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The Influence of Printing Parameters on Leakage and Strength of Fused Deposition Modelling 3D Printed Parts

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ABSTRACT

Fused deposition modelling (FDM) 3D printing technology has become popular for producing prototypes and final parts in various industries, including the automotive, aerospace, and medical sectors. The leakage of such components is often an important factor in determining their possible applications. This paper focuses on researching the influence of printing parameters on leakage and relating the results to the strength of parts produced using this technology. The printing parameters considered were temperature and layer height. PLA (polylactic acid) was chosen as the material due to its biodegradability and biocompatibility. Leakage measurements were carried out using an empty cylinder-shaped vessel filled with air under pressure. The leakage value was observed as a pressure drop over time. It was shown that 3D-printed FDM vessels are not perfectly leak-proof, but the value of observed leakage may be acceptable for selected applications (leakage below 2.5 Pa/s). The results showed a high correlation between the height of the printed layer in both the leakage and strength of the tested samples, while reducing the height increased the tightness and strength of the 3D-printed parts. The effect of printing temperature was less significant.

Keywords: 3D printing, FDM, tightness, leakage, pneumatic.

INTRODUCTION

3D printing technology, also known as additive manufacturing (AM), has been a rapidly growing area in engineering and manufacturing in recent years. One of the most popular 3D printing processes is fused deposition modelling (FDM), characterized by its simplicity and accessibility of equipment or materials [1]. It is widely used in various fields, from hobby applications, prototypes, or finished parts, often in small series production [2]. It is based on adding successive layers of semi-fluid thermoplastic material on a working platform, transforming it into a solid form. The input material is rolled onto a spool and directed to an extruder, which supplies the appropriate volume of material to a movable printing head. At the end, there is a nozzle of a specific diameter through which the material is placed on the working platform. The working platform is then lowered by the layer height value so that another layer can be built on top of it. The process is repeated until the target element is obtained. Other versions of this technique can also be found on the market [3]. The technology (FDM) is characterized by creating a model without removing material, thereby reducing waste. Manufacturing costs are also reduced due to the lack of need for additional tools [4]. More complex shapes are also possible. Its main disadvantages include low efficiency, high surface roughness, or lower manufacturing accuracy than other methods [5].

A variety of materials are used depending on the application. However, the available materials are mainly limited to thermoplastics or their composites. Due to their thermomechanical properties and chemical resistance, some of the most popular include polycarbonate (PC), polylactic acid (PLA), polynylsulfone (PPSF or PPSU) or acrylonitrile-butadiene-styrene (ABS) [6]. However, polyethylene terephthalate glycol (PETG) and polyetheretherketone (PEEK) are less commonly used due to their higher melting point, which is difficult to achieve with this technology. In addition, many commercial extruders are limited to nozzle temperatures up to 300 °C [7]. Additional fibres can be used in the printed material to improve the properties of the parts being manufactured [8]. Among the various materials, PLA stands out for its possible biodegradable and bio-compatible properties. For this reason, it is used in medicine, packaging, containers, or automotive components [9, 10].

An FDM 3D printed model consists of two main parts: the inner structure (fill) and the outer wall [11]. Parameters such as the layer height, printing velocity, cooling rate, and temperature influence the model's final properties [12, 13]. The layer height most often varies in the range of 0.17–0.33 mm and affects the printing time of the part and the surface roughness [14]. The same is valid for velocity. In turn, the strength, weight, and time are strongly influenced by the degree and type of filling [15]. The triangular infill pattern is assumed to show the highest tensile strength, while the honeycomb shows the lowest [16].

An important issue related to printed components is their tightness. This issue is relevant to parts such as tanks, hydraulic and pneumatic elements, or vessels. Due to their multilayer form, printed models can be characterized by leakage. This is related to the fact that the extruded material for the new layer must merge with the previous one to form a coherent model. In this case, there must be interlayer pressure and a change of state of the already formed layer to semi-plastic again. With this technology, despite the circular printing nozzle cross-section through which the material is extruded, the resulting layer's cross-section is oval [17]. This causes discontinuities to form during printing in the form of gaps. Recommended operations that can improve the tightness include: increasing the thickness of the model walls, increasing the degree of filling, or applying a suitable coating to the model in the form of paint or epoxy resin. In the case of ABS, the surface can be smoothed with acetone vapour. During the printing process, a significant problem is ensuring a constant flow of material through the nozzle, which is only sometimes possible since the diameter of the filament along its length may have some variation. In this case, the flow rate can be increased above 100% to improve the tightness in the printing parameters. Stronger adhesion between layers will also occur at higher temperatures. However, increasing the temperature gradient may cause the print to crack due to higher interlayer stresses. The capability of increasing the tightness of vacuum parts due to changing the orientation of the polymer chains is described in [18].

Owing to the character of 3D models printed with FDM technology and the number of printing parameters [19], the problem of leakage is a complicated issue. To date, this topic has rarely been addressed in scientific publications. In this work, the tightness of models was investigated in the case of PLA, due to its universality. Different values of temperature and layer height were taken into account. In order to evaluate the correlation of leakage and interlayer adhesive forces for the studied parameters, strength tests were carried out.

PRINTER AND MATERIALS

For leakage and strength testing, PLA was chosen, with its properties presented in Table 1. An FDM printer called DDDBot with a working area of 200×200×270 was used for printing purposes. This printer was made by a Polish manufacturer. It has a closed working space and a heated table made of hardened glass.

The machine operates in a Cartesian system, where the printing head changes position in the X and Y direction, while the working platform is lowered along the Z direction. The printer had a closed working space. During printing, the temperature of the working platform was 70 °C, and inside the printer the temperature was 35–40 °C. The printing head used a nozzle with a diameter of 0.4 mm. The speed during printing was 15 mm/s, and the model was cooled using a fan.

MODELS AND TYPE OF TEST

The dimensions of the specimen for the leakage test are shown in Figure 1a. It takes the form

Table 1. Filament properties for material – manufacturer specifications (Fiberlogy, www.zadar.pl)

Material property, EASY PLA	Value
Density	1.24 g/cm^3
Filament diameter	1.75±0.02 mm
Melting temperature	155–160 °C
Recommended printing temperature	200–230 °C
Young's modulus	3500 MPa
Tensile strength R_m	53 MPa

of a cylindrical tank. There is a space in the center filled with compressed air. The tank ends with a hexagonal hole with a threaded metal nut. The purpose is to enable a reliable and tight connection in the measuring system, as plastic threads do not provide this. Parts with two wall thicknesses of t = 0.4 and 0.8 mm were printed, that is, with single and double the thickness of the printing nozzle. The area above the space was printed with an infill of 25% with a rectilinear pattern. The strength-tested component is shown in Figure 1b. The dimensions are based on the DIN EN ISO 527-2 standard, where guidelines for plastic specimens are presented. Due to the required clamping force in the testing machine, its length was increased to 95 mm. Additionally, a circular hollow section with a diameter of 6 mm is in the middle instead of a rectangular section. The wall thickness, in this case, was 0.8 mm. This type of geometry aimed to assess the adhesion force between the layers. It was also important that the movement of the printing head was similar to the one creating the model for leakage tests (circular movement).

In the case of the research performed, the parts were printed for four temperatures: 190, 200, 210, 220 °C and three layer heights: 0.1, 0.15, and 0.2 mm. Figure 2 shows the pneumatic scheme for the leakage measurement. The pressure source was a tank with a pressure of 200 kPa (2 bar). First, the airflow went through a valve and corresponding conduits. The pressure (p) in the system was measured using an electronic sensor. When the pressure in the specimen was about 200 kPa, the valve was closed, and the pressure drop rate over time was measured. The data was recorded on a computer using LabView software.

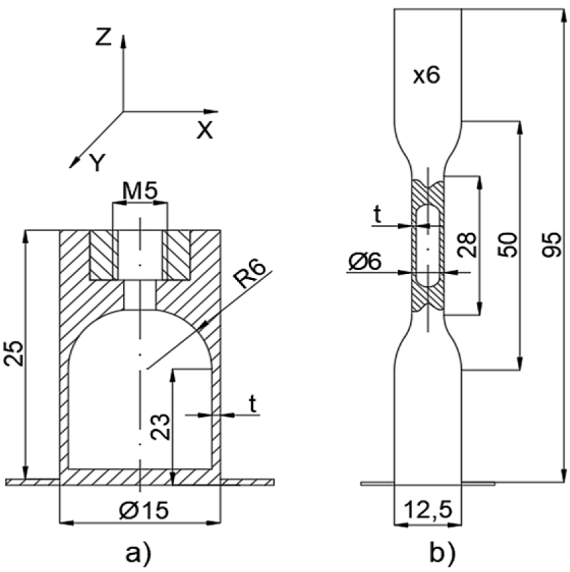

Fig. 1. Samples adopted for testing a) leakage tests; b) strength tests

RESULTS

Sample leakage test results are presented in Figure 3 and represent the change in pressure over time. The pressure decrease is related to the

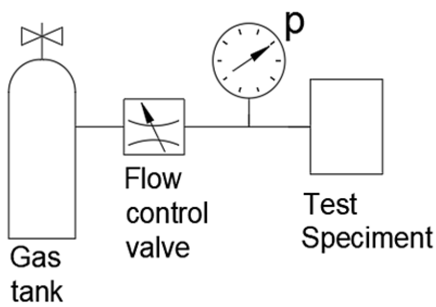

Fig. 2. Pneumatic diagram of the leak measurement system

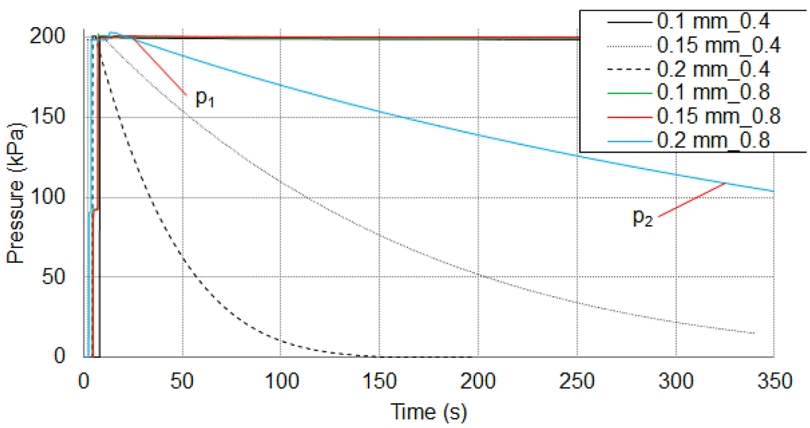

Fig. 3. Leakage test results for 200 °C, different layer heights and wall thicknesses (t)

leakage. The decrease has the character of a gradual drop in value, which is close to linear. Meanwhile, with elements characterized by higher leakage, the decrease is exponential. The leakage parameter was defined as the ratio of the difference in pressure to time:

$$L = \frac{p_1 - p_2}{t} \tag{1}$$

where: L – leakage parameter;
t – time.

For most measurements, the time interval was 300 s. It was shorter if the measured pressure dropped quickly to 0 Pa. An example is the measurement for a layer height of 0.2 mm and a wall thickness of 0.4 mm, where a value of 0 Pa was obtained for about 150 s. Measured by the presented method, the leakage of the pneumatic system alone without the printed part was 0.001 kPa/s.

Leakage measurement results for tank thicknesses t = 0.4 and 0.8 mm are presented in Figure 4 and Figure 5, respectively. There is a notable influence of layer height on leakage values. For a thickness of 0.8 mm and a layer of 0.1 and 0.15 mm for different temperatures, the average leakage values were about 1.3 Pa/s. However, the leakage was no higher than 1.8 Pa/s. A larger layer thickness of 0.2 mm resulted in about 31 times more leakage. For a wall thickness of 0.4 mm, we obtained leaks for the 0.1, 0.15, and 0.2 mm layers of 1.3, 152, and 38 times higher, respectively. There is no clear trend in the case of an increase in temperature for the 0.1 and 0.15 mm layer. There is an increasing trend only for the 0.2 mm layer. The obtained results suggest that the layer height has a more significant influence on the leakage value than the printing temperature. In turn, the obtained leakage values allow printing components to be used in pneumatic systems. For example, for a pneumatic actuator, the leakage between the piston and piston rod can be about 6 Pa/s [20].

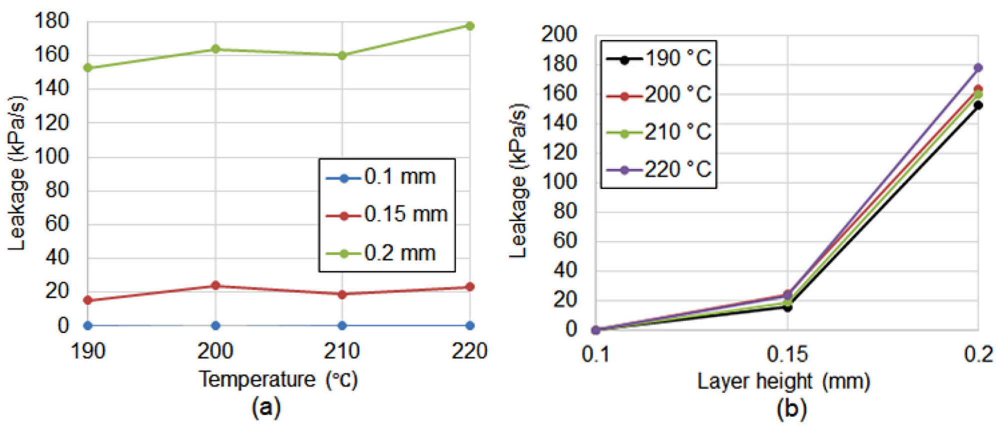

Fig. 4. Leakage results for wall thickness t = 0.4 mm (a) different temperatures for different layer heights; (b) different layer heights for different temperatures

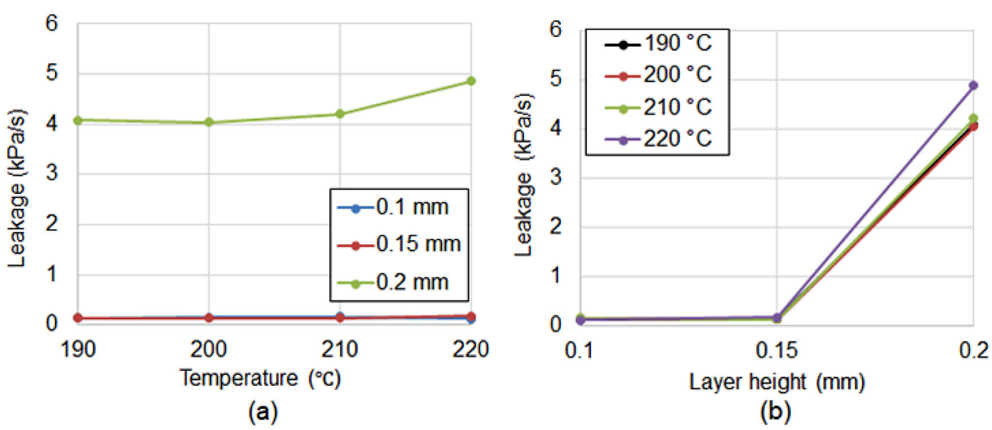

Fig. 5. Leakage results for wall thickness t = 0.8 mm (a) different temperatures for different layer heights; (b) different layer heights for different temperatures

The location of the leak is also essential. Measurements of this type were made using a printed model submerged in water. Photographs from such tests are shown in Figure 6, printed at 200 °C and different wall thicknesses and layer heights. Similar results were observed for other temperatures. Leakage was observed as air bubbles on the outer wall of the specimen. The intensity of the leakage is consistent with the results presented earlier. No significant leakage was observed for wall thickness t = 0.8 mm for layer heights of 0.1 and 0.15 mm. For t = 0.4 mm, this was the case only for a layer height of 0.1 mm. Visible leakage was observed for the remaining cases. The highest leakage is seen primarily for heights above 23 mm in Figure 1a. This is where the geometry of a cylinder shape ends, and the semicircular shape with a radius of 6 mm and the model filling begins.

In the case of printed specimens during repeated tests, the results are not always reproducible. Table 2 shows the parameters' variability considering different layer height values. An increase in layer height results in a higher variability. However, the trend is the opposite in the case of wall thickness. A notable case is the layer height of 0.2 mm for t = 0.8 mm, where the highest variability was obtained. This is because the sample of this type showed some level of leakage, unlike the 0.4 mm wall thickness, where leakage occurred very quickly and can be assumed to be entirely unsealed.

Table 2. Variability of leakage values

Layer height [mm]	Tank thickness t = 0.4 mm	Tank thickness t = 0.8 mm
0.1	± 37%	± 11%
0.15	± 42%	± 24%
0.2	± 45%	± 90%

STRENGTH TESTING

The mechanical properties of the printed specimens were obtained using an MTS Acumen 3 testing machine. Specimen shape and dimensions are shown in Figure 1b. A specimen was clamped in the jaws in Figure 7a and axially stretched at a displacement rate of 1 mm/s until breaking in Figure 7b. The test result was the maximum force recorded during the test. Three specimens were tested for each combination of parameters: printing temperature and layer height. The mean values of strength were calculated and used in further analysis.

The results are summarised in the form of graphs as a function of maximum force versus printing temperature in Figure 8a and printed layer height in Figure 8b. In the case of layer height, the general trend in the strength of the samples reflects a trend that was previously observed for leakage tests in Figure 4b and Figure 5b. The smaller the layer height, the higher the strength (tightness). At the same time, there is a clear decrease for the 0.2 mm layer, which is also

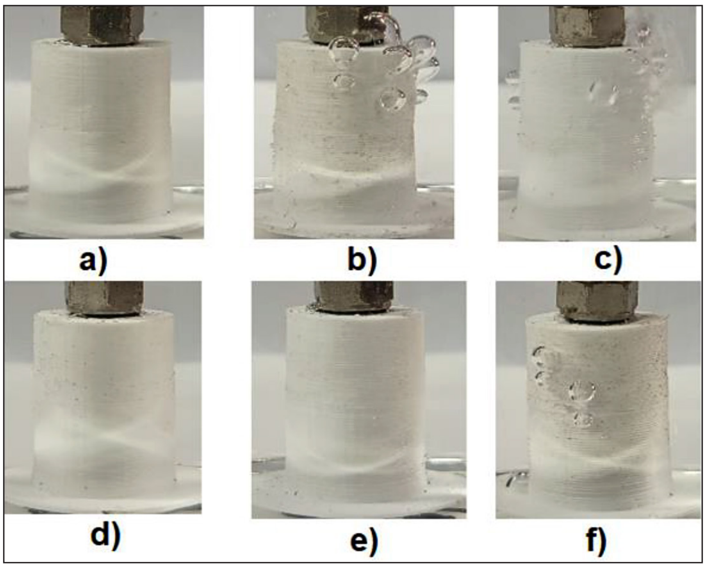

Fig. 6. Measurement of leakage for 200 °C for different wall thicknesses and different layer heights a) t = 0.4 mm, 0.1 mm, b) t = 0.4 mm, 0.15 mm, c) t = 0.4 mm, 0.2 mm, d) t = 0.8 mm, 0.1 mm, e) t = 0.8 mm, 0.15 mm, f) t = 0.8 mm, 0.2 mm

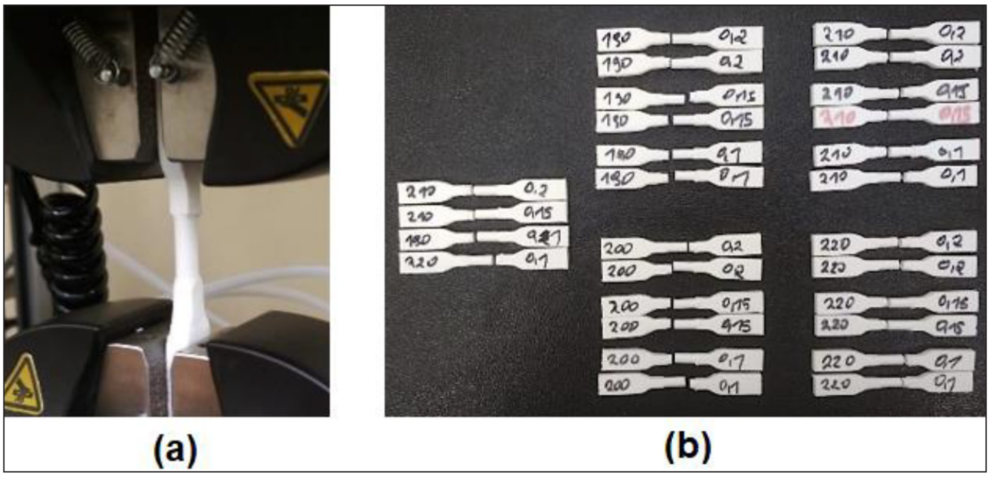

Fig. 7. Tensile strength test: a) specimen clamped in the testing machine, b) selected specimens after breaking

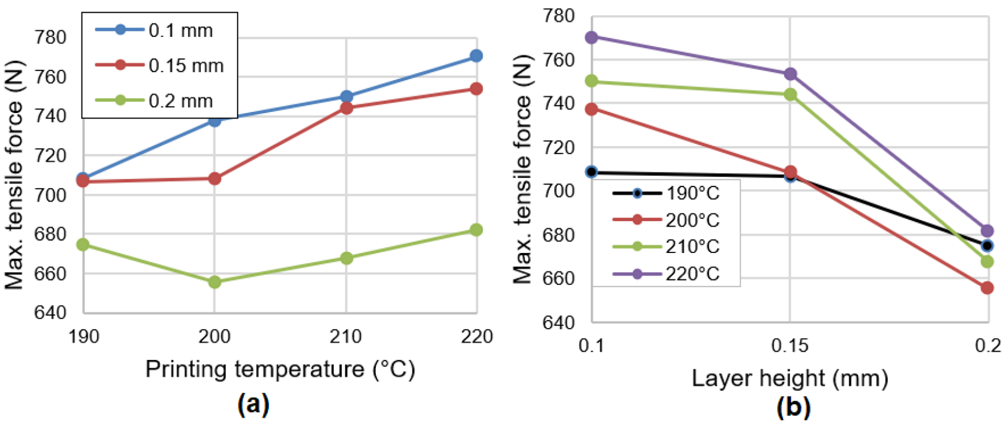

Fig. 8. Maximum tensile test force obtained for the specimens as a function of: a) printing temperature, b) thickness of a single layer

consistent with the leakage measurement results. In contrast, an increase in temperature for layer height of 0.1 and 0.15 mm increases strength (Fig. 8a). However, the increase is no greater than 10% at 190 °C and 220 °C. For samples printed with a 0.2 mm layer, no significant correlation between strength and printing temperature was found.

The general conclusion from the tensile tests is that the effect of layer height on the tensile strength of the specimens is dominant. At the same time, the printing temperature has less influence on the value (0.2 mm). The similar strength results for the 0.15 mm and 0.1 mm layer heights suggest that when a 0.2 mm layer is used, there is a significant deterioration in the quality of the printed structure.

CONCLUSIONS

This paper presents the results of leakage tests and adhesion force between printed layers. The results showed that layer height has a greater influence on leakage and strength than printing temperature. This may be related to the fact that a lower height means that the layers adhere to each other with a higher surface area. This corresponds to the known trend where model roughness decreases with decreasing layer height. Leakage, on the other hand, is caused by gaps between layers due to discontinuities in the material. At the same time, the printing temperature has less influence on leakage.

Better results in leakage tests were obtained by printing parts with a wall thickness of 0.8 mm than with 0.4 mm. In the case of the test specimens, the area most prone to leakage was the tank's closing spherical area, not the side walls of the model.

Leakage values of less than 2.5 Pa/s for the printed models can be considered a leakage criterion. However, in some applications, such as precision measuring instruments or vacuum systems, such a pressure drop may already be unacceptable.

Further studies could focus on the mass value of leakage or consider different materials.

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