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Dimensional accuracy of acrylonitrile butadiene styrene and polylactic acid samples printed in vacuum-assisted material extrusion system

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Abstract

This paper discusses the impact of integrating a vacuum system into a material extrusion 3D printing process for acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) materials. The study aimed to investigate the effect of a vacuum system on the dimensional accuracy of the printed samples. Upon completion of the printing process, the samples' dimensions were carefully assessed using a Coordinate Measuring Machine (CMM). The geometrical dimensions measured are the diameter, corner radius, fillet, thickness, width, length and angle. Based on the result obtained, the material has yet to reach 100% of the desired geometry, which was identified due to the shrinkage of the material after the printing process. The results show that the vacuum system improved material flow and reduced dimensional deviations by reducing air molecules and minimizing convection. The results indicated a significant enhancement in dimensional accuracy for both ABS and PLA samples when using the vacuum system. ABS samples showed a 4% increase in accuracy, while PLA samples exhibited a 2% improvement compared to samples printed without vacuum assistance. These improvements were achieved by optimizing process parameters such as layer height (0.15 mm), infill percentage (10%), printing speed (45 mm s^{-1}), and bed temperature (60 °C). These parameters were selected to ensure finer details, improved precision, structural support, stability, better adhesion, and reduced warping.

Nomenclature

FDM	Fused Deposition Modelling
AM	Additive Manufacturing
ABS	Acrylonitrile Butadiene Styrene
PLA	Polylactic Acid
CMM	Coordinate Measuring Machine
DA	Dimensional Accuracy
CAD	Computer-Aided Design
STL	Standard Triangle Language

1. Introduction

Additive manufacturing (AM) is a process that has entered our lives due to the insufficiency of old methods; it enables the computer-aided design of a three-dimensional model to be presented as a product [1–3]. In the AM procedure, a three-dimensional model is created utilizing the model data due to the material being deposited layer by layer [4]. The use of AM facilitates the expeditious production of components with intricate geometries, enabling enhanced design freedom and fostering opportunities for innovation [5]. The numerous advantages of 3D printing over traditional energy-intensive methods primarily account for its popularity. These advantages include the capability to produce intricate geometries as a single unit without any joints, reduced costs in terms of materials and labour, superior surface finish, decreased energy requirements, simplified processing with a single step involving CAD model creation, printing, and installation, near-net shape finishing, rapid production, and shorter lead times [6].

Fused Deposition Modeling (FDM) technique is a prominent method in 3D printing, accounting for over 40% of global systems [2]. The use of polymer-based material in the FDM process is widespread due to its accessibility and cost-effectiveness [7]. The raw ingredients that are often found include Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), Polycarbonate (PC), PC/ABS mix, epoxy, epoxy resins, polyamide (nylon), thermoset, and thermoplastic polyurethane. Thermoplastic polymers are used in material extrusion and powder bed melting processes. The powder bed melting technique in the material extrusion method is best suited for using complex thermoplastics and semi-crystalline polymers. Rigid thermoplastics, such as ABS and PLA, are characterized by their high-temperature resistance, attributed to their random molecular organization and relatively low melting point. Hence, the use of techniques such as FDM [8–10] enables efficient manipulation of viscosity across a broad range and facilitates rapid temperature control.

The FDM technique is influenced by several processing factors that impact the quality of the produced component, its mechanical characteristics, the time required for the build process, and the level of dimensional accuracy [11]. The FDM processing settings include air gap, orientation, infill %, raster angle, layer thickness, and more variables. The selection of process parameters must be conducted cautiously, considering the specific application for which the item was created [12]. Certain process factors have more significance in meeting specific output requirements than others. It is essential to identify and optimize these crucial process factors. As a result of this, scholars have conducted inquiries and used a range of experimental or statistical Design of Experiment (DOE) methodologies to enhance the mechanical characteristics and overall quality of the FDM process by optimizing its parameters [7, 13, 14].

It was found that the effect of process parameters on the accuracy of linear and radial dimensions of PLA parts produced with FDM was studied [13]. The study was aimed at how the layer's thickness, the raster's angle, and the orientation affect DA. It was discovered that the actual component size was smaller than the CAD model because the material shrank as it cooled after each layer was deposited. Due to cutting and squaring the edges, there was more error in the radial dimension than in the linear size [15].

In contrast, dimensioning errors develop when a component undergoes repeated iterations of shape and size modifications. Due to that, the internal and external diameters have wider margins of error compared to the liner dimensions [16]. Indeed, the design of the navigation template is also essential due to the loss of precision caused by parameter selection, material selection, or the accuracy of the STL file [17].

The effect of various FDM process settings on dimensional accuracy, surface quality, and mechanical qualities was examined [18]. The researchers concluded that layer thickness is a significant determinant of dimensional accuracy and one of the most studied variables in this area. In addition, low values for layer thickness, number of shells, and extrusion temperature allow the production of components with excellent dimensional accuracy [19]. More studies were required to determine the effect of several process parameters on dimensional accuracy, including infill pattern and raster width, on dimensional accuracy [20–22].

1.1. Vacuum technology

The term 'vacuum' originates from the Latin word 'vacua,' signifying 'empty.' Nonetheless, an actual space does not exist in the natural world. A vacuum is a space with reduced gas particles compared to its surrounding atmosphere [23]. In simpler terms, a vacuum refers to any area containing fewer gas particles, atoms, and molecules, resulting in lower particle density and gas pressure than the external atmosphere [24].

In contrast, a vacuum represents a void where matter particles are absent. In practical settings, achieving an absolute vacuum is unfeasible. Consequently, 'vacuum' refers to a space with gas pressure lower than atmospheric pressure. For instance, at 30 kPa, the typical atmospheric pressure results from constant collisions between air molecules. By reducing the number of air molecules, various research and industry applications can be realized [25].

Vacuum degrees span a broad spectrum, as illustrated in table 1. Molecules continually engage in energy transmission through collisions at specific atmospheric pressures. A higher molecule density facilitates energy transmission through more straightforward collisions. When molecules are closer together, they collide from all directions. However, reducing the quantity of air molecules leads to a diminished medium for energy transfer.

Table 1. Vacuum pressure range.

	Pressure range (mbar)
Rough vacuum	<1.013103−1
Medium vacuum	<1–10−3
High vacuum	<10−3–10−7
Ultrahigh vacuum	<10−7
Remark:	300 mbar (mount everest)
A new definition of beginning rough vacuum:	Lowest pressure on earth's surface

Modifications in vacuum pressure induce alterations in the physical characteristics of air, resulting in diverse effects on thermal behaviour [26]. Reduced air particle presence curtails heat loss via convection. A vacuum setup establishes an airless void within a confined space. As pressure increases, the molecule count decreases. In one atmosphere, molecules interact, exchanging energy. Energy readily shifts from denser to sparser molecules. Conversely, fewer air molecules mean a limited energy transfer medium. Consequently, shifts in air pressure's physical characteristics influence its thermal conduct [27–29].

Vacuum technology finds widespread use across diverse applications, industries, and research ventures. The capacity to generate a vacuum by eliminating air and fluid finds utility in processes like drying, food processing, die-casting, and resin infusion moulding [30]. A distinctive property of vacuum is reducing air molecules, thus curbing convection and impeding heat transfer between molecules [31]. Depending on vacuum intensity, heat retention can extend. Diminished air molecules within a chamber minimize thermal energy transfer through convection [32, 33]. Consequently, applying a vacuum with varying strength can reduce heat loss and maintain it over an extended duration [34, 35].

Studies show that a low-pressure environment where the convection process can be slowed down was produced using the vacuum-assisted FDM. Stronger bonds were formed significantly more effectively by the fusion of layers [36]. Removing the rapid cooling that led to tension and distortion is possible. Compared to non-vacuum bonding, the bonding formation between each layer resulting from the heat energy of semi-molten ABS material was more efficient and superior, increasing the dimensional accuracy of the samples [37].

2. Methodology

Figure 1 shows the dimensions of the sample. In figures 2 and 3, the specimen was crafted in a trapezoidal configuration, boasting a 25 mm width, a 10 mm diameter hole, a corner radius of 10 mm, and an elevation of 50 mm. The trapezoidal configuration was chosen as sample geometry as it fulfils all sketch features: fillet, chamfer, hole, parallelism, and flatness of sides. These features and properties are perfect for creating a complete dimensional accuracy measurement. The creation of the 3D model for the test samples was realized through Fusion 360 CAD software. Following this, the CAD data files were converted into STL format. The Ultimaker S2 FDM printer, an open-source platform, was harnessed to produce red ABS and black PLA materials. The properties of both ABS and PLA are tabulated in table 2.

In pursuing this research endeavour, an automated approach was embraced, upholding the paramount value of consistency. Sixteen samples were crafted, four at standard temperature conditions and four within a vacuum chamber for each material. The uniformity extended to maintaining identical layer heights, vacuum pressure levels, flow rates, printing temperatures, infill densities, and print speeds during printing.

The Ultimaker S2 FDM printer stands out for its impressive features that enhance its versatility and performance in additive manufacturing. With a generous maximum printing area, users can effortlessly craft larger and more intricate objects in a single print job, pushing the boundaries of creative design. The printer's advanced dual extrusion system empowers creators to experiment with multiple materials and colours, seamlessly blending them into their projects for enhanced visual and functional appeal. Flexibility in nozzle sizes allows for precision adjustments, catering to diverse printing requirements. Moreover, the printer's wide range of temperature settings for the extruder and heated print bed accommodates various filament materials, expanding the possibilities of material compatibility and application diversity. Including a heated build platform mitigates warping concerns and ensures secure adhesion, especially with materials prone to distortion. The Ultimaker S2 FDM printer amalgamates its spacious build area, dual extrusion capabilities, adaptable nozzles, temperature control, and heated bed to provide an adjustable and dependable platform for achieving exceptional 3D prints across various applications.

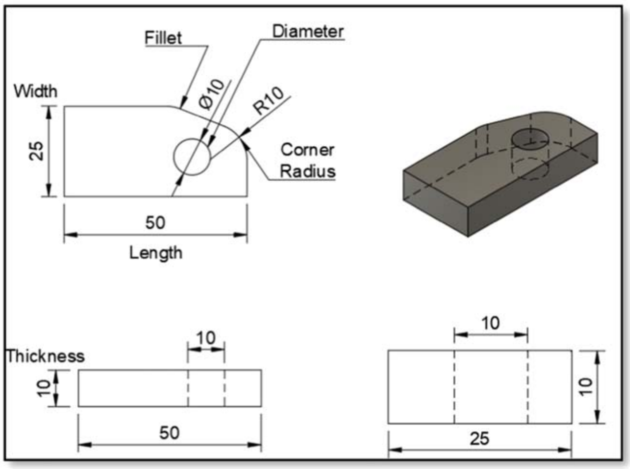

Figure 1. Dimensions of the sample.

Figure 2. Sample printed for ABS.

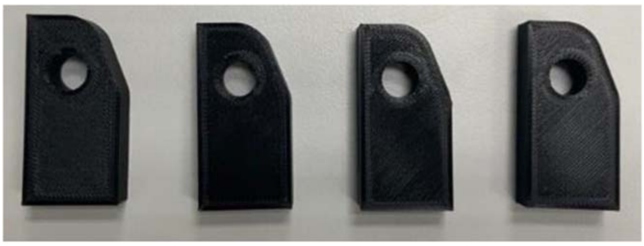

Figure 3. Sample printed for PLA.

Table 2. Properties of ABS & PLA.

Properties	ABS	PLA
Tensile strength	27 MPa	37 MPa
Elongation	3.5%–50%	6%
Flexural modulus	2.1–7.6 GPa	4 GPa
Density	1.0–1.4 g cm^{-3}	1.3 g cm^{-3}
Melting point	200 °C	173 °C

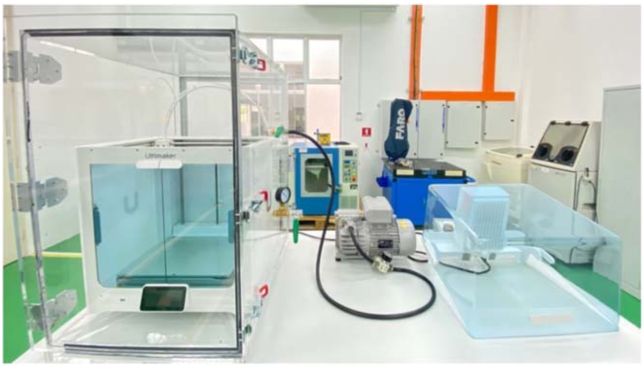

Figure 4. Experiment set up.

Table 3. Setting parameters ABS.

Parameters	Value
Infill percentage	10%
Infill pattern	Trihexagonal
Printing temperature	270.0
Bed temperature	60
Print speed	45.0 mm s^{-1}
Support angle	/ No support

Table 4. Setting parameters PLA.

Parameters	Value
Infill percentage	10%
Infill pattern	Trihexagonal
Printing temperature	215.0
Bed temperature	60
Print speed	45.0 mm s^{-1}
Support angle	90.0/No support

2.1. Experimental setup

The experimental configuration of the integrated 3D printing system with a vacuum setup is depicted in figure 4. The arrangement involves an acrylic rectangular enclosure, 12 mm thick, with internal dimensions measuring 350 × 390 × 400 mm. This enclosure securely encases the 3D printer, creating a controlled environment for experimentation, as shown in figure 4. Notably, at the time of the experiment, the thickest available acrylic wall thickness for this setup was 12 mm. The selection of the Ultimaker S2 printer for this endeavour was attributed to its compact size and suitability for the research objectives.

Two commonly used materials, Acrylonitrile Butadiene Styrene (ABS) and Polylactic Acid (PLA), were chosen for this study due to their compatibility with vacuum technology and their widespread acceptance and availability across various applications. The experimental design was thoughtfully devised to yield optimal outcomes. This design permits the manipulation of multiple inputs and levels to assess their impact on the response. In this investigation, the variables considered encompass vacuum pressure set at 20 kPa as a safety factor towards the vacuum chamber, layer thickness set at 0.15 as it gives the best surface finishing of the samples and the choice of material of ABS & PLA. Based on the findings, 20 kPa emerged as the optimal vacuum pressure. Higher vacuum pressure may be beneficial to improve the effect during the printing process. However, 20 kPa vacuum pressure was utilized to ensure the vacuum chamber was always safe. For safety considerations and to mitigate the potential effects of buckling failure within the vacuum chamber, a constant vacuum pressure of 20 kPa was upheld throughout the printing process. This controlled approach ensured consistent and reliable experimental conditions.

Table 5. Expected accuracy versus actual result.

Characteristics	Expected value	Actual value
Diameter	10	9.8782
Corner radius	10	9.5249
Fillet	10	9.7479
Thickness	10	9.5381
Width	25	24.0653
Length	50	48.9044
Angle	90°	89.693°

Table 6. Expected accuracy versus actual result.

Characteristics	Expected value	Actual value
Diameter	10	9.9692
Corner radius	10	9.9855
Fillet	10	10.2306
Thickness	10	10.1634
Width	25	24.9867
Length	50	49.9910
Angle	90°	89.955°

3. Results and discussion

The predetermined printing parameters for both ABS and PLS are shown in tables 3 and 4. Before the printing process starts, a pre-set parameter has been established for this project. This project guarantees that the filament used is consistent regarding material qualities rather than varying based on other factors. Achieving constant parameters is crucial for understanding how the materials will be printed within the specified constraints. The parameters were sliced and simulated using CURA software before printing to anticipate the printing duration and mitigate any unforeseen errors during the printing process of the different samples.

3.1. Data of ABS samples

Table 5 below shows the result obtained when the ABS sample was tested using a Coordinate Measuring Machine (CMM). CMM is a device that measures the geometry of physical objects by using a probe to sense discrete points on the object's surface. The sensor tracks and locates each axis. CMM was used to check the dimensions of the 3D printed models and determine their accuracy levels; such diameter was measured on the inner circle, and length and width were measured from one edge to another edge to get the dimensions. The table shows the expected accuracy and the actual result obtained.

The findings from the ABS sample printing experiments demonstrate an apparent disparity between the expected and actual values. The comparison between these values highlights a substantial range, with deviations falling within the +/− 0.5 mm range. For instance, when examining the curve and thickness of the part, the expected dimension is 9.5249 mm, while the actual size measures 9.5381 mm. These results indicate that achieving the correct dimensions for the position with ABS material poses significant challenges.

Next, to evaluate the precision of the test samples, the accuracy percentage was determined by comparing the actual values with the expected values. The outcomes indicate that none of the samples attained a perfect accuracy of 100%. The achieved percentage accuracy ranged within a range of +/−5% concerning the expected values, suggesting that there is potential for improvement to reach the desired level of accuracy. Nevertheless, the angle and diameter parts demonstrated a close approximation to 100% accuracy, with percentages of 99.66% and 98.78%, respectively. It is important to note that the ABS-printed samples exhibit variability, with some parts accurately printed while others show deviations from the expected values.

3.2. Data of ABS samples printed in vacuum

Table 6 presents the measurement results obtained from the CMM testing of the samples. The expected measurements are listed on the right side of the table, while the actual measurements were recorded using the CMM. Are shown on the left side. This table provides a clear comparison between the expected and existing data, allowing us to assess the accuracy of the printed parts.

The results obtained from printing ABS samples in a vacuum environment reveal promising findings, as the comparison between the expected and actual values indicates a high degree of proximity. The diameter, curve,

Table 7. Expected accuracy versus actual result.

Characteristics	Expected value	Actual value
Diameter	10	9.8732
Curve	10	9.4527
Fillet	10	10.2877
Thickness	10	9.9734
Width	25	24.6591
Length	50	49.5091
Angle	90	89.858

Table 8. Expected accuracy versus actual result.

Characteristics	Expected value	Actual value
Diameter	10	9.9096
Corner radius	10	10.3324
Fillet	10	9.6617
Thickness	10	10.1737
Width	25	24.7768
Length	50	49.8127
Angle	90°	89.868°

and length exhibit values that closely align with the desired measurements. A vacuum system significantly contributes to achieving dimensional accuracy for these specific parts.

The percentage accuracy for the test samples was within a tolerance range of +/−2% for achieving 100% accuracy, which indicates that none achieved perfect accuracy. However, most of the parts demonstrated a remarkable level of precision, with only a few exceptions. For instance, the fillet and thickness parts, which are 97.69% and 98.37%, deviated further from the expected values compared to other components.

3.3. Data of PLA samples

Table 7 presents the measurement results obtained from the CMM testing of the samples, with the expected measurement data listed on the right side and the corresponding actual data recorded using CMM on the left side.

The results obtained from printing PLA samples demonstrate a favourable outcome, as the comparison between the expected and actual values reveals a high level of closeness. The diameter, width, length, and angle exhibit values that closely align with the desired measurements. It indicates that PLA is suitable for achieving dimensional accuracy in these specific parts.

The percentage accuracy for the test samples, within a tolerance range of +/−3% for achieving 100% accuracy, reveals that none of the samples achieved perfect accuracy. However, most parts displayed a significant level of precision, with only a few exceptions. For instance, the curve, fillet, and thickness parts, which are 94.535%, 97.12%, and 97.85%, deviated further from the expected values compared to other components. These findings underscore the suitability of PLA for achieving dimensional accuracy in 3D printing applications.

3.4. Data of PLA samples printed in vacuum

Table 8 displays the measurement outcomes from the CMM testing of the samples, with the expected measurement data presented on the right side and the corresponding actual data recorded using CMM on the left side.

The results obtained from printing PLA samples in a vacuum environment exhibit a favourable outcome, as the comparison between the expected and actual values demonstrates a high level of proximity. The diameter, thickness, width, length, and angle closely align with the desired measurements. It indicates that a vacuum system significantly contributes to achieving dimensional accuracy in these parts.

The percentage accuracy for the test samples, within a tolerance range of +/−3% for achieving 100% accuracy, reveals that none of the samples achieved perfect accuracy. However, most parts showcased considerable precision, with only a few exceptions. For instance, the curve and fillet parts, which are 96.68% and 96.62%, deviated further from the expected values compared to other components. It underscores how the PLA material, when printed within a vacuum environment, contributes to minimizing deviations and enhancing overall precision.

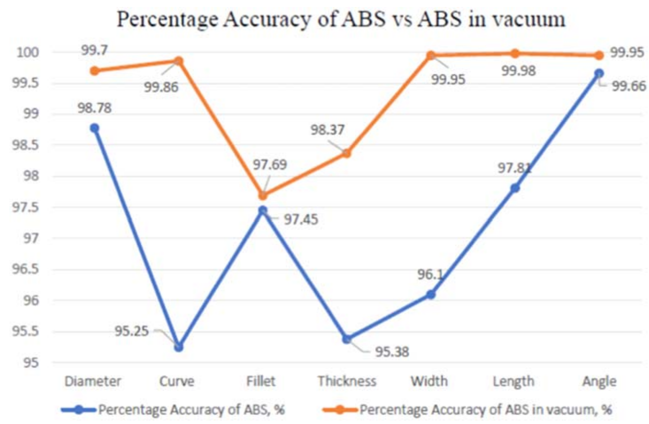

Figure 5. Percentage accuracy of ABS versus ABS in vacuum.

3.5. Improvement of ABS samples

The results obtained from comparing the ABS samples with and without vacuum assistance highlight a significant improvement in dimensional accuracy when vacuum technology is employed. Initially, the ABS samples printed without vacuum assistance exhibited a notably low accuracy percentage compared to the expected and actual values. However, an apparent enhancement in dimensional accuracy was observed when ABS printing was performed in a vacuum environment.

The difference in increased dimensional accuracy between the two becomes evident by analyzing figure 5, which depicts the ABS sample data and the ABS sample in a vacuum. The figure shows percentage accuracy in the *Y* axis versus the measured dimensional features or geometry in the *X* axis. The graph clearly illustrates that the ABS samples printed with vacuum assistance achieved higher dimensional accuracy levels than those printed without vacuum assistance. The improvement in dimensional accuracy of the ABS sample in a vacuum was approximately 4% when compared to the non-vacuum samples. It implies that the vacuum assistance positively impacted the printing process, improving dimensional precision.

The difference in increased dimensional accuracy between the two becomes evident by analyzing figure 5, which depicts the ABS sample data and the ABS sample in a vacuum. The graph clearly illustrates that the ABS samples printed with vacuum assistance achieved higher dimensional accuracy levels than those printed without vacuum assistance. The improvement in dimensional accuracy of the ABS sample in a vacuum was approximately 4% when compared to the non-vacuum samples. It implies that the vacuum assistance positively impacted the printing process, improving dimensional precision.

The response to vacuum assistance for ABS can be attributed to several factors. Firstly, the vacuum environment helps eliminate or minimize air presence during printing. It is crucial as air can cause warping, inconsistencies, or dimensional distortions in the ABS prints. By reducing the exposure to air, the vacuum system contributes to more stable and controlled printing conditions, leading to enhanced accuracy.

Additionally, the vacuum technology aids in controlling the cooling process of the ABS material. By regulating the cooling rate, the vacuum system helps prevent rapid or uneven cooling, leading to shrinkage and dimensional inaccuracies in the printed parts. The controlled cooling provided by the vacuum environment improves the overall dimensional stability and accuracy of the ABS prints.

Furthermore, vacuum assistance helps to mitigate the impact of external factors such as air currents or temperature variations. These factors can introduce variations in the printing environment, affecting the dimensional accuracy of ABS prints. By creating a controlled and stable environment, the vacuum system ensures consistent conditions throughout the printing process, improving precision.

3.6. Improvement of PLA samples

The comparison of PLA samples with and without vacuum assistance reveals a notable improvement in dimensional accuracy when utilizing vacuum technology. The data shows that both the PLA sample and the PLA sample in a vacuum environment exhibit similar values; however, the PLA in a vacuum demonstrates slightly higher dimensional accuracy.

Upon analyzing figure 6, representing the PLA sample data and the PLA sample in a vacuum, a slight difference in increased dimensional accuracy becomes apparent. The graph illustrates that the PLA samples printed with vacuum assistance achieved slightly higher dimensional accuracy levels than those printed without vacuum assistance. The improvement in dimensional accuracy for the PLA sample in a vacuum was

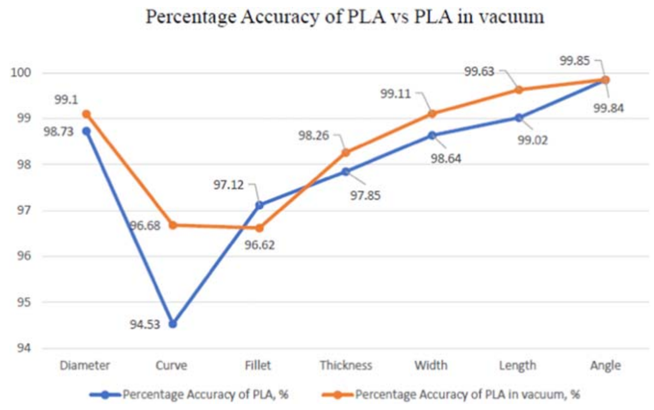

Figure 6. Percentage accuracy of PLA versus PLA in vacuum.

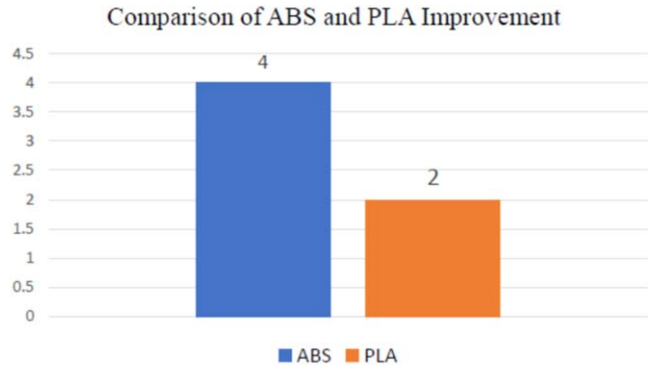

Figure 7. Comparison of ABS and PLA improvement.

approximately 2% compared to the non-vacuum samples. It indicates that the vacuum assistance had a positive impact on improving the precision of PLA prints.

The response to vacuum assistance for PLA can be attributed to several factors. Firstly, the vacuum environment reduces the presence of air during the printing process. By minimizing air exposure, the vacuum system helps prevent inconsistencies, warping, or other dimensional distortions in PLA prints. This controlled environment contributes to more accurate and reliable printing results.

Furthermore, vacuum assistance helps regulate and stabilize the cooling process of the PLA material. Controlled cooling is crucial in minimizing shrinkage and distortions that can affect the dimensional accuracy of printed parts. The vacuum system helps maintain a consistent and optimal cooling rate, improving dimensional stability in PLA prints.

Moreover, vacuum assistance helps mitigate the influence of external factors, such as air currents or temperature fluctuations, on the printing process. These factors can introduce variations and inconsistencies, affecting the dimensional accuracy of PLA prints. By creating a controlled and stable environment, the vacuum system ensures consistent conditions throughout the printing process, improving precision.

3.7. Comparison of ABS and PLA samples

When comparing the improvement achieved with and without vacuum for ABS and PLA materials, the graph indicates a 4% improvement for ABS and a 2% improvement for PLA. This discrepancy in advance can be attributed to the differences in the mechanical properties of ABS and PLA, as shown in figure 7.

As a result, the impact of vacuum assistance on PLA prints is less significant compared to ABS. PLA exhibits a lower sensitivity to environmental factors. PLA has lower temperature resistance and is generally more rigid compared to ABS. Its lower thermal expansion coefficient and rigidity make PLA less prone to warping and dimensional changes caused by temperature variations. Therefore, the improvement achieved with vacuum assistance is negligible at 2%. While vacuum assistance enhances dimensional accuracy by reducing air exposure and maintaining a controlled environment, the effect is less pronounced due to PLA's inherent properties.

4. Conclusion

In conclusion, this study effectively compared and evaluated ABS and PLA samples exposed to vacuum and atmospheric pressures. Leveraging the Ultimaker S2, an open-source FDM printer, in conjunction with a vacuum chamber set at 20 kPa, a unique printing environment was created by situating the printer within the vacuum chamber. The outcome of this setup shed light on the profound influence of vacuum pressure on the dimensional precision of printed specimens, notably by mitigating stress concentration and minimizing the effects of rapid temperature fluctuations. Notably, the most substantial enhancement in dimensional accuracy under vacuum pressure was observed in the ABS sample. This contrast was corroborated by measurements from the CMM machine, which highlighted the disparity between vacuum and atmospheric conditions. The vacuum system generates an environment devoid of air molecules, a space characterized by emptiness where molecule density diminishes with increasing pressure. Consequently, air pressure alterations distinctly affected the samples' thermal characteristics. These findings underscore several advantages associated with polymer printing in vacuum environments.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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