Vacuum components obtained by 3D printing using biodegradable plastic

Componentes de vácuo obtidos por impressão 3D usando plástico biodegradável

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ABSTRACT

This work investigated the behavior of vacuum components obtained by 3D printing using a biodegradable plastic called PLA (polylactic acid). This material was chosen because it has low cost and low environmental impact. The most used printing technique for this material is the fused filament fabrication (FFF) type. The vacuum components were obtained from the deposition of molten PLA filaments. However, traditional printing techniques are not optimized for vacuum behavior. Therefore, a unidirectional deposition method was developed, which significantly increased the performance. Furthermore, surface treatments were carried out to further enhance the results, making it possible to obtain vacuum components for operation in the 1 mbar range possible.

KEYWORDS: 3D printing, PLA, Vacuum components.

RESUMO

Neste trabalho, foi investigado o comportamento de componentes de vácuo obtidos por impressão 3D usando um plástico biodegradável conhecido como PLA (ácido polilático). Esse material foi escolhido por ter baixo custo e baixo impacto ambiental. A técnica de impressão mais utilizada para esse material é do tipo fabricação de filamento fundido (FFF). Isso significa que os componentes de vácuo foram obtidos a partir da deposição de filamentos fundidos de PLA. No entanto, as técnicas tradicionais de impressão não estão otimizadas para o comportamento em vácuo. Portanto, foi desenvolvido um método de deposição chamado unidirecional que incrementa significativamente o comportamento em vácuo. Além disso, foram realizados tratamentos superficiais que permitem incrementar ainda mais o resultado, tornando possível obter componentes de vácuo para operação na faixa de 1 mbar.

PALAVRAS-CHAVE: Impressão 3D, PLA, Componentes de vácuo.

INTRODUCTION

Polylactic acid (PLA) is a biodegradable polymer obtained from renewable sources and sold worldwide on a large scale. It is a safe material for human health and economically viable.[1] It also has many advantages for fused filament fabrication (FFF)-type 3D printers due to its low melting temperature (~ 180 °C). Therefore, several applications have been explored; however, the application as a material to form components of vacuum systems has been neglected so far. The use of descriptors fused deposition modeling (FDM)-type 3D printers PLA vacuum technology in Google Academic search reveals only 19 results, none related to developing parts and pieces for vacuum technology.

It is well known that additive synthesis facilitates prototyping and is now a standard process in scientific and industrial development laboratories. The use of 3D printing to obtain vacuum components presents difficulties regarding the outgassing and permeability of the parts; however, the low cost and great flexibility can be attractive,[2] especially in applications where the final pressure is around 1 mbar, which means the use of such parts and pieces in the low vacuum region, i.e., a region with fewer tightness requirements.

In some industrial applications such as vacuum food packaging,[3,4] the production of containers with thermal insulating walls,[5] the fixing and transport of parts and mechanical forming,[6] pressure between 0.1 and 1 mbar are commonly used.

Therefore, this work seeks to establish the main difficulties related to applying components obtained by 3-D printing for applications with pressures close to 1 mbar and developing a new production process with PLA for vacuum systems.

MATERIALS AND METHODS

In this work, blank flanges were produced in the KF-25 pattern of PLA using FFF-type 3D printing (Creality Ender 3 V2). They were produced in the usual manner, meaning no modification to printing factors, but also in the modified manner, which means optimization for vacuum behavior.

The flanges were printed using two different techniques. The first one is standard printing (called "braided" because of its appearance when observed under an optical microscope). This technique is optimized for mechanical resistance and printing time, but not for tightness.

Another printing technique was developed to increase the vacuum performance by bringing the printing filaments closer together and minimizing holes in the structure; the printing technique was optimized to fill voids. The printed filaments were deposited side by side in one direction. The proposed name for this method is the unidirectional printing technique. As a consequence of this method, the flanges were printed vertically, as seen in Fig. 1.

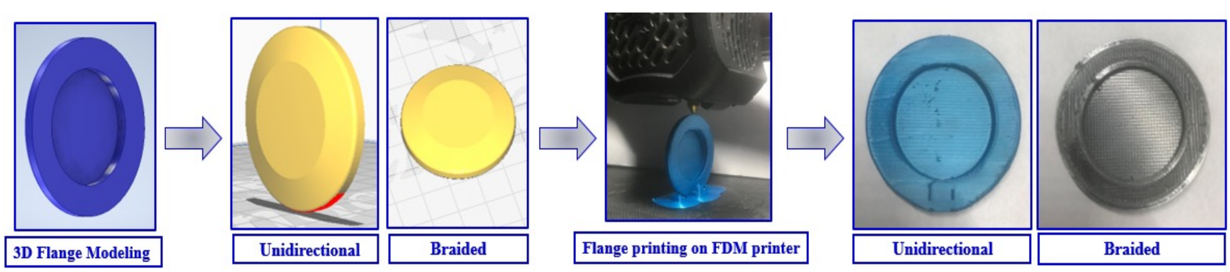

Figure 1: Flowchart of the proposed flange manufacturing sequence.

Source: Elaborated by the authors.

Some variations in the sample production processes were tested, always on flanges printed with the unidirectional technique. Samples were printed using three different casting nozzle diameters (0.4, 0.6, and 0.8 mm). Moreover, after printing, some surface treatments were tested. The first one was the mechanical polishing of flanges. Additionally, a thin layer (0.8 μm) of aluminium was deposited on the sample after mechanical polishing. A thermal evaporation technique was used to deposit an aluminium layer using Edwards Auto 306 evaporator equipment from Laboratório de Sistemas Integráveis, Universidade de São Paulo (LSI-USP).

All samples produced were analyzed under an optical microscope (Karl Zeiss Jeneval); this analysis allows us to observe each sample's surface characteristics. Some of these observations can be seen in the Figs. 2-5.

Finally, a test in a real situation was carried out. The flanges were used on real vacuum equipment. Edwards Auto 306 evaporator equipment from the LSI-USP was used again for this. The flange's tightness was tested by replacing an aluminium flange (the original part of the equipment) of this thermal evaporator. The behavior of pressure as a function of time was observed and the results are presented in Figs. 6-9.

RESULTS AND DISCUSSION

Due to the change in the part's growth method during printing and to compare the two manufacturing methods, both flanges (unidirectional and braided) were subjected to analysis under an optical microscope. Figures 2 and 3 present microscopic images of the braided and unidirectional flanges, respectively. There are significant and numerous pores in each layer of the braided flange (Fig. 2). These pores average approximately 170 μm. The flange obtained by the unidirectional technique has low porosity and only small non-uniformities due to the vertical growth of the flange (Fig. 3).

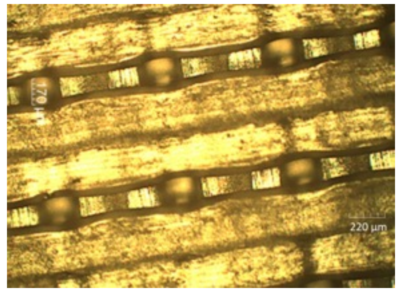

Figure 2: Microscopic image of the braided flange.
Source: Elaborated by the authors.

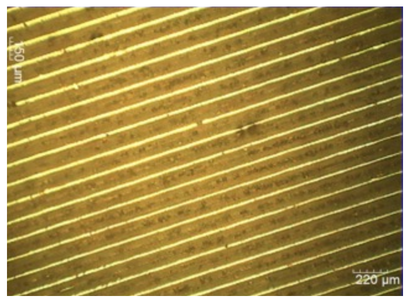

Figure 3: Microscopic image of the unidirectional flange.
Source: Elaborated by the authors.

The unidirectional flange even underwent a polishing process to improve its performance. Mechanical polishing is believed to improve the seal between the o-ring and the printed flange. There is also the known effect of reducing degassing by reducing of surface roughness. Both effects contribute to improved results.

Figure 4 shows a microscopic image of the sample surface after polishing. The surface improved because there was a reduction in non-uniformities. Figure 5 shows a KF-25 printed in 3D, using the unidirectional technique after a polishing process and coated with aluminium. This procedure allows for the most relevant results of this work.

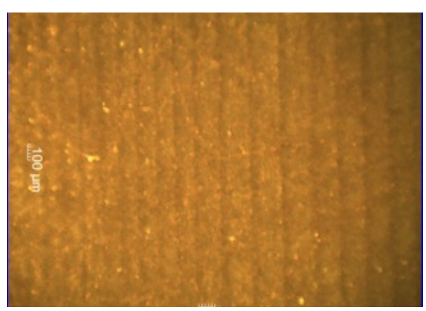

Figure 4: Surface sample after polishing. This procedure aims to improve contact between the surface and the o-ring.
Source: Elaborated by the authors.

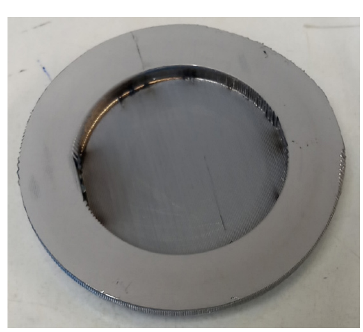

Figure 5: Image of KF-25 3D printed PLA blank flanges at the end of the manufacturing process. The unidirectional technique was used followed by surface polishing and aluminium coating.
Source: Elaborated by the authors.

The pressure in the vacuum system was observed as a function of pumping time, and the results are shown in Fig. 6. All these samples were printed with 0.4 mm of nozzle diameter. The unidirectional technique increased the pressure result and a polishing process increased the pressure result a little more.

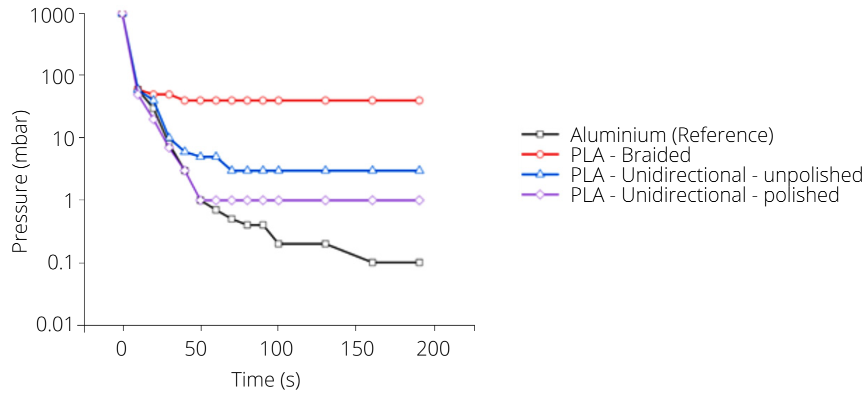

Figure 6: Pressure as a function of time for the different flanges obtained.

Source: Elaborated by the authors.

A performance study as a function of casting nozzle diameter can be seen in Fig. 7. Final pressure was obtained after 5 minutes of pumping, according to the nozzle diameter used to prepare the samples. Two sets of samples are shown. The difference lies in the surface. The first has polished PLA and the other has a layer (~ 0.8 μm) of Al.

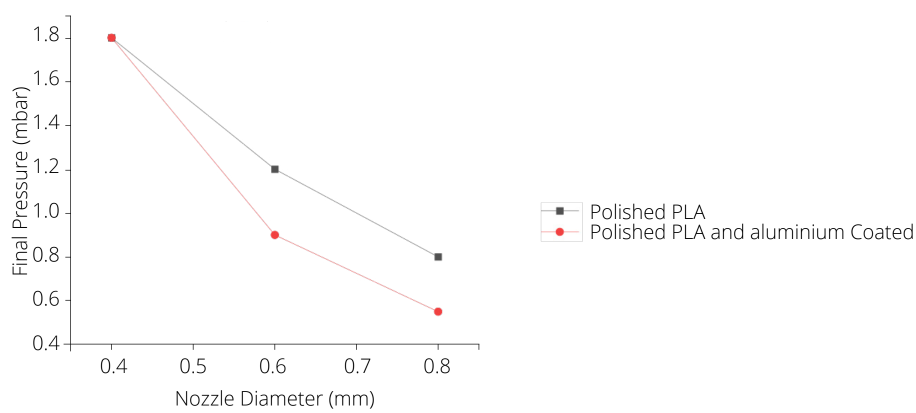

Figure 7: Performance study versus casting nozzle diameter.

Source: Elaborated by the authors.

The final pressure obtained with an aluminium commercial flange is used as a reference. The final pressure achieved is 10 times better with the unidirectional technique than the traditional (braided) printing technique. When polishing the unidirectional flange, the result was even better (Fig. 6). This is due to the reduction of surface roughness, which improves sealing with the o-ring.

Increasing the diameter of the casting nozzle improves the pressure result (Fig. 7). This indicates that with a larger diameter of the filament produced, the adhesion between the filaments could be greater, and the sealing of the part as a whole could be better, at least in the range analyzed.

Furthermore, it is also possible to observe that the aluminium coating does not present a significant difference in the behavior of the flange printed with a 0.4 mm nozzle; however, it allows even lower pressures to be obtained in samples printed with larger nozzles (0.6 and 0.8 mm), reaching 5.5 × 10-1 mbar in the best case.

The pressure variation as a function of pumping time for flanges obtained with different diameters of the casting nozzle can be observed in Fig. 8. These samples have been polished and have a thin aluminium layer (~ 0.8 μm). Final pressure levels can be noted for each case. Considering there is no pressure variation at these points, there is a different gas source for each flange type.

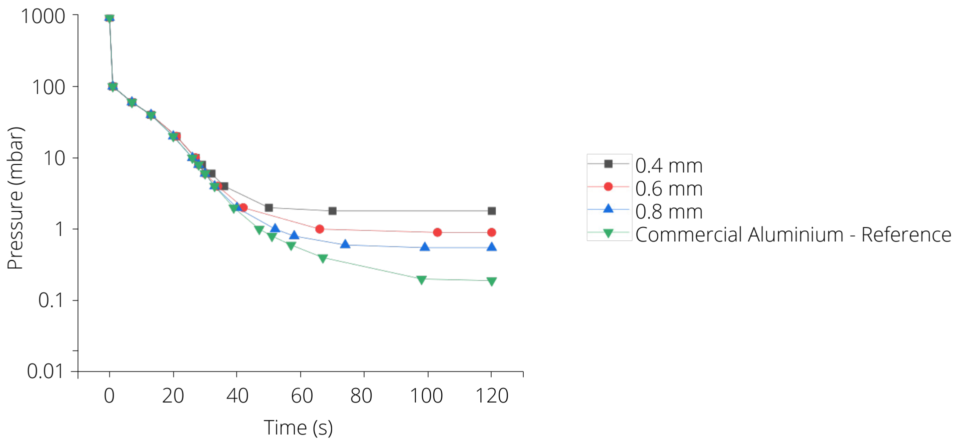

Figure 8: Pressure as a function of pumping time for flanges obtained by different nozzle diameters.

Source: Elaborated by the authors.

As all flanges have the same area and surface treatment (except the commercial KF-25), this indicates a gas source that permeates the surface of these flanges. As the throughput of this gas source decreases with the increase in the diameter of the casting nozzle, it is concluded that there are still small spaces between the filaments that make up the flanges.

A study of the pressure rise after stopping pumping allows an estimate of the system's total throughput. Figure 9 shows pressure as a function of time after the end of the pumping process for each type of flange. These data show that the pressure variation is about two orders of magnitude greater in the printed flanges compared to the commercial aluminium flange. The KF-25 3D was printed with different nozzle diameters, polished and coated with a thin layer of aluminium. The reference sample is a commercial aluminium KF-25.

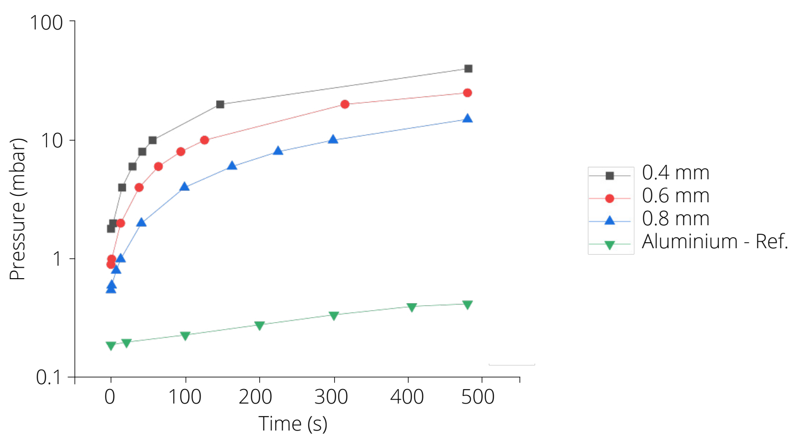

Figure 9: Pumping process.

Source: Elaborated by the authors.

The objective of printed materials is not to surpass the quality of traditional materials used in vacuum technology. The objective is to present a flexible and low-cost alternative. Knowledge of its characteristics makes it possible to select applications for which this is a viable alternative. The flanges presented in this paper allow working in the range of 1 mbar of final pressure as long as unidirectional printing, polishing, and metallization techniques are applied.

CONCLUSIONS

This work investigated obtaining vacuum components using FFF-type 3D printing with PLA filaments, a biodegradable material. PLA has many potential advantages, such as its compatibility with food and possible application as customized vacuum packaging. However, there are technological challenges to this.

The development of blind flanges made it possible to understand the behavior of this material in a vacuum. The traditional printing technique (braided) showed great difficulty in obtaining reduced pressures and observation of such pieces under an optical microscope, which identified pores of 170 μm. Such pores were reduced with the unidirectional printing technique, with no pores observed under the optical microscope. This development reduced the final pressure from 40 mbar (braided) to 4 mbar (unidirectional). Polishing such samples allowed for an even greater reduction in pressure.

Subsequently, different diameters of casting nozzles were tested. The increase in diameter resulted in lower pressures obtained as long as the flanges were polished. To increase the final pressure result, the samples underwent an aluminium coating process using a thermal evaporation technique with a thickness of 0.8 μm.

The best pressure result obtained was 5.5 × 10-1 mbar, with the printed flange with a 0.8 mm nozzle diameter polished and coated with aluminium.

This indicates that 3D printing of vacuum components using the presented methods can be used in applications with 1 mbar or greater end pressures. There are industrial applications for this pressure range, such as vacuum food packaging.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS'CONTRIBUTION

Conceptualization: Rangel RC; **Methodology:** Rangel RC, Degasperi FT; **Research:** Gulino HC; **Funding Acquisition:** Gulino HC; **Resources:** Rangel RC; **Supervision:** Degasperi FT; **Writing - First Draft:** Gulino HC; **Writing - Proofreading & Editing:** Rangel RC; **Final Approval:** Degasperi FT.

DATA AVAILABILITY STATEMENT

All dataset were generated or analyzed in the current study.

FUNDING

Nothing to declare.

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