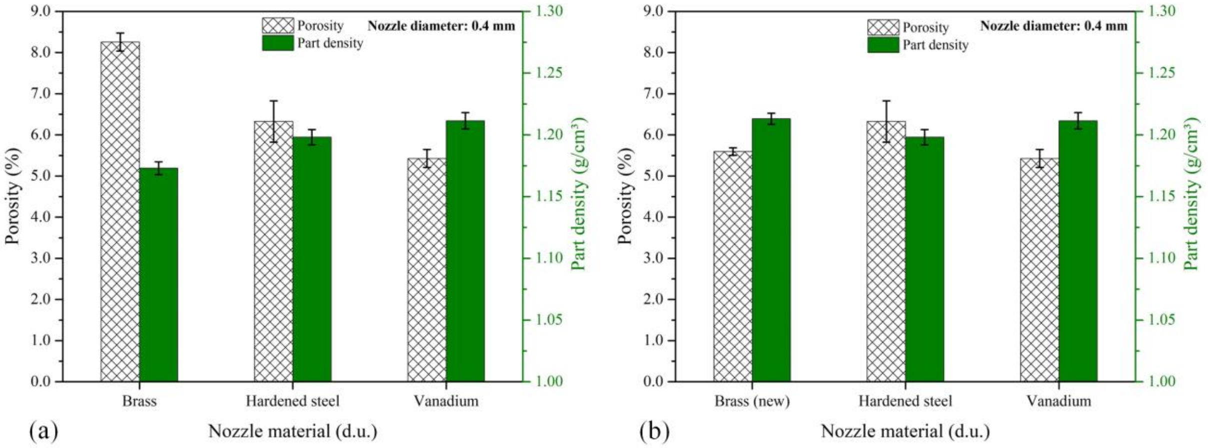

Figure 3: Porosity and density of cubes as a function of nozzle material: (a) worn brass nozzle and (b) new brass nozzle comparisons.

4. Conclusions

Brass nozzles are susceptible to functional wear. A previously used 0.4 mm brass nozzle did not behave according to theoretical expectations, that is, with better nozzle conductivity. This would provide better adhesion between and within the layers and, therefore, greater mechanical strength and less porosity. So, users should be warned about the period of good nozzle performance because it is concluded that the nozzles have a service life. In addition, the printing of unidirectional filaments, even in situations where the nozzle had lower thermal conductivity, generated better mechanical properties, respecting the assumptions of the load distribution relationship on the deposited filaments and not on the adhesion lines between and inside of the layers. However, it is noteworthy that the design for 3D printing must consider construction guidelines that favor as much as possible the heat conduction from the bed to the layers, including in unidirectional deposition conditions, since the steel and

Vanadium™ nozzles had its responses enhanced, compared to the others, in the "on the plane" condition with filaments at 45°/-45°. The PLA used in this study has good fluidity at low thermal level, which may have affected the thermal conductivity analysis of the nozzles. Future studies should test printing materials that require a higher extrusion temperature and with less fluidity at low temperatures.

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Acknowledgments

To LDPS-FEUP, to INEGI, and to LabMat-UFSC-Brazil. Ana Pais acknowledges the doctoral grant SFRH/BD/151362/2021 financed by the Portuguese Foundation for Science and Technology (FCT), Ministério da Ciência, Tecnologia e Ensino Superior (MCTES), with funds from State Budget (OE), European Social Fund (ESF) and Por Norte, under the MIT Portugal Program.