

INFLUENCE OF LAYER AND FIBRE ORIENTATION ON TENSILE STRENGTH OF PLA AND PETG SAMPLES

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The use of additive technologies in industrial production provides companies with a competitive advantage. However, implementing 3D printing poses challenges, from selecting the right technology and material to operator qualifications and mechanical properties of the prints. This study investigates the influence of fibre orientation and print quality on mechanical properties. Samples were 3D printed from PLA using a Bambu Lab A1 mini FDM printer and slicer.

Tensile tests showed FDM can achieve consistent results, and changing fibre orientation can increase tensile strength by nearly 50% and strain at strength by up to 3%. Some orientations however, while increasing strength, result in reduced print quality. These findings could guide industrial FDM printing and broader material and parameter testing.

KEYWORDS

fused deposition modelling, tensile testing, additive manufacturing, PLA, PETG, fibre orientation

1 INTRODUCTION

Every industrial company is looking for new ways to increase its competitiveness in the market. There are many ways and areas through which this goal can be achieved. One of them is a fast and innovative method of production, especially in the field of prototyping. For this reason, many companies are introducing or considering the introduction of 3D printing into their manufacturing processes. Thanks to this, 3D printing has experienced a great boom in the last decade. It is used in industry, medicine, art and academia and is also increasingly popular among the general public [Shelare 2023, Alba 2021, Rajan 2022]. The pace of development and implementation in industry is constantly accelerating, especially due to increasingly attractive costs [Kafle 2021, Rasu 2023].

The principle of 3D printing is based on creating a product from newly emerging layers of the supplied material [Kafle 2021]. It is therefore an additive technology, unlike conventional methods, which are mainly based on removing excess material. This significantly reduces or completely eliminates the creation of waste material. Products can be printed solid or hollow, however, for practical reasons (mechanical properties, weight, printing time) only a certain percentage of infill is usually chosen. The structure and percentage of infill can be adjusted according to the required properties and the material used. Currently, it is possible to print from a wide range of plastics, metals, resins and composite materials [Shelare 2023, Yahya 2023].

However, the scope of this research was mainly to find a cost-effective solution for polymer based rapid prototyping of complex parts. Therefore, the following technologies were considered [Yahya 2023, Lemi 2025, Zhou 2020]:

- Fused Deposition Modelling (FDM)

- Selective Laser Sintering (SLS)
- Stereolithography (SLA)
- Digital Light Processing (DLP)
- Liquid Crystal Display (LCD)
- Multi Jet Fusion (MJF)
- Poly Jet (PJ)

After a detailed study, FDM technology was chosen for further research, mainly due to its low acquisition and operating costs [Alba 2021, Rajan 2022]. Another reason was that FDM printing does not require excessive technical knowledge or any other special skills [Alba 2021, Rajan 2022]. By choosing the right combination of hardware, software and material, even an inexperienced operator can very quickly achieve satisfactory results. There is a wide variety of different companies that manufacture and supply 3D printers, materials and printing software. By directly comparing a number of test samples that were created using Creality, Průša research and Bambu Lab printers, it was decided to further proceed with only Bambu Lab products due to their outstanding performance.

2 MATERIALS AND METHODS

The aim of this experiment was to test the impact of layer orientation and print quality on the tensile strength of the samples. An overview of the layer orientations chosen for this experiment can be seen in Table 1 below, and Figures 2,3 show a diagram of sample rotations in planes Z and Y. Each orientation was tested in sets of five to ensure data robustness and consistency. The orientations of samples four and five were removed from the experiment, because once the samples were sliced it turned out that the orientation of sample four is similar to sample two, just inverted. Therefore, it is assumed that the deformation and tensile strength would be similar. The same goes for samples five and one.

Sample	Translation T[X;Y;Z]	Rotation R[X';Y';Z']
Sample 1.n	90;90;2	0;0;0
Sample 2.n	90;90;2	0;0;22,5
Sample 3.n	90;90;2	0;0;45
Sample 4.n	90;90;2	0;0;67,5
Sample 5.n	90;90;2	0;0;90
Sample 6.n	90;90;5,67	0;22,5;0
Sample 7.n	90;90;8,49	0;45;0
Sample 8.n	90;90;10	0;67,5;0
Sample 9.n	90;90;10	0;90;0

Table 1. Overview of configuration of test samples

Samples were created according to ISO 527-2 using Dassault Systèmes SolidWorks 2022. Specifically, sample type 1A was selected for testing. The shape and dimensions of the samples, as given by the standard, are shown in Figure 1 below.

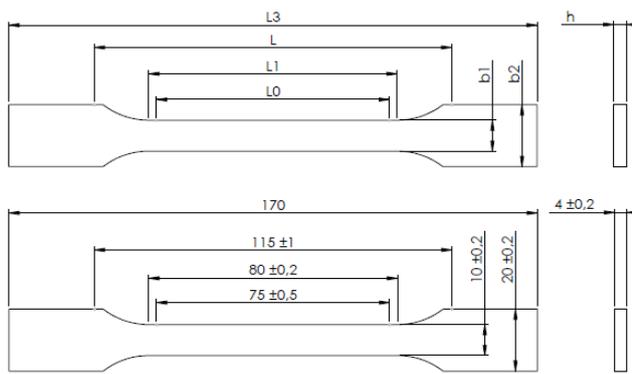


Figure 1. Sample dimensions according to ISO 527-2 type 1A

The process of tensile testing 3D printed samples usually consists of the following steps [Lemi 2025, Wahyudi 2025]. First, the sample is designed according to a standard using CAD software. Next, the sample is exported to an STL file and this file is then imported to a slicer, where it is positioned on a print bed and the printing parameters are set. Export of a G-code follows and the G-code is then sent to a printer and finally, once cooled down, the prints can be removed from the printer bed and tested. This process is time consuming [Kanli 2024] as the steps are usually done manually and can lead to errors if more than one operator is involved, as data and information need to be passed on between each step. Also, each step requires a certain level of technical knowledge, which requires skilled operators. The following approach was chosen to minimise the risk of errors, to reduce the required skill and to speed up the process, especially since a similar type of experiment is planned to be repeated with different parameters and materials. The 3D model was carefully designed in such a way that the axes of the global coordinate system of the sample are oriented in the same directions as the axes of the coordinate system of the slicer. The model was also designed as parametric. This allows for the quick and easy redesign of test samples to different standards if needed and the alignment of coordinate systems ensures that whenever the model is opened in the slicer the model orientation remains the same as intended. However, since samples must be printed in more than one orientation the following steps were added.

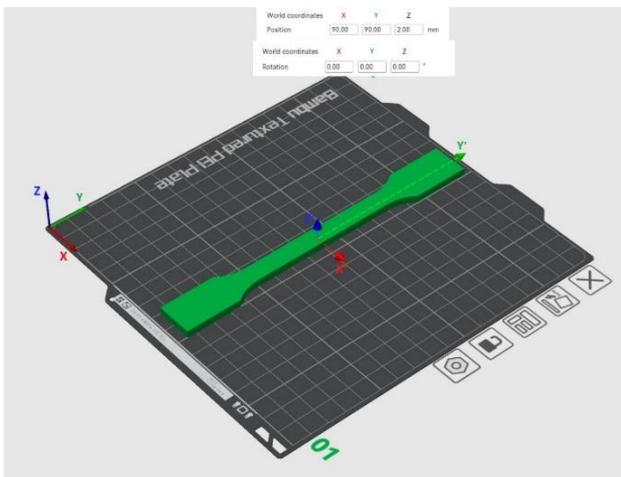


Figure 2. Orientation of global (X,Y,Z) and local (X',Y',Z') coordinate systems in the slicer

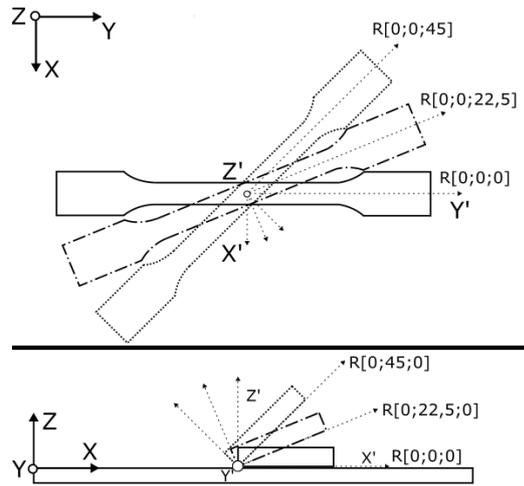


Figure 3. Orientation of global (X,Y,Z) and local (X',Y',Z') coordinate systems in the slicer

It was decided to use automation to eliminate the need to manually reposition each set of samples to the desired orientation every time a new set is loaded to the slicer. The requested rotation and translation for each sample set was stored in an Excel file. Then, using Microsoft VBA and SolidWorks API the values were loaded and the prepared model was repositioned as requested using a transformation matrix. This was followed by exporting the STL files. The result was that, when loaded to the slicer, every STL file showed samples already in the correct position and orientation.

A Bambu Lab default print profile named "0.2 Standard@BBLA1M" was used to eliminate the impact of print parameters other than the orientation of samples on the heat bed and to further reduce the required technical knowledge of the operator. A brief summary of default print profiles is shown in Tables 2 and 3. To ensure the compatibility of the default print profile with the filament material a generic Bambu PLA and PETG were used as both the print material as well as the slicer's material profile. PLA was selected for this experiment because it prints the easiest, is cheap to both print and acquire and is widely available [Sedlak 2023]. PETG was chosen due to its good mechanical properties and layer cohesion. All of the samples were printed using a Bambu Lab A1 mini printer. The printer, material and slicer were used from the same manufacturer to avoid compatibility issues and ensure interoperability.

Nozzle temperature	220 °C
Bed temperature	60 °C
Layer height	0.2 mm
Perimeters	2
Infill density	15 %
Infill type	Grid
Top shells	5
Top surface pattern	Monotonic
Bottom shells	3
Bottom surface pattern	Monotonic

Table 2. PLA printing parameters overview

Nozzle temperature	255 °C
Bed temperature	70 °C
Layer height	0.2 mm

Perimeters	2
Infill density	15 %
Infill type	Grid
Top shells	5
Top surface pattern	Monotonic
Bottom shells	3
Bottom surface pattern	Monotonic

Table 3. PETG printing parameters overview

3 RESULTS

Each type of sample was tested in sets of five. Recorded values for each set of samples were plotted in a chart to verify the consistency of the results and whether the printing quality impacted the test results. Figures 4 and 5 illustrate an example of the detailed results obtained from one set of samples, in this case sample set 7 for each material. The maximum values measured for each material are given in Table 4 and 5. It can be seen that the behaviour of all 5 samples was almost identical all the way to the strength limit and even beyond. A similar consistency of results was achieved for all sample sets. Therefore, it was concluded that there are only negligible differences in the print quality and that the achieved results can be considered valid.

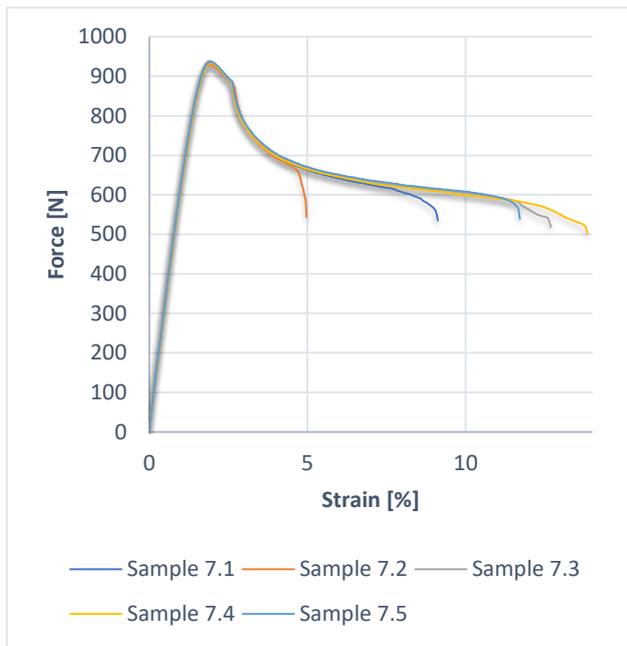


Figure 4. Tensile test results for sample set 7, PLA

Sample	7.1	7.2	7.3	7.4	7.5
Max. force [N]	934	929	939	933	936
Strain at yield [%]	1.90	1.89	1.91	1.96	1.90
Tensile strength [MPa]	40.9	41.6	42.1	41.8	42.0

Table 4. Test results of sample set 7, PLA

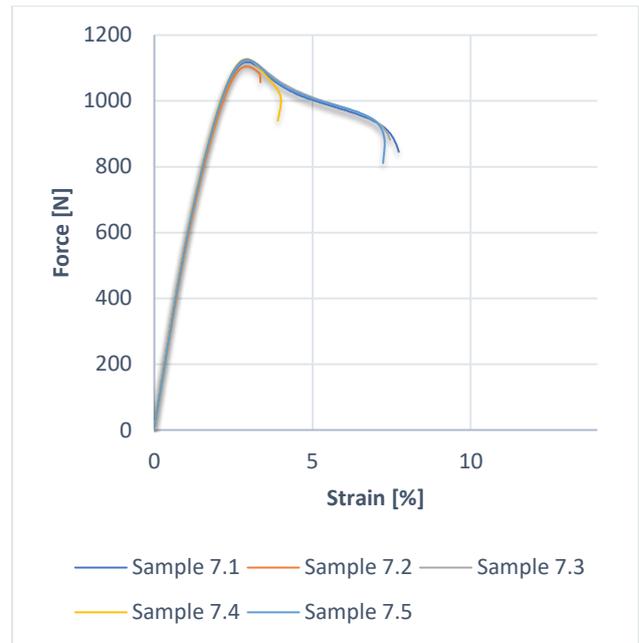


Figure 5. Tensile test results for sample set 7, PETG

Sample	7.1	7.2	7.3	7.4	7.5
Max. force [N]	1118	1104	1124	1128	1126
Strain at yield [%]	1.91	1.91	1.90	1.95	1.93
Tensile strength [MPa]	40.6	40.1	40.9	41.0	41.0

Table 5. Test results of sample set 7, PETG

The values obtained from each sample set were averaged and plotted in one summary chart shown in Figure 6 for PLA and Figure 7 for PETG. Rotating the samples along the Z'-axis provided unsatisfactory results. There was a slight increase of tensile strength that averaged at 4.3%, however, maximum elongation decreased by 18.2%. On the other hand, rotating samples along the Y'-axis caused a significant increase in both strength and strain in most cases. The largest portion of this increase is due to the top and bottom layers being replaced by the perimeters. If the sample is lying flat on the heat bed in the default position (sample set 1), the top and bottom layers are printed in a monotonic pattern that alternates -45° and +45° from the X-axis (as given by the default print setting). However, by tilting the sample around the Y'-axis, the top and bottom layers no longer exist as they are essentially replaced by the perimeters. The perimeters are printed along the length of the sample, therefore the load acts normal to the cross section of the sample instead of perpendicular to the layers or at an angle, as is the case with other orientations. This is the reason why sample sets 6 to 9 performed significantly better with both materials.

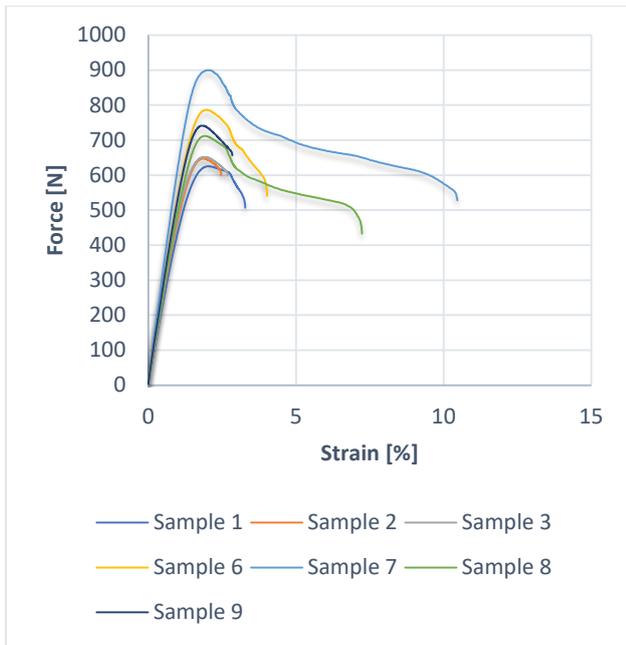


Figure 6. Averaged tensile test results, PLA

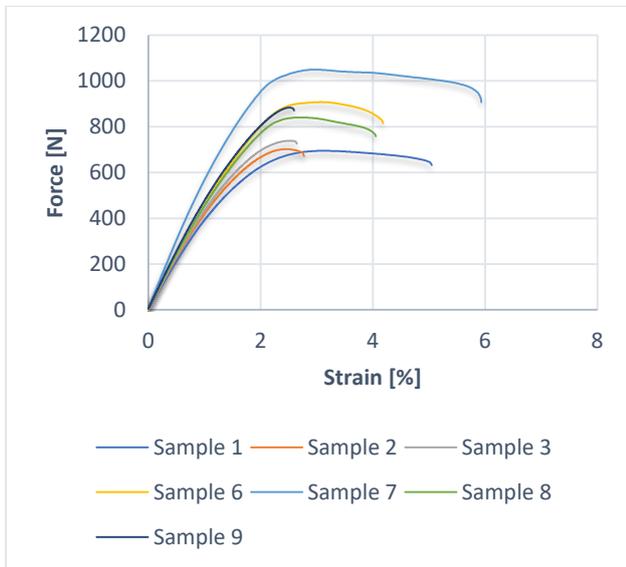


Figure 7. Averaged tensile test results, PETG

The difference between sample sets 6 to 9 is caused by two factors. The first factor is the contact area between the layers in combination with the print quality of the overhangs. An angle of 45° provides the best ratio between the overhang print quality and the size of the layer contact area, thus sample set 7 proved to be the best for both materials, both strength and strain wise. The difference between sample sets 6, 8 and 9 was caused by a second factor - infill. No matter how the sample is oriented, the infill pattern keeps being printed in the same way - parallel to the heat bed. In other words, the orientation and shape of the infill always stays the same in regards to the heat bed no matter the orientation of the sample. This, in combination with the changing orientation of the samples, caused uneven distribution of material across the cross section resulting in different mechanical properties. The dip in strength is very clearly visible on sample sets 8 and 9 in Figure 8. If it were not for the infill, sample 8 would have similar properties to sample 6. Figures 9 and 10 show the difference between strain at strength and strain at break of the samples.

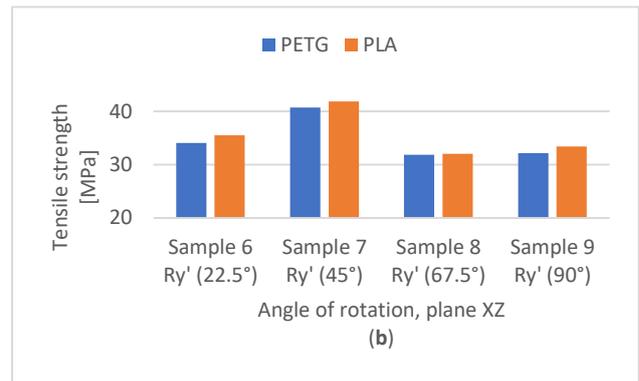
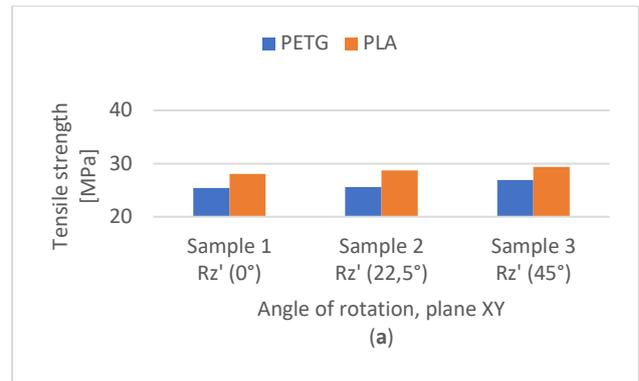


Figure 8. (a) Tensile strength vs. angle in plane XY; (b) Tensile strength vs. angle in plane XZ

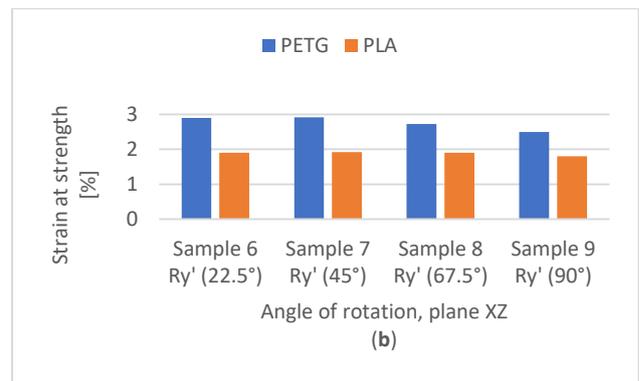
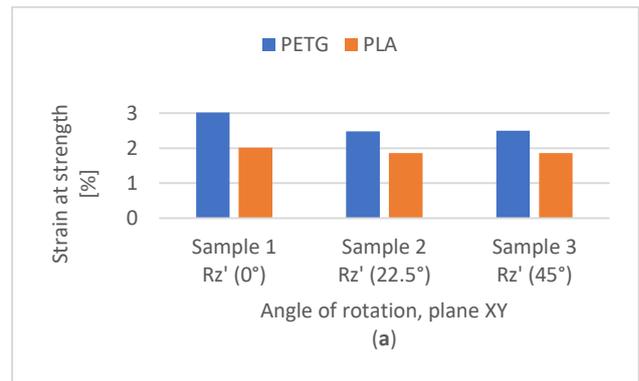


Figure 9. (a) Strain at strength vs. angle in plane XY; (b) Strain at strength vs. angle in plane XZ

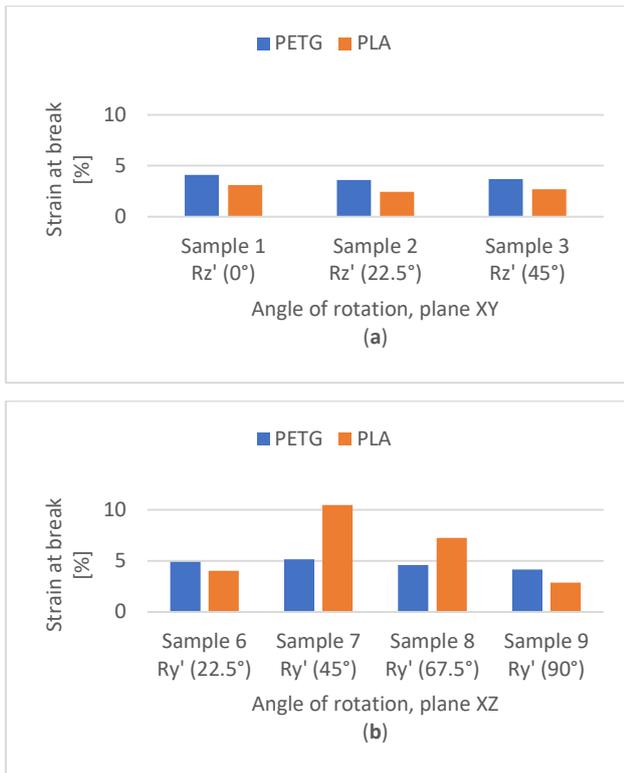


Figure 10. (a) Strain at break vs. angle in plane XY; (b) Strain at break vs. angle in plane XZ

4 DISCUSSION

Samples that were tested in the direction along the fibres showed increased tensile strength. The increase was around 24% on average for PLA and 37% for PETG. The difference between the weakest and strongest orientation was 49 and 60 % respectively as can be seen from Figure 8. The highest tensile strength was achieved with samples that were printed along the Y-axis and at an angle of 45°. These results confirmed our expectations. Samples printed in the default orientation were of the highest overall quality, with the least number of defects or surface imperfections, however they were also the weakest. From a direct comparison of the quality and strength of individual samples, it can be concluded that notches and various surface defects do not necessarily mean a significant loss of strength, or that the loss of strength caused by these imperfections is significant when compared to the increase in strength that comes from a more optimal fibre orientation and internal structure layout.

The tensile tests also showed that the orientation of the print had a negligible effect on the deformation up to the strength limit. However, past this point a significant difference was observed. Strain at strength differed by less than 4% among PLA specimens, The highest observed increase of strain at break was between sample sets 2 and 7 and reached a value of 327%. In the case of PETG, the variance of strain at strength ranged within 17%. The increase of strain at break peaked at 41% and was again observed between sample sets 2 and 7.

In conclusion, it can be said that print orientation has a significant impact on both mechanical and visual properties. The orientation of sample 7 turned out to be the best compromise. Such prints have great strength and elongation, while maintaining sufficient quality. Further testing will be performed

with different materials to determine if other materials follow the same principle

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