THE CENTER FOR

DESIGN, MANUFACTURING, AND MATERIALS

FUNDAMENTALS OF ADDITIVE TECHNOLOGIES #MA06243

TENSILE TESTING OF 3D-PRINTED PLASTICS

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Objective

The goal of this laboratory practice is to acquire basic skills of tensile testing of unreinforced 3D-printed plastics manufactured by binder jetting technology. This manual explains how to test specimens according to ASTM D638-02 “Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials”.

Input

A set of specimens fully prepared for tensile testing.

Output

Data set of mechanical characteristics of the tested specimens:

- stress-strain curves in terms of engineering values,
- modulus of elasticity,
- tensile strength,
- nominal strain at break,
- mean values, standard deviations and coefficient of variation.

Testing facilities

Instron 5969 electromechanical testing machine, extensometers, callipers, markers.

STEP 1. MARKING OF THE SPECIMENS AND MEASURING OF SPECIMENS' DIMENSIONS

1.1 Materials

For WanHao duplicator was used:

Multidimensional material and activator (cherry color): liquid photopolymer. It has no smell, low shrinkage (<0,5%), it is safe, tough and durable, stable, and heat-resistant. Producer: Harz Labs. Appropriate for LCD and DLP printing technologies.

For Zortrax was used:

Castable photosensitive resin for jewelry (white color), 5'th class of biocompatibility. It has low ash content at relatively low burn-up temperature. Producer: Esun. This material provides high precision, smooth surface, fine flexibility,finest details with low odor.

For Picasso and Ultimaker was used:
Polylactic acid (PLA). PLA is a thermoplastic that was made from renewable resources such as corn starch, tapioca roots, etc. PLA is ideal for 3D prints where aesthetics are important. Due to its lower printing temperature it is easier to print with and therefore better suited for parts with fine details.
For Picaso, we successfully produced the multi material printing of two PLA's of different colours.

1. Specimens were printed on four different printers with two different printing techniques:
    a. FDM
        i. Picaso Designer X Pro
        ii. Ultimaker 5S
    b. Liquid stereolithography
        i. Wanhao Duplicator S7 plus (6 Specimens)
        ii. Zortrax Inkspire (6 specimens)
2. For FDM we printed specimens on the four different orientations
    a. Horizontal
    b. Standing
    c. Rotation about longer side 45°
    d. Rotation about shorter side 35°
3. For Liquid stereolithography printers we only printed horizontal oriented specimens
4. For all the samples measurements were made right before the test and entered data right into the software. From the software we got the excel file with measurements.
5. Average values:
    a. Picaso:
       width = 3.30 mm;
       Thickness = 3.32 mm;
       Cross section Area = 424.90 mm^2
    b. Ultimaker:
       width = 3.40 mm;
       Thickness = 3.44 mm;
       Cross section Area = 401.44 mm^2

c. Wanhao:
   width = 3.52 mm;
   Thickness = 3.19 mm;
   Cross section Area = 11.21 mm^2
d. Zortrax:
   width = 3.52 mm;
   Thickness = 3.11 mm;
   Cross section Area = 10.93 mm^2

STEP 2. TEST PREPARATION

Test dates:

- **Picasa: 19 March 2020**
- **Ultimaker: 19 March 2020**
- **Wanhao: 12 March 2020**
- **Zortrax: 12 March 2020**

2.1. We place the specimens in the grips. Important that we are testing only the thinner part of the sample. Thicker parts are made specifically to be placed in the grips.

2.2. We put the extensometer to the thinner section of the specimen. Extensometer has a gage limit of 50 mm and the allowable travel is ± 5 mm. To secure the extensometer we set the limit to 9% strain. After that extensometer has to be removed

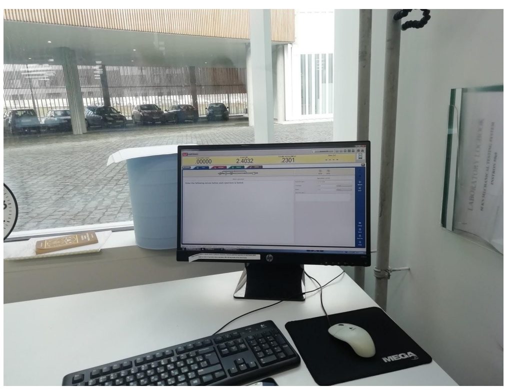
3. CARRYING OUT THE TEST

3.1. TA Stepan prepared the software for us.

3.2. Before each test we specify the name of the specimen (example: G1-01-PLR-2020, which means group 1, sample 1, plastic red (wanhao) and 2020 year)). We also enter the measurement data for each specimen and the loading rate (for Wanhao/Zortrax we used 5 mm/s)

3.3. On the control panel we have to press “Balance all” button to zero the extensometer and apparatus values

3.4. Click start on the software and then click start on the Control panel

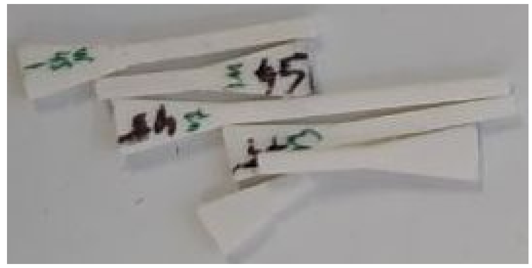


3.5 When the specimen breaks the apparatus stops the experiment if it sees 40% load drop. Otherwise we have to stop the experiment manually.

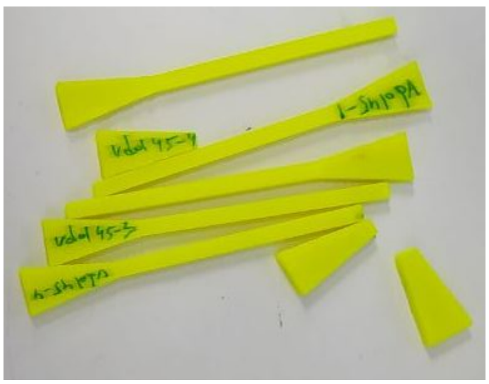
3.6. We save the data and proceed to the next sample.

1. **Pictures of the initial and broken specimens.**

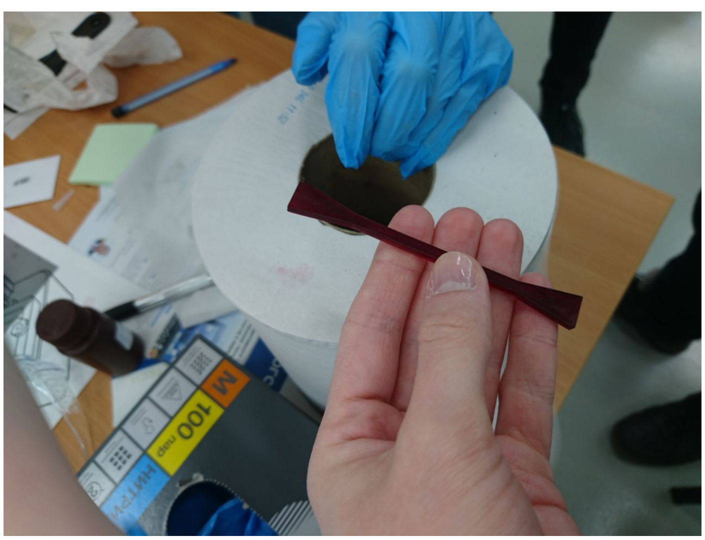
2.1 FDM: Ultimaker tests: initial and broken specimens pictures



2.2 FDM: Picaso tests: initial and broken specimens pictures



2.3 Liquid stereolithography: Wanhao Duplicator tests: initial and broken specimens pictures



2.4 Liquid stereolithography: Zortrax Inkspire tests: initial and broken specimens picture

STEP 4. DATA PROCESSING

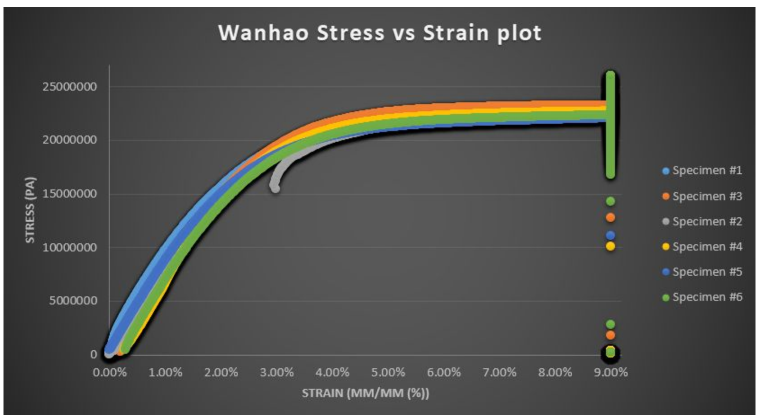
4.2. Stress Strain curve

The engineering stress σ is calculated with the following formula

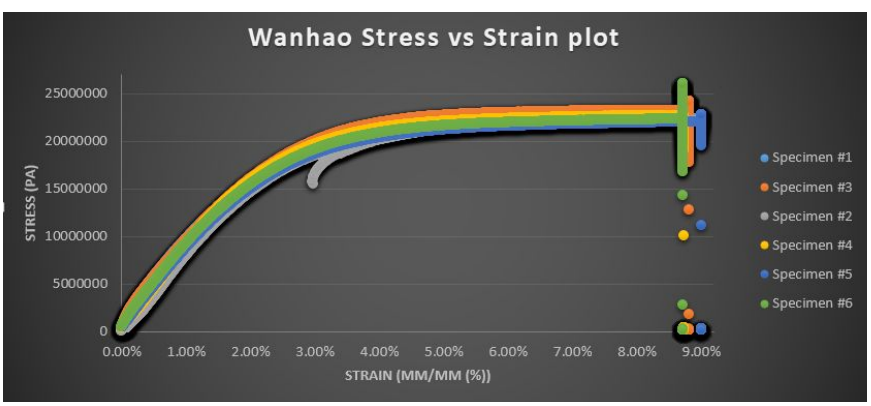
$$\sigma = \frac{F}{A_0}$$

Calculations were done in the Excel spreadsheet. All the plots were also created in the excel software. The strain results we get directly from the software. We use stress and strain values to build the plot shown below

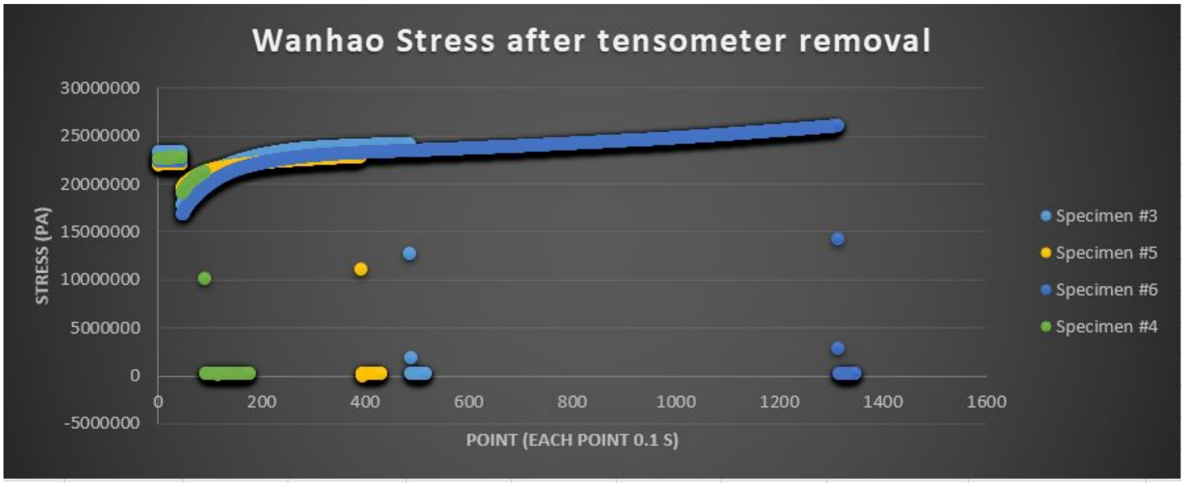
Wanhao



In the plot above we can clearly see the plastic behaviour of the samples. All the samples show similar behaviour, therefore we can state that the experiment was done clear. Below we show the plot of the stress vs time after 9% stress. Some samples did not have zero strain in the beginning so we zero the strain and have the following plot. However we can see that they are not all at 9% because of the delta shift.

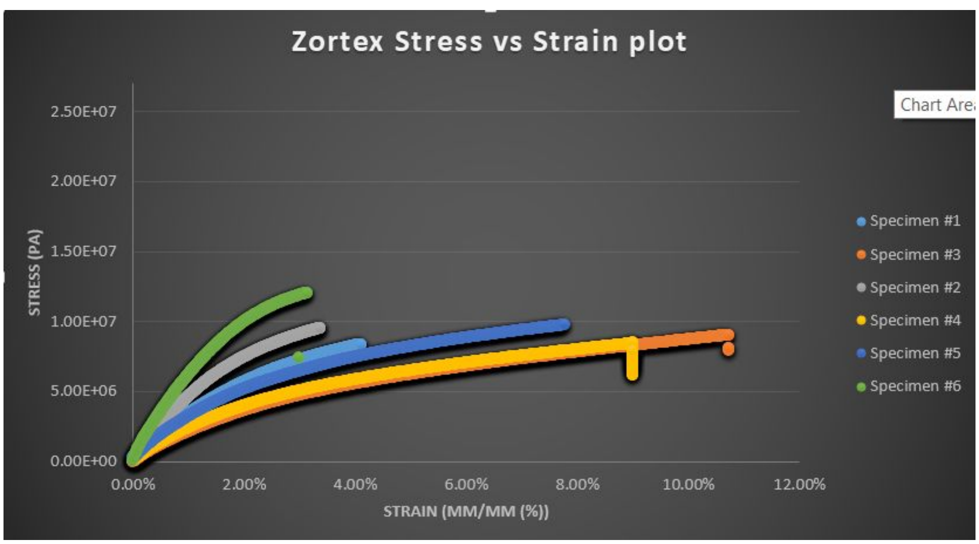


Since the extensometer is set to a maximum 9% strain, our data points for the stress when it reaches 9% stress are all at a value of 9%. There is data only for 4 specimens because, unfortunately, two specimens were broken while removing the extensometer. After extensometer removal we observe the fast drop in stress and then again it reaches asymptotic behaviour as before. Also we can clearly see when the specimen breaks.



Zortrax

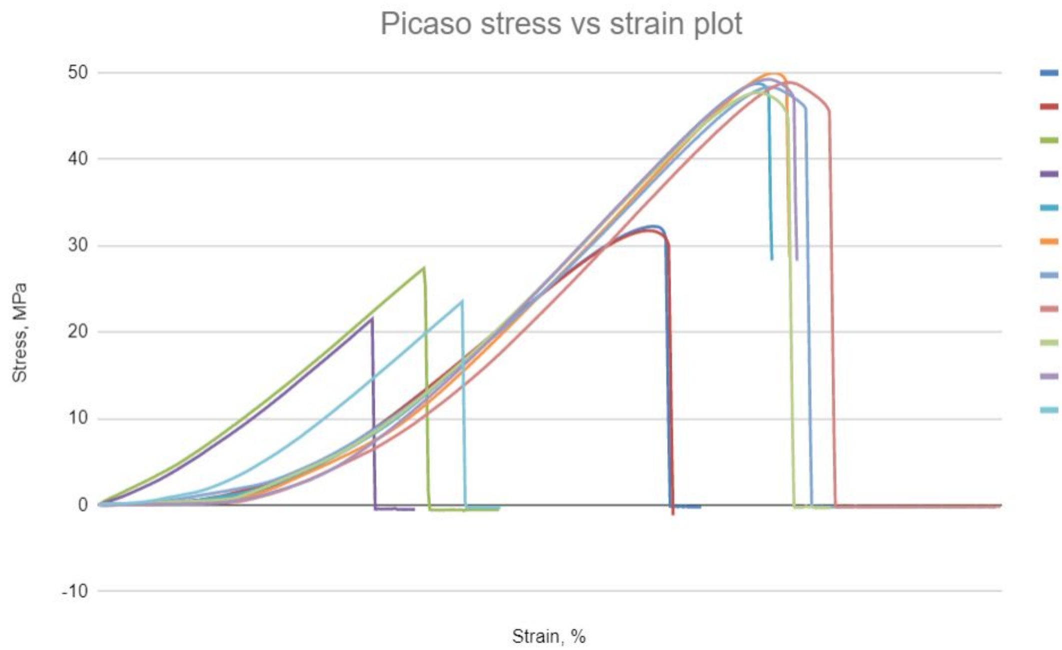
We use the same approach as above for the zortrax printer specimens. The plot is shown below. We deleted the data that were after the specimens were broken (there were jumps), to get a clear plot.



Zortrax samples are more elastic as we can see (they deforme more at the lower load). Also the samples are not as consistent as the samples from Wanhao printer. We suppose this is because Zortrax is a new printer in the lab. In addition, overall Zortrax is a less quality printer than Wanhao.

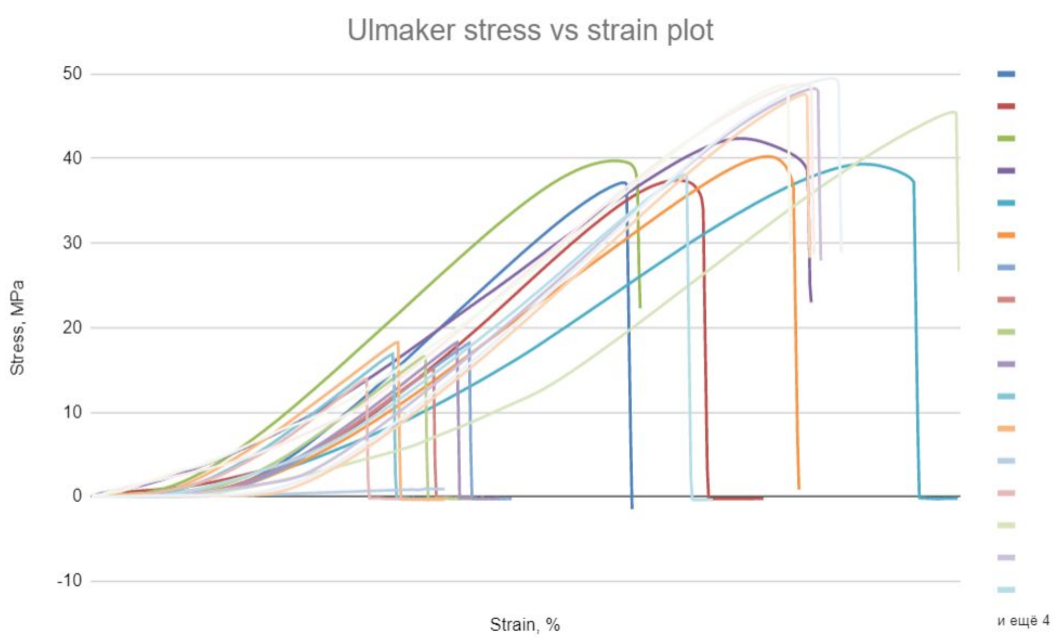
Picaso

Below is a stress-strain plot for Picaso. We see 3 groups: the left are the staying vertically samples, the center are laying across samples and the rightest are laying along. The samples which stayed, withstood the least load, while the laying samples withstood ~2.5 bigger load.



Ultimaker

Below is a stress-strain plot for Ultimaker. We see 4 groups: the leftest are the staying vertically samples, the center are staying under 30 and 45 degree samples and the rightest (and the highest by y) are laying along the platform. Here exists the same distribution: the samples which stayed, withstood the least load, while the laying samples withstood ~2.5 times bigger load.



4.3. Calculations of modulus of elasticity

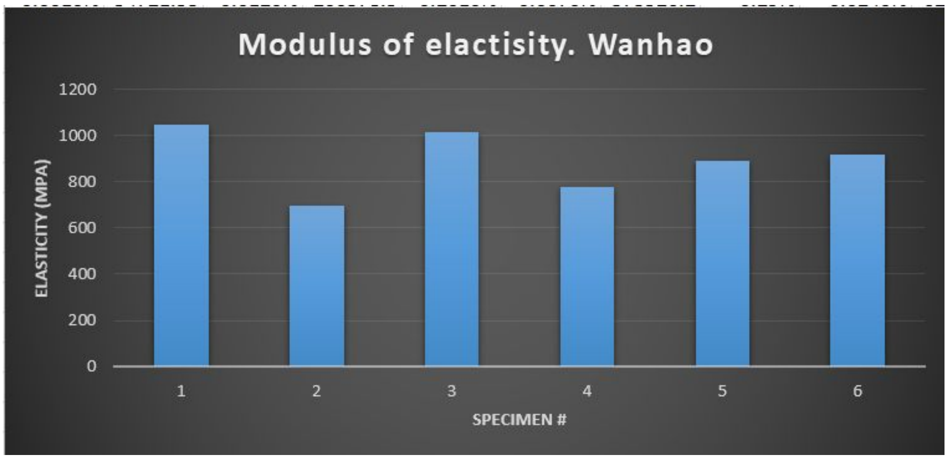
To calculate modulus of elasticity we used the formula shown below

$$E = \frac{\Delta\sigma}{\Delta\varepsilon}.$$

We take data at the area of 0.1% to 0.3% range of strains because we are sure that at the beginning there is linear behaviour.

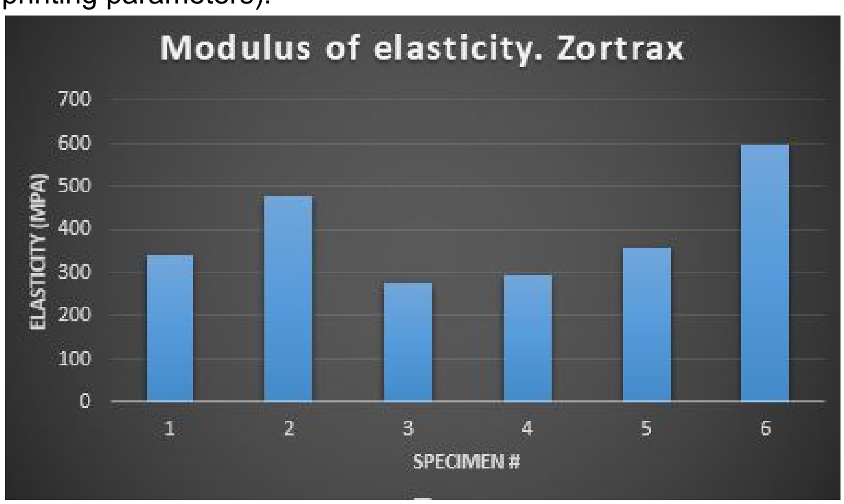
Wanhao

Below we show the modulus of elasticity for all six Wanhao samples. We observe that overall the values are similar. Except the second sample that has too low elasticity compared to the rest samples.



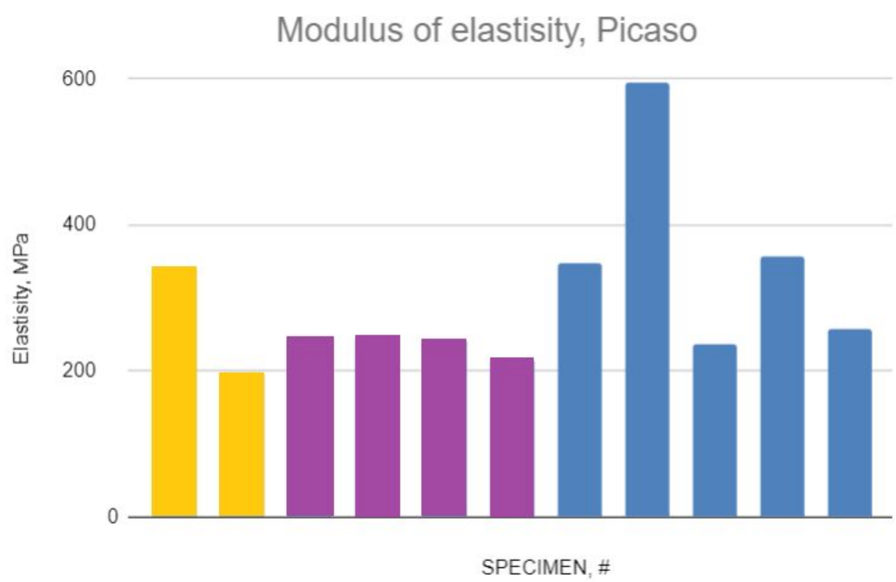
Zortrax

Below modulus of elasticity of Zortrax samples is shown. We observe greater variance between the samples. As stated before, Zortrax is a lower quality printer, and this causes less stable print (even though we kept all the samples with the same orientation and same printing parameters).



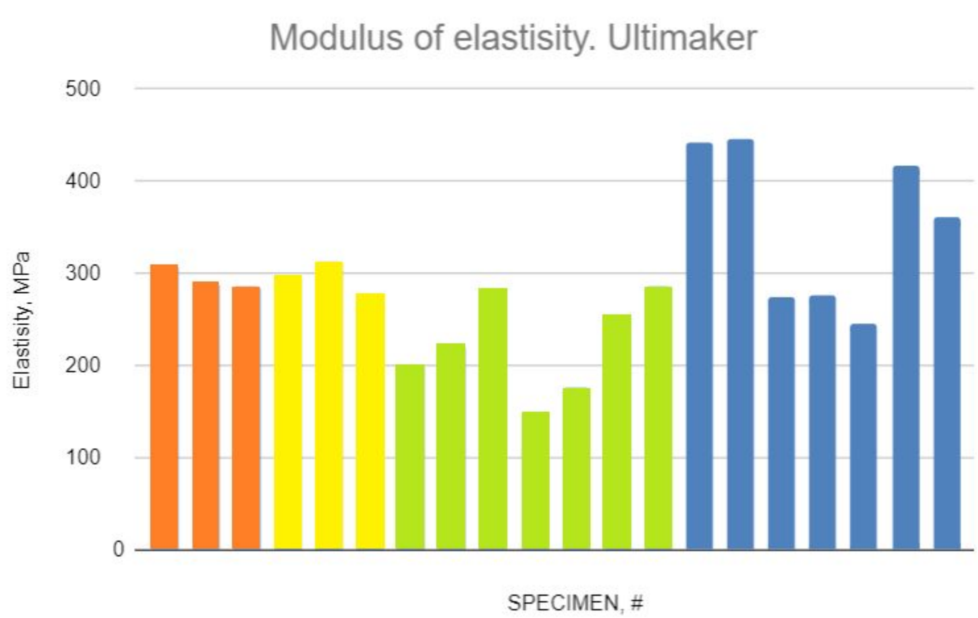
Picaso

Below modulus of elasticity of Picaso samples is shown. Yellow samples in the picture are laying across the platform, purple are standing vertically, blue are laying along. We observe big variance between the samples (~30%). Standing samples have almost constant elasticity.



Ultimaker

Below modulus of elasticity of Ultimaker samples is shown. Orange samples in the picture are staying under 30 degrees on the platform, yellow are staying under 45 degrees on the platform, green are standing vertically, and blue are laying along. Again we observe big variance between the samples. The laying samples are the most elastic, the vertical oriented are the least.



STEP 5. STATISTICAL ANALYSIS OF THE TEST RESULTS

5.1. Modulus of elasticity:

Wanhao:

Average value of the modulus of elasticity = 891.94 MPa
Standard deviation (used the excel function) = 124.04 MPa
Coefficient of variation = 13.91 %

Zortrax:

Average value of the modulus of elasticity = 391.24 MPa
Standard deviation (used the excel function) = 112.54 MPa
Coefficient of variation = 28.76 %

Picaso:

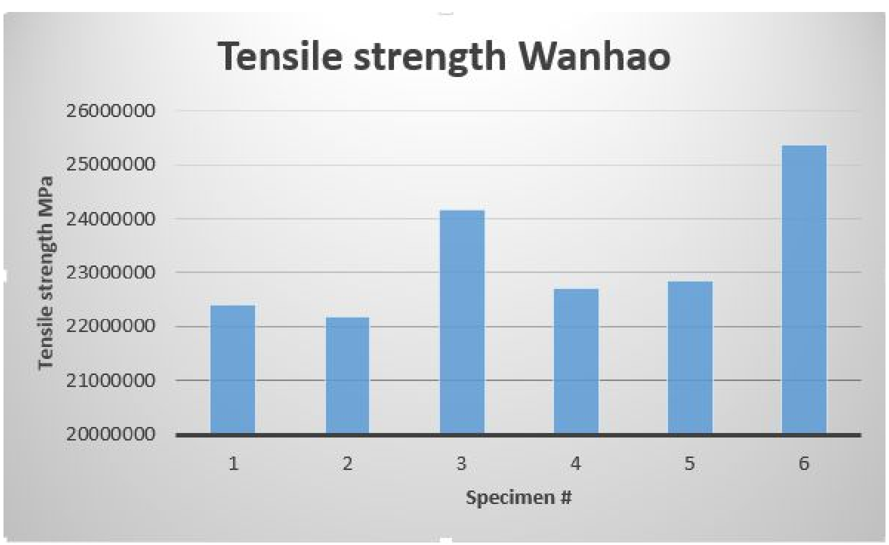
Average value of the modulus of elasticity = 298.95 MPa
Standard deviation (used the excel function) = 112.24 MPa
Coefficient of variation = 37.55 %

Ultimaker:

Average value of the modulus of elasticity = 290.64 MPa
Standard deviation (used the excel function) = 79.23 MPa
Coefficient of variation = 27.26 %

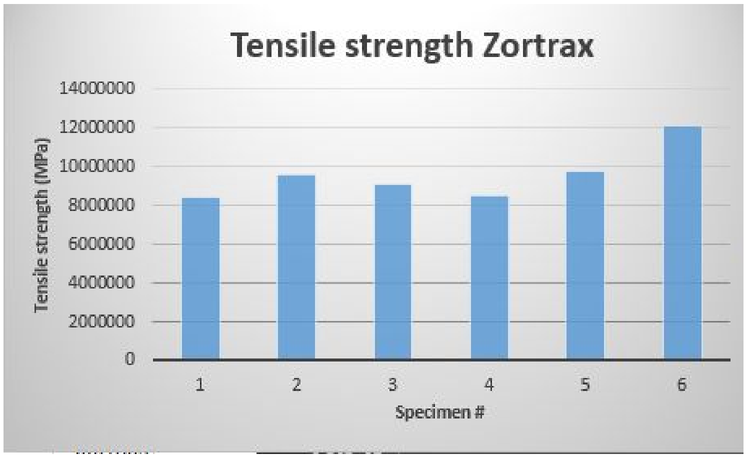
5.2. Tensile strength:

Wanhao:



Average value of the tensile strength = 23.28 MPa
Standard deviation (used the excel function) = 1.13 MPa
Coefficient of variation = 4.86 %

Zortrax:

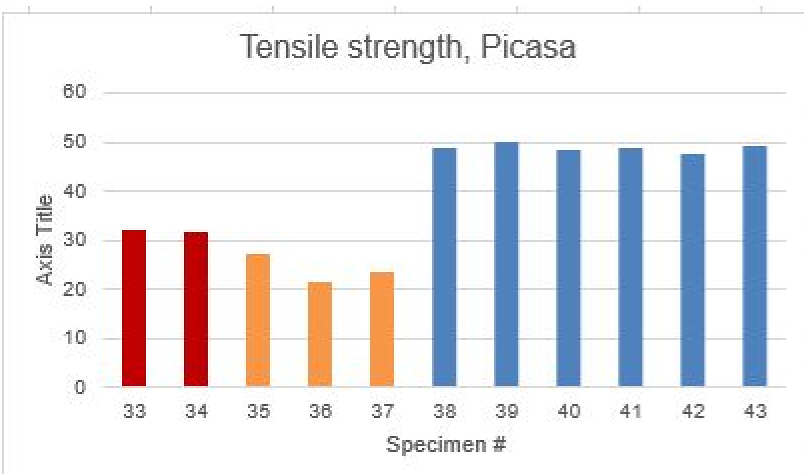


Average value of the tensile strength = 9.54 MPa

Standard deviation (used the excel function) = 1.23 MPa

Coefficient of variation = 12.95 %

Picaso:



In the plot there are three different orientations (we have printed 4, but for some reason lab person Stepan tested only 3). Red are Horizontal, Orange - vertical, Blue - rotation 45 degree around the longer side. Interesting that the strongest samples are the ones rotated.

Statistical data:

Horizontal:

Average value of the tensile strength = 32.00 MPa

Standard deviation (used the excel function) = 0.24 MPa

Coefficient of variation = 0.75%

Vertical:

Average value of the tensile strength = 30.30 MPa

Standard deviation (used the excel function) = 10.87 MPa

Coefficient of variation = 35.87 %

Long axis 45:

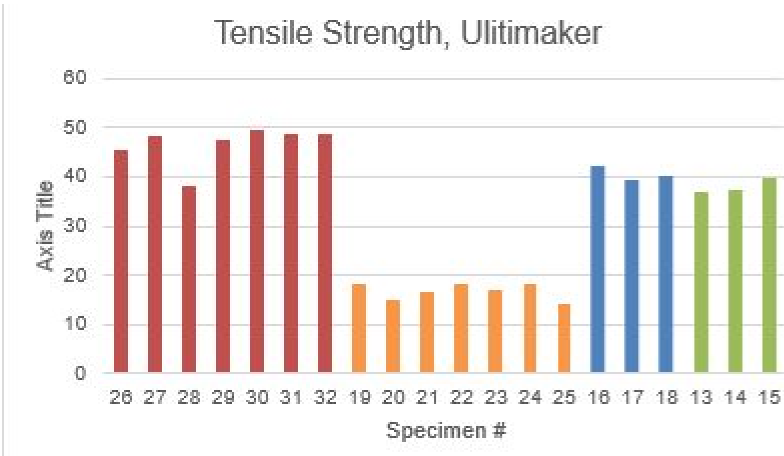
Average value of the tensile strength = 48.83 MPa

Standard deviation (used the excel function) = 0.78 MPa

Coefficient of variation = 1.60 %

We have some great and consistent results for the 45 degree and horizontal samples!

Ultimaker:



For the Ultimaker plot I use the same color coded scheme: Red are Horizontal, Orange - vertical, Blue - rotation 45 degree around the longer side. Interesting that the strongest samples are the ones rotated. But we also have green - rotated 30 degrees around the shorter side.

Horizontal:

Average value of the tensile strength = 46.62 MPa

Standard deviation (used the excel function) = 3.68 MPa

Coefficient of variation = 7.88 %

Vertical:

Average value of the tensile strength = 16.74 MPa

Standard deviation (used the excel function) = 1.57 MPa

Coefficient of variation = 9.40 %

Long side 45:

Average value of the tensile strength = 40.65 MPa

Standard deviation (used the excel function) = 1.27 MPa

Coefficient of variation = 3.13 %

Short side 30:

Average value of the tensile strength = 38.10MPa

Standard deviation (used the excel function) = 1.16 MPa

Coefficient of variation = 3.05 %

Variariation for all results is within 10%, therefore we consider results good.

Overall among all 4 printers, if we compare horizontal samples Ultimaker has the strongest samples. Picaso second place. Wanhao third and Zortrax the weakest.

5.3. Nominal strain at break:

Wanhao:

Extensometer was removed at 9% strain and samples broke above that value.

So we can only say that Wanhao samples had >9% nominal strain.

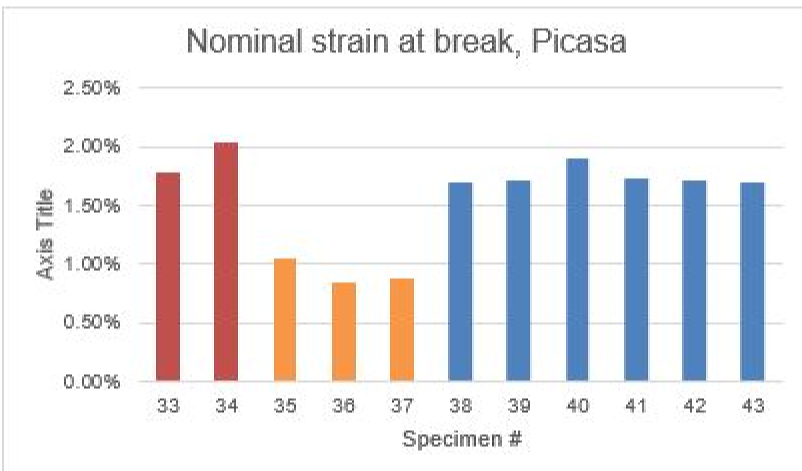
Zortrax:

Average value of the nominal strain at break = 6.35%

Standard deviation (used the excel function) = 2.95%

Coefficient of variation = 46.47%

Picaso:



Horizontal:

Average value of the nominal strain = 1.91%

Standard deviation (used the excel function) = 0.12%

Coefficient of variation = 6.38%

Vertical:

Average value of the nominal strain = 1.12%

Standard deviation (used the excel function) = 0.34%

Coefficient of variation = 30.74%

Long side 45:

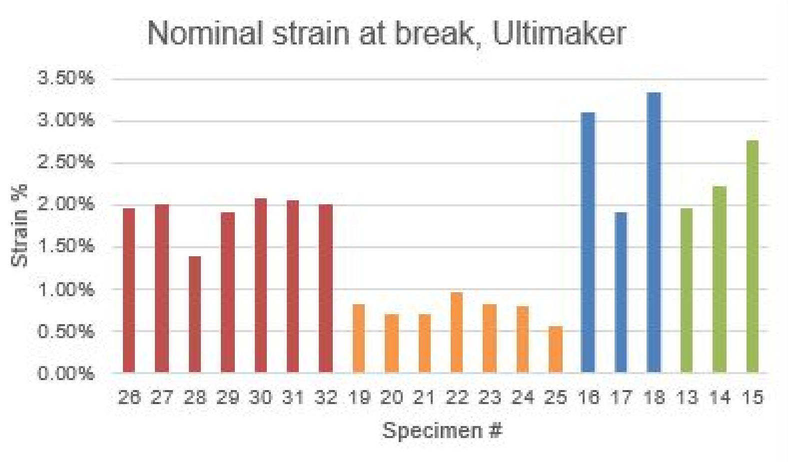
Average value of the nominal strain = 1.75%

Standard deviation (used the excel function) = 0.07%

Coefficient of variation = 4.23%

Taking into account that we have very small values, we have very good variation! Except the vertical samples (same as for the strength).

Ultimaker:



Horizontal:

Average value of the nominal strain = 1.92%

Standard deviation (used the excel function) = 0.22%

Coefficient of variation = 11.33 %

Vertical:

Average value of the nominal strain = 0.77 %

Standard deviation (used the excel function) = 0.11%

Coefficient of variation = 14.80 %

Long side 45:

Average value of the nominal strain =2.78%

Standard deviation (used the excel function) = 0.63%

Coefficient of variation = 22.52 %

Short side 30:

Average value of the nominal strain = 2.31%

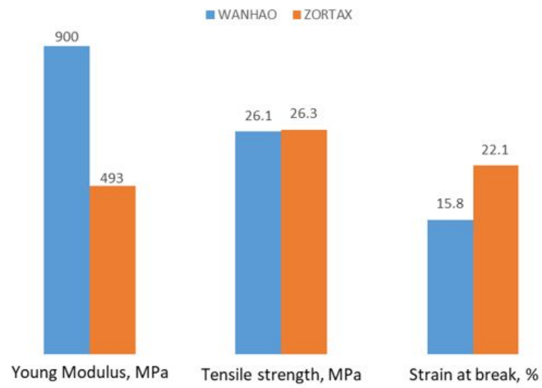
Standard deviation (used the excel function) = 0.34%

Coefficient of variation = 14.71 %

Overall we observe that all the plastic samples are breaking at the same extension. Within the 4% strain. However, wanhao samples were breaking at >10% strain. We observed that even by touching Wanhao samples were more flexible.

STEP 6. COMPARISON

On the figure below we show second group data for Wanhao and Zortrax printers.

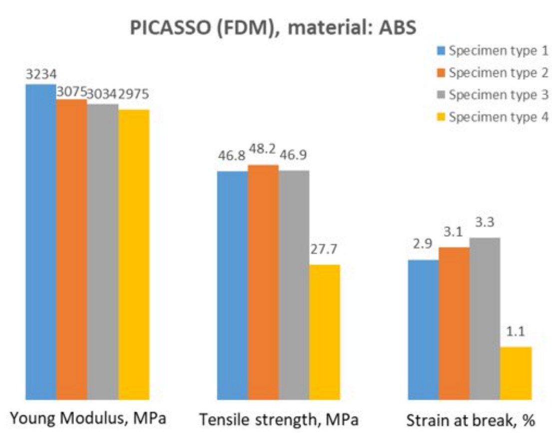


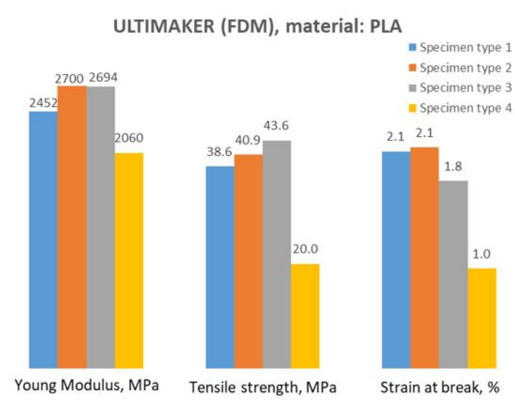
Looking at the modulus of elasticity, they also found that wanhao has greater elasticity. In addition the values are very similar. For Wanhao we got an average 891.94 MPa which is super close to the Group 2 values. For Zortrax we got 391.24 MPa average, which is not that close to Group 2 value. However, Zortrax printer samples are not consistent in general, therefore we did not expect to have similar values.

Regarding the tensile strength, we have similar values for Wanhao (23.28 MPa) compared to Group 2 , however our value for the Zortrax printer is much smaller (9.54 MPa).

Group 2 values for strain at break look weird to us because extensometer can measure only up to 10% strain and I am not sure how they got values such as that.

Below we show data for the Picaso and Ultimaker printers





We got elasticity modulus ~300 MPa for both printers. Group 2 has ~3000. One of us might have made a mistake with tens, because other than that our results are close. Regarding the tensile strength - our value for Picaso ~ 32 Mpa and Ultimaker ~46 Mpa. We do have slightly different values. However, we might have printed with different parameters.

For the nominal strain we have ~1.92% for both printers. Group 2 has slightly greater values. Again printing parameters might be the cause.

STEP 6. STATISTICAL ANALYSIS OF THE TEST RESULTS

6.6. Liquid stereolithography

Comparing the results of the mechanical testing of the liquid stereolithography printers we see that Wanhao printer is more consistent in the printing capabilities than Zortrax. In addition, Wanhao samples are more resistant to the extension load and are less deformable than Zortrax samples.

6.7. FDM

Most interesting observation is that we expected for the strongest samples to be oriented horizontally. However, for both Picaso and Ultimaker the strongest samples were rotated along the axis. We think this is because when we rotate the layers at the angle to the axis we are stretching the samples. So when we are applying extencion force, layers are moving at the angle and all together pushing into each other that way supporting each other. For vertical, the weakest sample, layers are perpendicular to the load vector and we are literally separating the layers, which is the weakest part (layer connection).

Also a comment about the consistency of the results. Overall our results were very consistent (with little exceptions). Even though we did not have many samples, our variance is mostly within ~7%, sometimes even below 3%.

6.8. Overall

Looking at all four printers we can state that ultimaker samples are most consistent and strongest (the most resistant to the extension load). Picaso samples are very close to the strength and consistency of the Ultimaker. Both FDM printers shown that printing at the angle gives us specimens that are most resistant to the extension load.

Our data showed that FDM printers provide stronger specimens overall because they have the greatest tensile strengths as well as they have greater modulus of elasticity.

Comparison of our data to the data of the other group has shown that our results are valid. Except modulus of elasticity for FDA printers. We believe either us or them made a mistake in tens.

Wanhao printer (material) is the most flexible material with the greatest greatest nominal strain values.