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Effect of Technological Parameters on the Mechanical Properties of Test Specimens Produced by Polyjet Technology

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Abstract

The expansion of additive manufacturing technologies enables the rapid and efficient production of parts with complex geometries, making them increasingly important in the production of functional prototypes and finished products. To ensure the reliable performance of these parts, it is essential to optimize the printing parameters and analyze the material properties of the printed parts. In this study, the thermomechanical properties of 3D printed test specimens produced by PolyJet technology were analysed, with a particular focus on the glass transition temperature and the loss factor. The investigation concentrated on the influence of printing orientation and layer thickness, as these key parameters affect the mechanical behaviour of the finished parts.

Keywords: *additive manufacturing, PolyJet technology, thermomechanical properties, layer thickness.*

1. Introduction

The mechanical properties of test specimens produced using PolyJet technology, such as tensile strength, elongation at break, and elastic modulus, significantly depend on the printing orientation and layer thickness. Tensile tests indicate that variations in printing direction and layer thickness fundamentally influence the mechanical behavior of the test specimens. Additionally, printing orientation affects hardness and glass transition temperature. Dynamic mechanical thermal analysis (DMTA) tests show that the values of complex elastic modulus and loss factor are orientation-dependent. [1] Furthermore, mechanical differences between various materials can also be observed, which change depending on printing parameters, facilitating the fine-tuning of properties required for specific applications.

1.1. Effect of printing orientation on mechanical properties

During the investigation of the mechanical properties of test specimens manufactured using the PolyJet process, the authors determined that the material exhibits anisotropic behavior. Their study found that within the same plane, changes in orientation did not result in significant differences in the elastic modulus. However, when comparing different build planes, tensile strength and elongation at break showed substantial variations. It was observed that specimens printed in a vertical orientation exhibited increased tensile strength but decreased elongation at break, whereas specimens printed in a horizontal orientation displayed the opposite trend. Changing the layer thickness did not affect the results for horizontally printed specimens but had an impact on the mechanical properties of vertically printed ones. In configurations parallel to the build direction, tensile strength significantly decreased compared to other orientations, reinforcing the anisotropic nature of the material [2].

A separate study using bending tests reached similar conclusions when comparing test specimens produced with different printing orientations. The results showed that specimens manufactured in the Y direction exhibited the highest flexural strength. For rigid materials, the lowest values were observed in the Z direction, whereas for more flexible materials, the lowest flexural strength was recorded in the X direction. Examination of the flexural modulus indicated that the Y orientation yielded more favorable results compared to the X direction, while in the Z direction, the modulus decreased with increasing material flexibility [3].

1.2. The effect of printing orientation and layer thickness on the glass transition temperature

The aim of the research was to investigate the viscoelastic and thermomechanical properties of test specimens printed using PolyJet technology under different printing parameters. In the first experiment, the researchers examined the effect of layer thickness and printing orientation on the glass transition temperature. According to the results, the highest glass transition temperature was observed in the X orientation, while the lowest was in the Y orientation, with a difference of approximately 20°C. Printing with a greater layer thickness resulted in a higher glass transition temperature [4].

1.3. Effect of material quality and printing orientation on the complex elastic modulus and loss factor

In this study, the variation of the complex elastic modulus of PolyJet-manufactured specimens was investigated as a function of in-plane orientation and testing configuration. The results showed no significant difference between horizontal and vertical printing; however, tensile testing yielded higher dynamic modulus values, while bending tests exhibited a higher loss factor. Additionally, the complex modulus and loss factor of different materials were examined. For stiffer materials, the elastic modulus varied by three orders of magnitude with increasing frequency, whereas for more flexible materials, this change was more than fourfold [5, 6].

Based on the reviewed literature sources, it is possible to identify the parameters that influence the mechanical properties of the manufactured parts. The studies clearly indicate that different printing orientations and layer thickness settings affect the mechanical characteristics of the test specimens. Additionally, the quality of the material used plays a key role in the obtained results.

2. Materials and methods

The aim of the present study is to investigate the glass transition temperature of the specimens printed using the PolyJet process, taking into account different layer thicknesses and printing orientations. In the experiment, the material quality remains constant, and its effect is not examined in the article.

2.1. Test specimens

The test specimens were printed in three different orientations: XYZ (A), XZY (B), ZXY (C) (Fig. 1).

The research results showed that printing orientation influenced the mechanical properties; however, the effect of further in-plane arrangements was negligible. The classification and naming of the test specimens are shown in Table 1. The layer thickness can be adjusted in parallel with the printing speed, so the chosen settings were (High Speed: HS) and (High Quality: HQ.

For the DMTA tests, rectangular specimens are required, and their dimensions were selected based on the measurement fixture used. The determined dimensions are 35×10×3 mm. The modeling of the specimens and their export to STL format were performed using Autodesk Fusion 360 software.

Table 1. *Grouping and naming of test specimens*

Orientation	High speed (HS)	High Quality (HQ)
XYZ (A)	HSA	HQA
XZY (B)	HSB	HQB
ZXY (C)	HSC	HQC

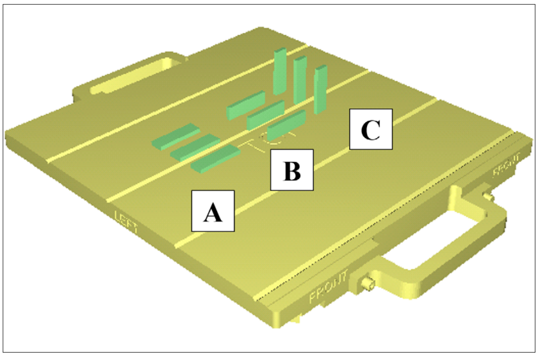

Fig. 1. *Test specimen arrangement in the Objet Studio slicing software*

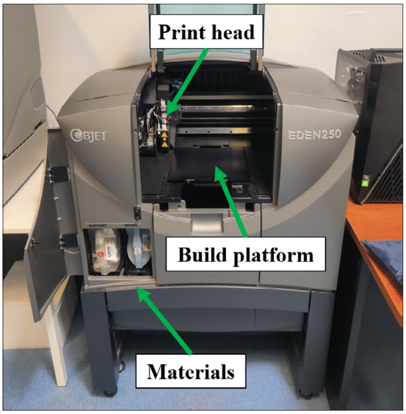

Fig. 2. *Objet Eden 250 PolyJet 3D printer*

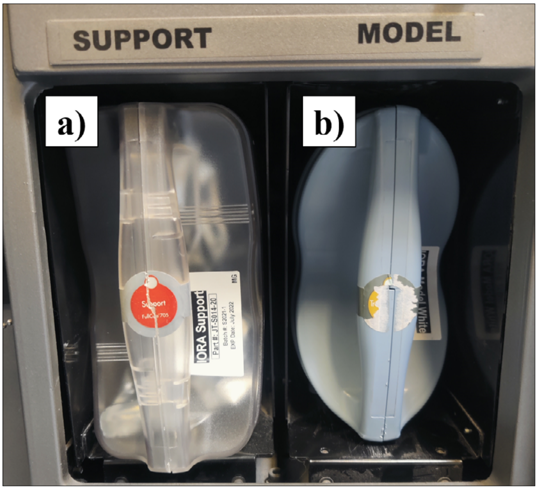

Fig. 3. *Materials in the PolyJet printer: a) support material and b) model material*

Table 2. *Mechanical properties of IORA Model White RGD835 material* **[1]**

Properties	Value	Standard
Tensile modulus	2000–3000 MPa	ASTM D638
Tensile strength	50–65 MPa	ASTM D638
Elongation at break	13–24%	ASTM D638
Impact strength (IZOD, notched, A 23°C)	20–30 J/mm^2	ASTM D256
Flexural strength	75–110 MPa	ASTM D790
Flexural modulus	2200–3200 MPa	ASTM D790
Deflection temperature (HDT) @ 0,45 MPa	46–51 °C	ASTM D648
Deflection temperature (HDT) @ 1,82 MPa	46–51 °C	ASTM D648
Glass transition temperature (Tg)	52–54 °C	ASTM D4065

2.2. PolyJet 3D printing machine

The test specimens were manufactured using a Stratasys Eden 250 PolyJet 3D printer (Fig. 2). The 3D printer used in this study can process two different types of materials: one for the model and one for the support. The printer's build platform measures 250×250 mm, with a maximum usable printing volume of 200 mm in the Z direction. Its resolution is 600 dpi along the X-axis, 300 dpi along the Y-axis, and 1600 dpi along the Z-axis [7].

2.3. Materials

The printing materials are IORA Support 705 for the support structure and IORA Model White RGD835 for the model material (Fig. 3) [8, 9].

The applied IORA Support 705 material provides excellent stability to ensure that the models maintain their shape and integrity throughout the entire printing process. With the support material, it is easy to create complex and intricate geometries. After printing is completed, the support material can be easily removed using a water jet, ensuring a clean and flawless final result [8].

IORA Model RGD835 materials are versatile and reliable 3D printing materials that belong to the PolyJet photopolymer family and are widely used across various industries. They offer high opacity and tensile strength, making them ideal for producing models that require fine details, such as various casings, fasteners, and prototypes. The high resolution of the PolyJet process ensures that printed parts are extremely precise and have excellent surface quality, which is particularly important for end-use products and precision components. These materials are an ideal choice not only for functional prototypes but also for the production of final products with impeccable aesthetic quality. The key properties of the model material are summarized in Table 2 [9].

2.4. Manufacturing specimens

In high-quality (HS) mode, the layer thickness of the printed test specimens was 16 μm. The specimens were surrounded by support material from all directions. The total printing time was 4 hours and 40 minutes. In high-quality (HQ) mode, the layer thickness was 29 μm, so the software divided the entire print into 1215 layers, with a total manufacturing time of 2 hours and 40 minutes (Fig. 4). The finished test specimens can be easily removed from the build platform using a specialized tool, and the surrounding support material can be washed away with a water jet. The manufactured test specimens are shown in Fig. 5.

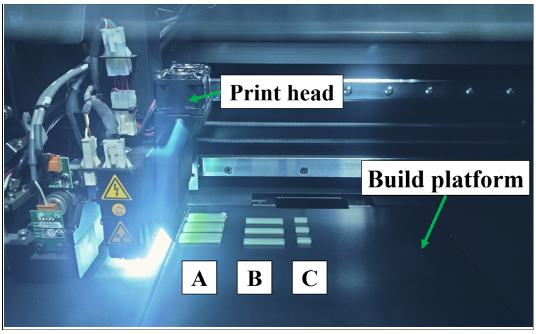

Fig. 4. *Objet Eden 250 during the printing process.*

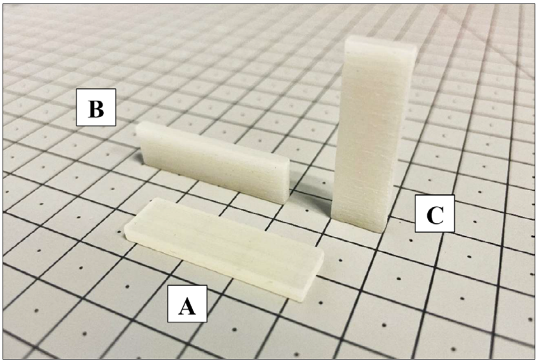

Fig. 5. *The finished specimens after cleaning.*

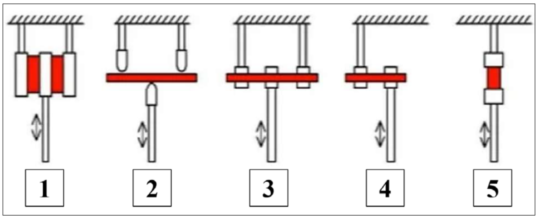

Fig. 6. *DMTA measurement modes: 1) shear; 2) three-point bending; 3) dual cantilever; 4) single cantilever; 5) tension/compression.* [10]

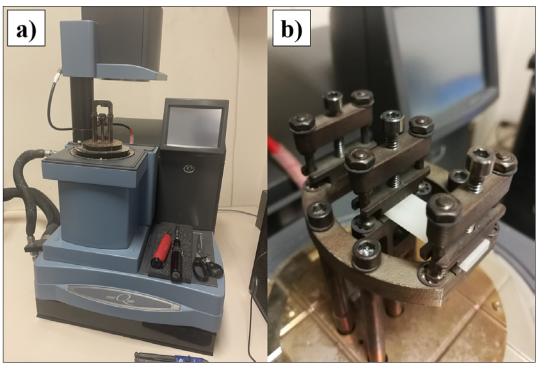

Fig. 7. *Measuring equipment: a) TA DMTA Q800 and b) fixed test specimen*

After printing, in the case of the PolyJet process, there is no need for post-curing of the test specimens, unlike traditional photopolymerization methods.

3. Testing method

Polymers are often subjected to dynamic loads. Therefore, it is important to understand their behavior under periodic, repetitive loading as well. In DMTA tests, the stress applied to the test specimen and its frequency are kept constant. The temperature is changed in a defined manner (usually at a constant rate over time), and the resulting deformation is measured. Based on these, the mechanical properties of the polymer can be determined. The material testing was conducted on a TA DMTA Q800 device, with a single-sided grip (Fig. 6/4) [1, 10].

The test specimen, with dimensions of 35×10×3 mm, was secured in two screw grips with a torque of approximately 1 Nm (**7. ábra**). The distance between the two grips was 17.2 mm.

During the DMTA measurement, one end of the test specimen is fixed, while the other is oscillated with a constant amplitude at different frequencies, while the temperature is gradually increased. Before the actual test, preliminary measurements were used to determine the most suitable experimental setup parameters (amplitude, frequency range, temperature range). In our case, the ideal oscillation amplitude was 10 μm. The temperature range was set from 40 to 90°C, with heating occurring in 2°C steps and a 1-minute temperature hold. The test specimen was oscillated at 11 frequencies between 1 and 21 Hz in linear 2 Hz at each temperature.

4. Results

The six different test specimens (orientation A, B, C, as well as HS and HQ settings) were measured individually according to the procedure described above. This study focuses on the glass transition temperature and the loss factor, so these data were primarily presented.

4.1. Frequency dependence of the glass transition temperature

Based on the measurement data, for each frequency, the maximum Tan(δ) value and the corresponding temperature must be determined. These temperature values were recorded in a table for each test specimen and frequency, and then averaged for the three different orientations of the test specimens. The analysis had to be per-

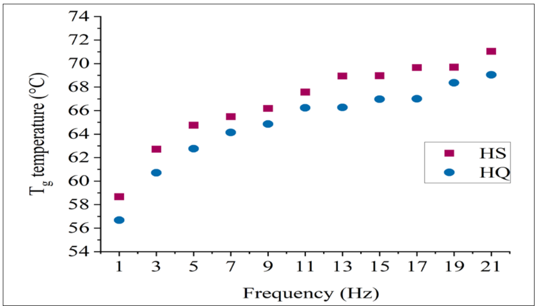

Fig. 8. *Frequency dependence of the glass transition temperature.*

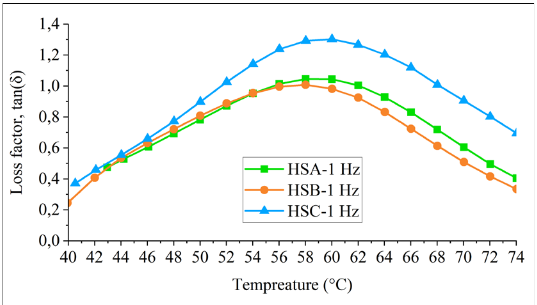

Fig. 9. *Loss factor curves as a function of temperature in the high-speed setting.*

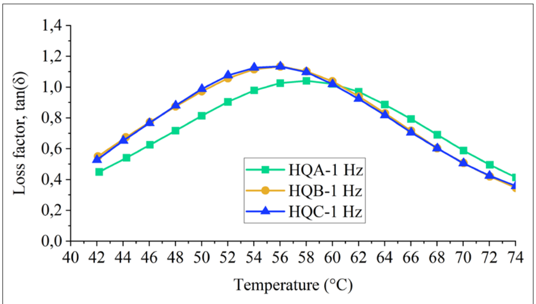

Fig. 10. *Loss factor curves as a function of temperature in the high-quality setting.*

formed for both printing settings (HS and HQ). The results are shown in **Fig. 8.**

The diagram shows that the glass transition temperature (Tg) changes as a function of the excitation frequency. With an increase in frequency, the glass transition temperature of the material increased, which was observed for both printing settings, whether in high speed or high-quality mode. Furthermore, the glass transition temperature of the test specimens produced in high speed mode was approximately 2°C higher than that of the high-quality test specimens.

4.2. Effect of printing orientation on the glass transition temperature

The measurement data can be used to plot the Tan(δ) curves for each test specimen at a frequency of 1 Hz. As shown in **Fig. 9, 10.** for both settings, there is a slight but noticeable difference in the tan(δ) peaks for the test specimens with different orientations, which causes a shift in the glass transition temperatures. The lowest values in the high-speed printing setting are observed in the „A" orientation, while the highest values are found in the „C" orientation test specimens.

4.3. Effect of printing settings on the glass transition temperature

Examining the effect of printing settings on the glass transition temperature, it can be observed that in the „A" orientation, the printing settings have no impact at any frequency (**Fig. 11**).

However, in the „B" orientation, a difference between the two settings can be observed. The glass transition temperature (T_g) of the high-quality specimen is 2°C lower (**Fig. 12**).

A similar but slightly larger difference can be observed in the „C" orientation, where the glass transition temperature (Tg) of the specimen printed with the high-quality setting is 4°C higher (**Fig. 13**).

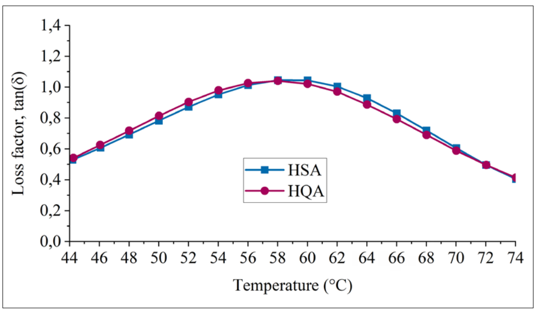

Fig. 11. *Loss factor distribution at 1 Hz Frequency: „A" orientation.*

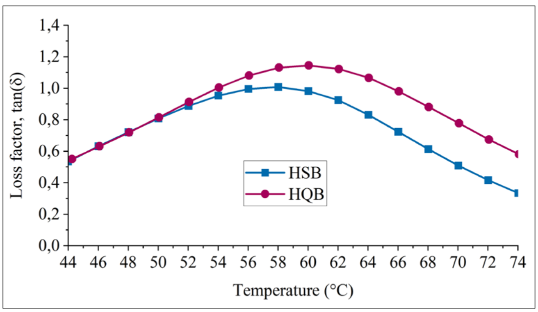

Fig. 12. *Loss factor distribution at 1 Hz Frequency: „B" orientation.*

This trend in the values can be observed at both low and higher frequencies.

4.4. Effect of printing settings and orientation on the loss factor

From the temperature-loss factor diagrams, it can be observed that the tan(δ) curves differ not only along the temperature axis but also in their peak values. The loss factor is the ratio of the lost energy to the elastically stored energy. The following diagrams indicate that there are differences in the tan(δ) peak values depending on both the printing orientations and printing settings (**Fig. 14** and **15**).

The test specimens printed in the „C" arrangement exhibit the highest tan(δ) peak values (least elastic), while those printed in the „A" arrangement have the lowest values (most elastic). The frequency has a slight influence on the tan(δ) peak values. Comparing the printing settings, it can be observed that the high-quality specimens have lower variability in their values. Based on the measurements, it can be concluded that the printing orientation and layer thickness affect the thermomechanical properties of the test specimens. The testing frequency shifts the glass transition temperature towards higher temperatures. The influence of printing orientation has a slight effect on the glass transition temperature, but no clear trend is observed in the results. When comparing the printing settings, it is evident that, except for the „A" arrangement, the high-quality specimens generally exhibit lower glass transition temperatures. Examining the loss factor peak values, the lowest values are found in the „A" arrangements, while the highest values are observed in the „C" test specimens. Based on the obtained results, it can be concluded that the printed products exhibit anisotropic properties.

5. Conclusions

The research examined the mechanical properties of test specimens manufactured by the PolyJet 3D printing process, with particular attention given to the effects of printing orientation and layer thickness. The studies found that orientation and layer thickness have a significant impact on the glass transition temperature and the loss factor, which influence the material's mechanical behavior. Higher glass transition temperatures were observed in test specimens printed at higher speeds. This research could contribute to fine-tuning manufacturing parameters, enabling a wider industrial application of PolyJet technology.

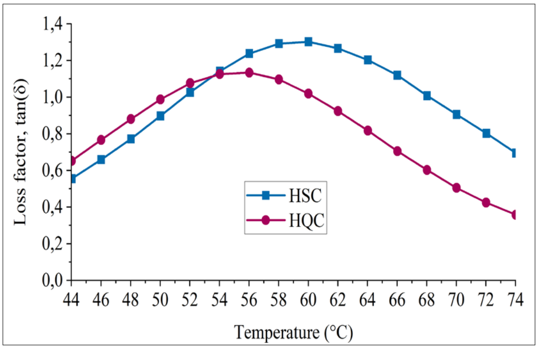

Fig. 13. *Loss factor distribution at 1 Hz Frequency: „C" orientation.*

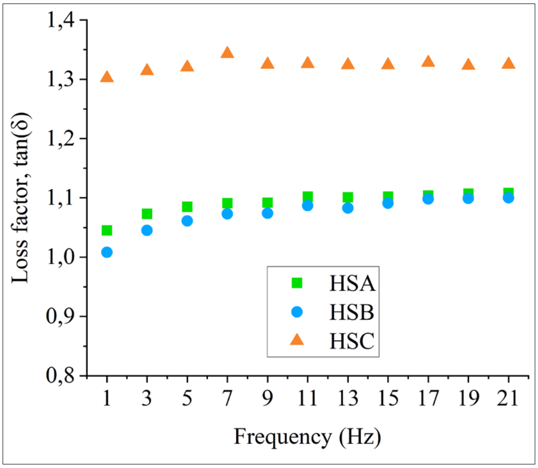

Fig. 14. *Maximum values of the loss factor for high-speed specimens.*

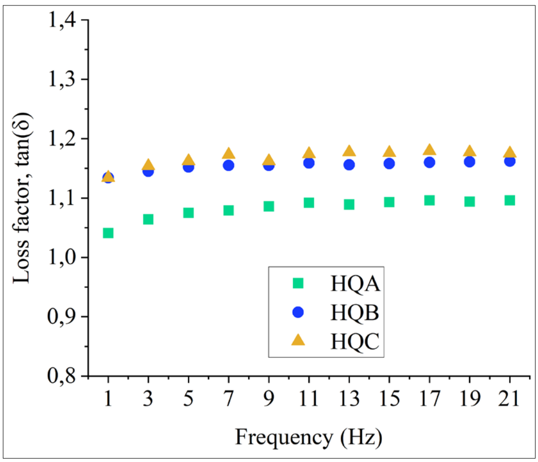

Fig. 15. *Maximum values of the loss factor for high-quality specimens.*

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