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INFLUENCE OF EXTRUSION TEMPERATURE ON THE INTERLAYER ADHESION OF PLA AND TPU IN FDM TECHNOLOGY

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Abstract: This paper investigates the effect of extrusion temperature on the adhesion between polylactic acid (PLA) and thermoplastic polyurethane (TPU) in fused deposition modeling (FDM) technology. The study is motivated by the development of sensor-equipped insoles combining rigid and flexible materials to enable both structural support and sensor integration. The research aims to identify the optimal printing parameters, with particular attention to material compatibility and temperature settings, in order to ensure structural integrity and performance of multi-material printed components. Two TPU materials with Shore hardness ratings of 95A and 98A were tested at extrusion temperatures of 210 °C, 230 °C, and 250 °C. These results are intended to support the design and manufacturing of functional, wearable 3D printed products.

Keywords: FDM, 3D printing, PLA, TPU, adhesion, extrusion temperature.

1. INTRODUCTION

Additive manufacturing, or 3D printing, is one of the leading technologies in modern industry, distinguished by its ability to produce parts with complex geometrical shapes, as well as by its cost-effectiveness and high level of precision [1].

Significant progress has been made in the field of 3D printing, particularly in combining multiple different polymeric materials to achieve desired properties such as strength, wear resistance, elasticity, and more. The wide range of available materials on the market allows for their effective combination.

Polylactic acid (PLA) is one of the most popular thermoplastic materials in 3D printing, known for its biodegradability and mechanical resistance [2]. In contrast, thermoplastic

polyurethane (TPU) is used for fabricating parts that require properties such as elasticity and flexibility. By combining these materials, it becomes possible to produce functional parts with hybrid characteristics [3].

Obtaining such characteristics is most achieved using the Fused Deposition Modeling (FDM) method, the most widely used 3D printing technique. This technology enables the production of smaller and complex parts, which can be made from one or a combination of a couple of different materials. For this reason, special attention is given to adhesion, both between the printed materials themselves and between the first layer and the build surface [4].

When it comes to first-layer adhesion, the most influential parameters are:

- Bed temperature (heating the bed improves adhesion by preventing rapid cooling and shrinkage of the material);
- Bed leveling and first-layer settings (proper leveling ensures better contact between the filament and the build surface) [5].

The most important factors influencing inter-layer adhesion are:

- Extruder temperature (ensures proper melting of the filament and its bonding with the previous layer);
- Printing speed and cooling (slower printing allows for better layer bonding, while excessive cooling can solidify the layer too quickly and weaken the bond);
- Material type (different materials have different adhesion properties);
- Environmental factors (ambient temperature, drafts, and air humidity can affect adhesion, especially for materials that require high printing temperatures) [6].

Poor bed adhesion can lead to warping, shifting, and complete print failure, while poor inter-layer adhesion results in delamination, low mechanical strength, and structural defects [6].

In the research [7], methods for determining the best printing parameters for interlayer adhesion are presented in the case of PC/ABS polymers. Print speed and layer height are considered the most significant parameters, as bond strength shows an inversely proportional relationship with print speed. The negative influence of high print speed can be observed from several aspects. The most significant aspect is the reduction of print accuracy and the distortion of the printing pattern, which leads to poor quality of bonded layers and may also result from an uneven temperature gradient between successive layers. On the other hand, low print speed promotes layer fusion and allows for better bonding of the subsequent layer, thereby improving bond strength. The second printing parameter that individually affects bond strength is layer height, and its behavior shows similarities with print speed. As the layer height increases, bond strength gradually decreases, because

increased layer height introduces gaps, meaning there is unwanted porosity within the specimen. These gaps are key factors that prevent rasters from properly adhering to each other. If lower layer height values are used, the gaps occur to a lesser extent, and there is a higher likelihood of strong interlayer adhesion. It has been proven that an infill density of around 85% and a low print speed of 20 mm/s are the most favorable printing conditions for achieving high bond strength. Conversely, maximum infill density combined with maximum print speed leads to the lowest bond strength values. This can be explained by the fact that at 100% infill density, there is a higher likelihood of stress accumulation due to restricted heat transfer, requiring the printed part more time to dissipate heat. If there is a minimal air gap in the print pattern, it can serve as a space for more efficient heat transfer [7].

This paper presents the effect of temperature on the adhesion between two materials, PLA and TPU, in FDM technology.

2. FUSED DEPOSITION MODELING (FDM)

FDM or Fused Deposition Modeling technology is one of the most widespread methods of 3D printing. This technology is based on the extrusion process of polymer materials. A thermoplastic material, in the form of a filament, is heated to its melting point and extruded through a nozzle with a diameter ranging from 0.1 to 2 mm, then deposited layer by layer onto the build surface, forming the final product in the shape of a three-dimensional object [8].

The advantage of this technology lies in the wide range of materials that can be used, such as PLA, ABS, TPU, and others, which enable product properties, ranging from rigidity and flexibility to resistance to chemical and mechanical influences. FDM is the leading 3D printing technology in experimental research due to its low cost, availability, and ease of use. Nozzle temperature, print speed, and layer thickness are the key parameters that must be adjusted appropriately in order for the final

product to achieve the desired quality and dimensional accuracy [9].

3. EXPERIMENTAL RESEARCH

The experimental research aimed to examine the adhesion between two different materials produced using FDM technology, through the creation of insoles with sensors designed to collect gait data. The insole consists of PLA material in which force-sensitive resistors (FSRs) are embedded, while TPU material is printed above the sensors to enhance comfort, as shown in Figure 1.



Figure 1. Sensoring insole fabricated from two materials: rigid PLA material (white part), and softer-elastic material TPU (black part)

The 3D printer used for sample fabrication was the Prusa Mk3 (Czech Republic), with one print head. Material changing was provided with a pause in the G-code, and the material was manually replaced. Adhesion testing was conducted on an Instron 34SC-2 universal testing machine (USA), with the data collection and processing supported by Bluehill Universal software. To ensure adequate precision and safety during the testing process, a custom fixture was designed. Its role was to hold the samples in the machine's standard flat grips. The fixture utilized metal pins for efficient force transfer from the machine to the samples, as shown in Figure 2.

Since standard adhesion tests are typically performed under shear stress—which is not present in the case of sensor-equipped insoles—a specially designed sample shape was used for testing. These samples were designed to evaluate material adhesion in 3D printing under conditions relevant to the actual use of the insoles. The sample dimensions are shown in Figure 3.

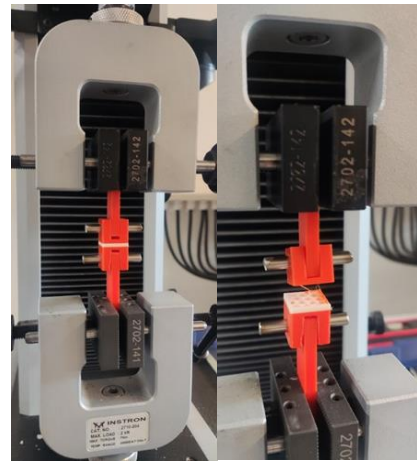


Figure 2. Specimen before and after testing on the Instron universal testing machine

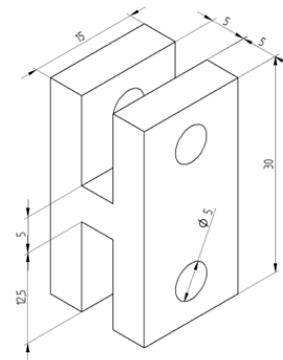


Figure 3. Dimensions of the specimens

3.1 Two different materials adhesion test

Two TPU materials from the manufacturer AzureFilm (Slovenia), with different hardness levels of 95A (softer) and 98A (harder) according to the Shore hardness scale, were used to fabricate 3D-printed insoles with sensors, and both were tested. The adhesion of TPU to PLA was tested for both hardness levels at varying temperature settings: 210°C, 230°C, and 250°C. In Figure 4, specimens for adhesion testing are presented, where white zones represent TPU material, and the orange zones are PLA.

For each temperature, three samples were produced and subsequently tested on a tensile testing machine. All specimens were printed with the same printing parameters (except nozzle temperatures): bed temperature 50 °C, printing speed 40mm/s, and layer thickness 0.2 mm.

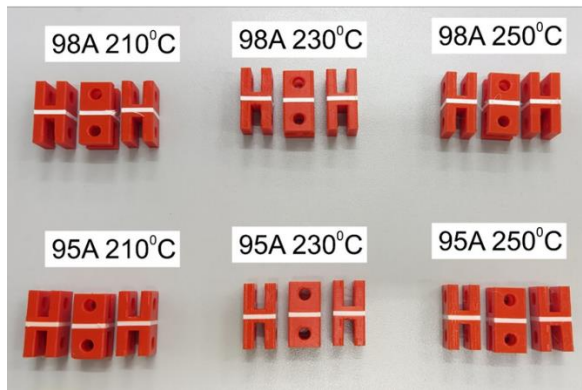


Figure 4. Testing specimens

The initial test results conducted at a temperature of 210 °C for the series of samples made from TPU materials with hardness levels of 98A and 95A are presented in Figure 5.

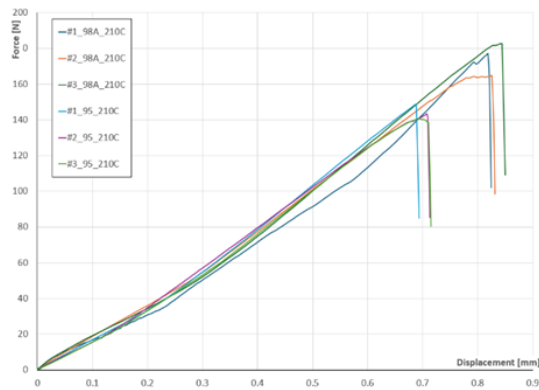


Figure 5. Diagram tensile test for determination of the maximal force for layer separation for temperature 210°C

From the data shown, it can be concluded that the samples made from TPU with a hardness of 98A exhibit better adhesion properties, with an average layer separation force of 174 N, compared to 144 N for the 95A samples. The results indicate that the more rigid material demonstrates stronger interlayer bonding.

In Figure 6, the study was conducted at a temperature of 230 °C, where a decrease in the required force for layer separation was observed for the more rigid TPU material, with a value of approximately 74 N. Meanwhile, the softer TPU material maintained a similar value, with an average separation force of 148 N, compared to the previous test.

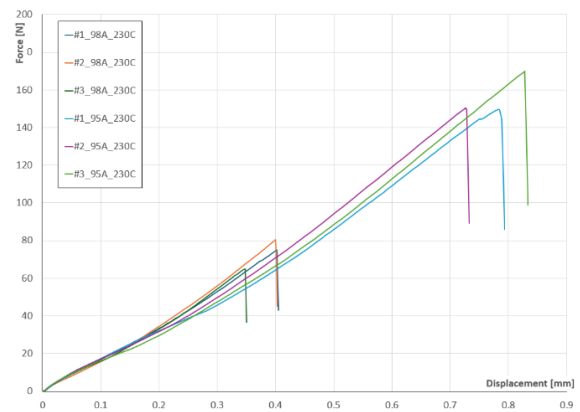


Figure 6. Diagram tensile test for determination of the maximal force for layer separation for temperature 230°C

An increase in temperature to 250 °C for the softer TPU material indicates stability in the layer separation force, with a value of 151 N, while the TPU material with a hardness of 98A shows lower force values of around 84 N compared to the initial temperature of 210 °C (Figure 7).



Figure 7. Diagram tensile test for determination of the maximal force for layer separation for temperature 250°C

Figures 8 and 9 show the layer separation force diagrams as a function of temperature for each hardness level of the TPU material. In Figure 8, the results are combined, and an identical trend can be observed in the curves for all three temperature values.

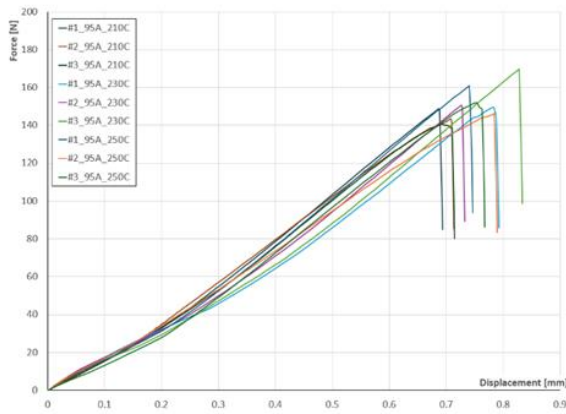


Figure 8. Layer separation force diagrams for TPU material, 95A hardness for temperatures 210°C, 230°C, and 250°C

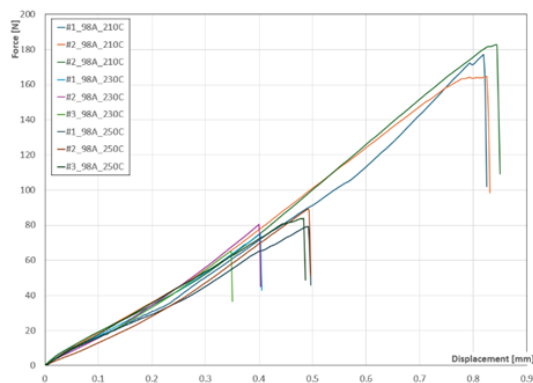


Figure 9. Layer separation force diagrams for TPU material, 98A hardness for temperatures 210°C, 230°C, and 250°C

Figure 9 highlights the behavior of the TPU material with a hardness of 98A, showing a sharp drop in separation force with increasing temperature.

4. CONCLUSION

Adjusting the optimal temperature parameters is essential in the production of sensor-equipped insoles to.

ensure their protection from damage during use. The temperature setting is directly dependent on the desired hardness level of the thermoplastic polyurethane (TPU).

The TPU material with a hardness of 98A demonstrates sensitivity to temperature changes during the 3D printing process, with the best results observed at a temperature of 210 °C. Printing below this temperature is not acceptable due to the material's inability to melt and flow through the nozzle, which leads to extruder head clogging and potential

damage. On the other hand, the TPU material with a hardness of 95A allows for a wider range of temperature processing, as it does not show significant variations in separation force at different temperatures.

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