THREE APPROACHES TO PLA FILAMENT MECHANICAL PROPERTIES DETERMINATION USING TENSILE TESTING

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Abstract. This study investigates the tensile mechanical properties of the Polylactic acid (PLA) polymer. For this purpose, the stress-strain curves, the tensile strength, and the Young's modulus were obtained experimentally. A total of 93 tests were conducted, testing specimens with a diameter of 1.75 and 2.85 mm of raw PLA filament and standard injection-moulded specimens of the same material. The results were compared with previously tested specimens of the same material, printed using the Fused Deposition Modelling (FDM) technology. Three testing approaches are proposed, which include the use of three different testing machines (single-column MFC T-500 machine, MESSPHYSIK micro tensile testing machine, and ZWICK 1475 universal testing machine), and three different ways of measuring longitudinal deformation (total specimen elongation measurement, local elongation measurement with a laser-speckle extensometer, and local elongation measurement with a contact extensometer). The influence of the testing machines, nominal length, clamp material, cross-sectional diameter, filament age, and production technology were examined during the tests. The tensile strength and the Young's modulus of the raw filament and the injection-moulded PLA were found to be similar to these of the best FDM-printed samples. The clamp material, filament age, and filament diameter do not significantly affect the results obtained. Increasing the nominal length positively impacts the results where an extensometer is not used.

Keywords: polylactide, PLA filament, mechanical properties, tensile test, tensile strength, Young's modulus.

Introduction

Polylactic acid (PLA) and other polymeric filaments such as acrylonitrile butadiene styrene (ABS) and polyethylene terephthalate glycol (PETG) are widely used in Fused Deposition Modelling (FDM) due to their mechanical properties and processing characteristics. Tensile testing is one of the primary methods used to evaluate the mechanical performance of these materials, providing insights into tensile strength, Young's modulus, elongation at break, and overall ductility. These parameters have an essential role both in the construction process and in computer-aided stress-strain analysis.

PLA is a biodegradable thermoplastic that is relatively stiff and offers good tensile strength and excellent processability. Several studies report that PLA typically has a tensile strength in the range of 28–59 MPa and a Young's modulus between 2.8 and 3.5 GPa [1-4]. These properties make PLA suitable for applications requiring high stiffness, while its brittleness remains a limitation. In tensile tests, PLA exhibits limited elongation at break, usually 2.5-6.0% [1], indicating its limited ductility. Some studies note that environmental factors, such as humidity, can further impact the mechanical properties, as the material is susceptible to hydrolytic degradation, which may reduce its strength over time [5].

While PLA offers high tensile strength and stiffness, it is often compared to ABS and PETG due to the latter materials' higher impact resistance and flexibility. ABS generally has lower tensile strength than PLA, typically between 25-40 MPa, but displays significantly higher elongation at break, often around 20-30% [3; 6]. This makes ABS a more ductile material, capable of withstanding larger deformations before fracture. PETG, on the other hand, combines some of the benefits of both PLA and ABS. It has a tensile strength range of 30–50 MPa and higher elongation at break, which can reach 50%. Studies reveal that PETG's ductility and layer adhesion properties are superior to PLA [7; 8].

Plenty of studies highlight the impact of print parameters on the tensile properties of 3D-printed parts [2; 4; 6-9]. For PLA, factors such as the infill pattern and density, layer height, nozzle temperature, and cooling fan speed significantly influence the tensile strength and Young's modulus. The orientation of printed samples relative to the tensile load is another critical factor. Samples printed with layers aligned parallel to the tensile load direction generally display higher tensile strength than those printed with layers perpendicular to the load. This is due to reduced stress concentrations at the layer boundaries, resulting in fewer points of failure during testing. In our own studies on the influence of 10 major printing parameters, including pattern and orientation, we tested 216 printed specimens and confirmed these conclusions [10]. Some of our previous results are used here for comparison.

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Traditional tensile testing methods, including ASTM D638 [11], and ISO 527-1/2 [12; 13] are widely used for characterising 3D-printed polymers. Using Digital Image Correlation (DIC), detailed insights into strain distribution and failure modes in printed specimens [14] can be provided. DIC also allows for real-time observation of strain localisation and fracture development, which helps identify weaknesses in inter-layer bonding and can guide the optimisation of print settings.

The current study aims to examine the mechanical properties of PLA filament material and to make a comparison with the mechanical properties of specimens produced with the same material using injection moulding and 3D-printing technologies. Trying three different approaches to tensile testing, we assess the influence of the different test parameters on the test results and compare this data with results from our previous studies. The results presented here are needed for our further research on the influence of the FDM process using an industrial robot on strength, as well as on related FEM analyses.

Raw Filament Specification

Verbatim© white filament with 1.75 mm and 2.85 mm diameters is used as a raw material. The manufacturer datasheet provides its basic material properties:

- tensile yield strength: σ_Y = 63 MPa;
- tensile elongation: ε = 4%;
- density: ρ = 1.24 g/cm³;
- glass transition temperature: T_{G} = 58 °C;
- melt temperature: T_M = 168 °C;
- melt flow rate (*MFR*): 3.0 g/10 min. at 190 °C, and 8.1 g/10 min. at 210 °C with a 21.2 N load.

After requesting additional information from the manufacturer, a Poisson's ratio of v = 0.36 was given.

Research parameters

In the current research, a total number of 93 specimens were tested. The experiments were planned to estimate the influence of the following parameters on the received results:

- *Testing machine*. Universal tensile testing machine Zwick type 1475 is our preferred equipment. It has a contact longitudinal extensometer and is the best choice for testing standard test specimens of different materials, including PLA. Nevertheless, this machine is unsuitable for testing small PLA filament diameters, as its load cell is not sensitive enough for such small loads. For filament testing, MFC T-500 and MESSPHYSIK tensile testing machines were used. MFC T-500 is designed to obtain engineering stress-strain curves (without extensometer), while MESSPHYSIK is equipped with laser speckle for precise strain measurement;
- *Nominal length* L_0. When testing cylindrical specimens without extensometers, the accuracy of strain measurement increases with L_0 as the deformation in the clamps influence on the overall result decreases. To assess this effect, two values of L_0 were used – 150 mm and 450 mm;
- *Clamps material*. Testing machines are initially equipped with metal clamps. When the tested material is relatively soft as PLA, it is highly deformed in the clamps, which may cause premature fracture. To avoid this, we produced specially designed, FDM-printed PLA clamps using the same PLA as the tested material for the MFC T-500 testing machine and carbon fibre-reinforced PLA for the MESSPHYSIK testing machine. Tests were also made with the original metal clamps;
- *Cross section*. Filaments of 1.75 mm and 2.85 mm diameter were tested;
- *Filament age*. Knowing that PLA can change its properties over time, especially when exposed to humidity, we decided to assess the change in mechanical properties over time. The specimens were prepared and tensile tested using newly opened and 120-day-old filaments kept open in room conditions.
- *Processing technology*. In our previous studies, we tested the PLA material properties after 3D printing with different process parameter sets. In the current study, we examine raw PLA in the form of filament and injection-moulded specimens from the same material and compare the results against each other as well as with our previous results.

The First Approach – nominal specimen length of 150 mm, without an extensometer

As a first approach, measurements were made with an MFC T-500 single-column tensile testing machine with a stroke length of 520 mm and a nominal force of 5 kN, shown in Figure 1 (a). The tests were made with a nominal length of L_0 = 150 mm of filament fresh out of the hermetically sealed package, with original metal clamps, and also, to discourage fracture at the clamps, with PLA clamps. All measurements were repeated three times with a testing speed of 1 mm/min for stiffness and 20 mm/min for strength until fracture. In total 12 specimens were tested, with representative stress-strain curves shown in Figure 1 (b). The mean strength and stiffness values with their maximum and minimum values as positive and negative error bars are shown in Figure 5.

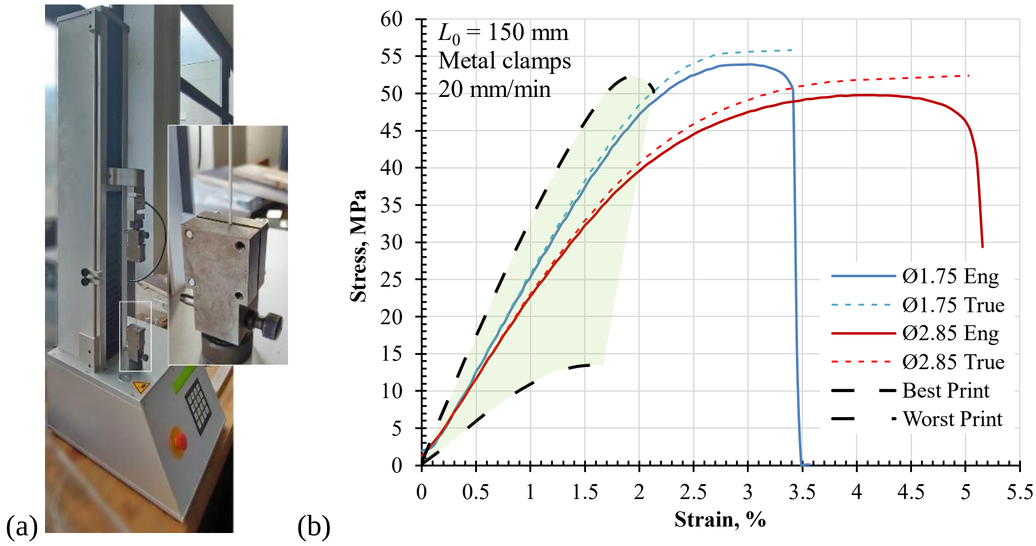


Fig 1. **Tensile test first approach:** (a) MFC T-500 tensile testing machine; (b) Stress-strain curves of raw filament at L_0 = 150 mm using metal clamps

Figure 1 (b) compares our previous results from the 216 FDM specimens. The large set of their stress-strain curves is presented as a green area between the "Best Print" and "Worst Print" lines. Printed PLA specimens had a brittle behaviour, with maximum strain near or lower than 2%, while the raw PLA filament strain at fracture is relatively larger and partly exceeds 5%. The tensile strength of the printed PLA varies from 13 to 53 MPa, and the Young's modulus ranges from 900 to 3300 MPa [10]. The raw material strengths are near or higher than the maximum value of the printed set.

During the first tests, the slope of the curves and the maximum strain depend on the filament diameter and the clamps' material. Soft PLA clams may avoid premature fracture but sometimes lead to sliding and even releasing the specimen during the test. The larger the diameter, the more significant these unwelcome effects are. The decision was to make a more substantial number of tests and to use only those curves where qualitative grip is observed visually and no chatting was observed in the stress-strain curve. The same approach is used with the metal clamps, where some tests are without premature fracture. Finally, we achieved a 49.4 MPa mean value for tensile strength with a standard deviation of 3.0 MPa and 2240 MPa for Young's modulus with a standard deviation of 290 MPa (Figure 5).

To account for the reduction in cross-sectional area during the test, engineering stress-strain curves $\sigma(\varepsilon)$ can be transformed into true stress-strain curves $\sigma_t(\varepsilon_t)$ using the following relationships [15]:

$$\varepsilon_t = \ln(1 + \varepsilon) ; \sigma_t = \sigma(1 + \varepsilon), \quad (1)$$

for the zone of even strain distribution (before necking) and with a tangent straight line afterwards. The true stress-strain curves are also shown in Figure 1 (b) with dashed lines. This transformation led to an increase in ultimate tensile stress of about 3.5-5.3%. Still, the Young's modulus is significantly lower than expected and cannot be obtained without precise strain measurement.

Using this first approach, we additionally tested three-month-old filament with the same design plan as the fresh filament, resulting in a total of 24 specimens with a nominal length of 150 mm. The results are also given in Figure 5. They show that an age of three months outside of the hermetically sealed package has no significant effect on the filament strength and stiffness.

The First Approach with a nominal specimen length of 450 mm

Using the first approach, we repeated the tests using a three times larger nominal specimen length L_0 = 450 mm instead of 150 mm, but this time, we only used new filament. The main goal was to study the influence of the nominal length on the Young's modulus when extensometers are not used.

Twelve specimens were tested, with the two diameters and the two types of clamps. The results are shown in Figures 2 and 5. Figure 2 shows that the diameter influence on the stress-strain curve decreases with the increase of nominal length. Figure 5 shows that increasing the nominal length does not affect ultimate tensile stress but increases the Young's modulus mean value by 19.6% – from 2240 MPa to 2680 MPa. This value is closer to the mean value achieved with our following test approaches but still 14.1% lower than the results with injection moulded specimens and contact extensometer. At the same time, the standard deviations decreased. So, the effect of increasing L_0 on the tensile test results when an extensometer is not used is entirely positive.

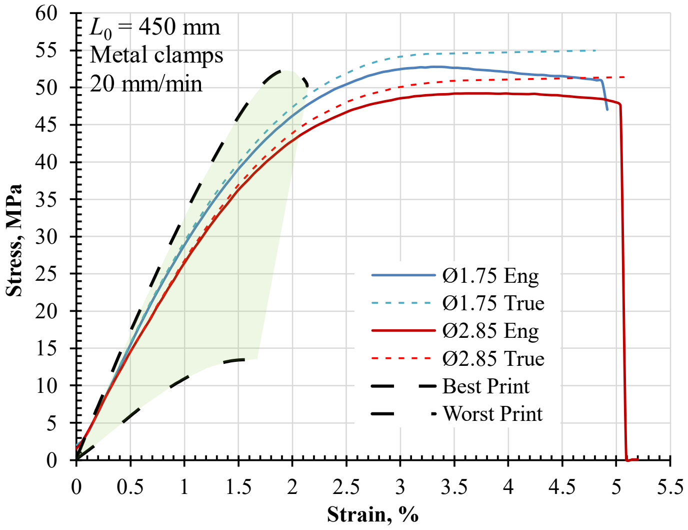


Fig 2. **Tensile test first approach:** Stress-strain curves of raw filament at L_0 = 450 mm

The Second approach – true longitudinal strain using laser-speckle

For precise determination of the Young's modulus, a MESSPHYSIK prototype of a micro-tensile-testing machine with up to 0.6 kN nominal force equipped with a laser-speckle extensometer was used, along with specially printed carbon-fibre reinforced PLA clamps – Figure 3 (a).

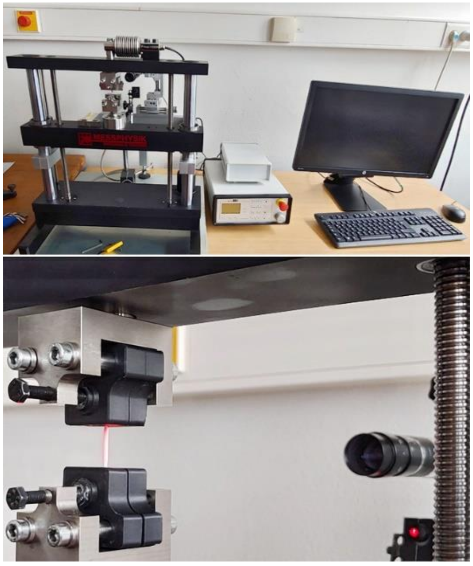
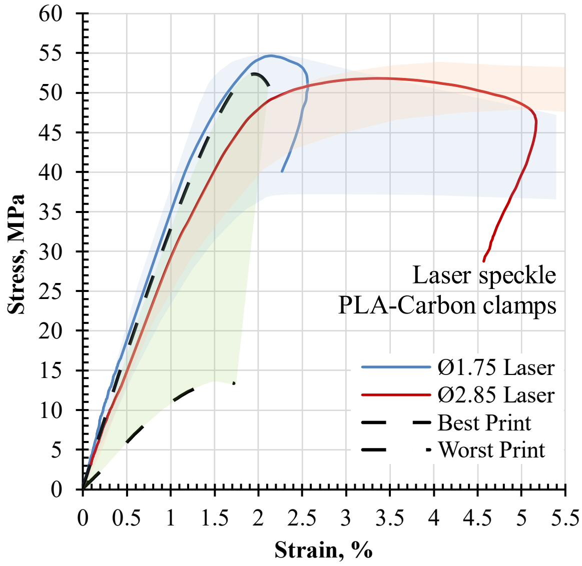
(a)  (b) 

Fig 3. **Tensile test second approach:** (a) MESSPHYSIK tensile testing machine with laser speckle; (b) Stress-strain curves

Overall, 30 specimens with the two diameters were tested. Since the surface of the filament is smooth, the surfaces were slightly roughened with sandpaper to increase the chances for a reliable strain measurement using the laser-speckle extensometer. Typical stress-strain curves are shown in Figure 3 (b). In the same figure, three areas of stress-strain curve distribution are outlined: previously mentioned FDM-printed specimens in green, Ø 1.75 mm filament in blue, and Ø 2.85 mm filament in red. The mean values of strength and stiffness are presented in Figure 5.

The MESSPHYSIK machine measures the Young's modulus of 3000 to 3120 MPa, which is closer to or even higher than the best printed specimens. The results are also very close to the injection moulded specimens (the third approach) but with higher standard deviations. The strength and the maximum strain values are similar to those of the previous approaches. Yet, the same problem with the slipping in the grips at higher forces was observed, which caused the large blue and red areas in Figure 3 (b). Achieving reliable results required several tests to be made and unsuccessful to be omitted. Still, the standard deviation stays high.

The third approach – injection-moulded specimens

To compare the results with standardised methods of testing, the injection moulding machine Arbug 320 C with moulds in accordance with ISO 527-2 [13] was used to produce 27 test specimens (Figure 4 (a, b)). The material used was Verbatim© PLA white filament, Ø 2.85 mm, after cutting into 10–15 mm long pieces to fit into the granulate inlet. Tested specimens are shown in Figure 4 (c), which shows that more than 80% of the specimens are not broken near the radius of curvature, so unwanted stress concentration is generally avoided. Despite the excellent specimen shape and gripping, nearly a third of the tests led to brittle fractures (but above 48 MPa). This behaviour did not affect the material stiffness.

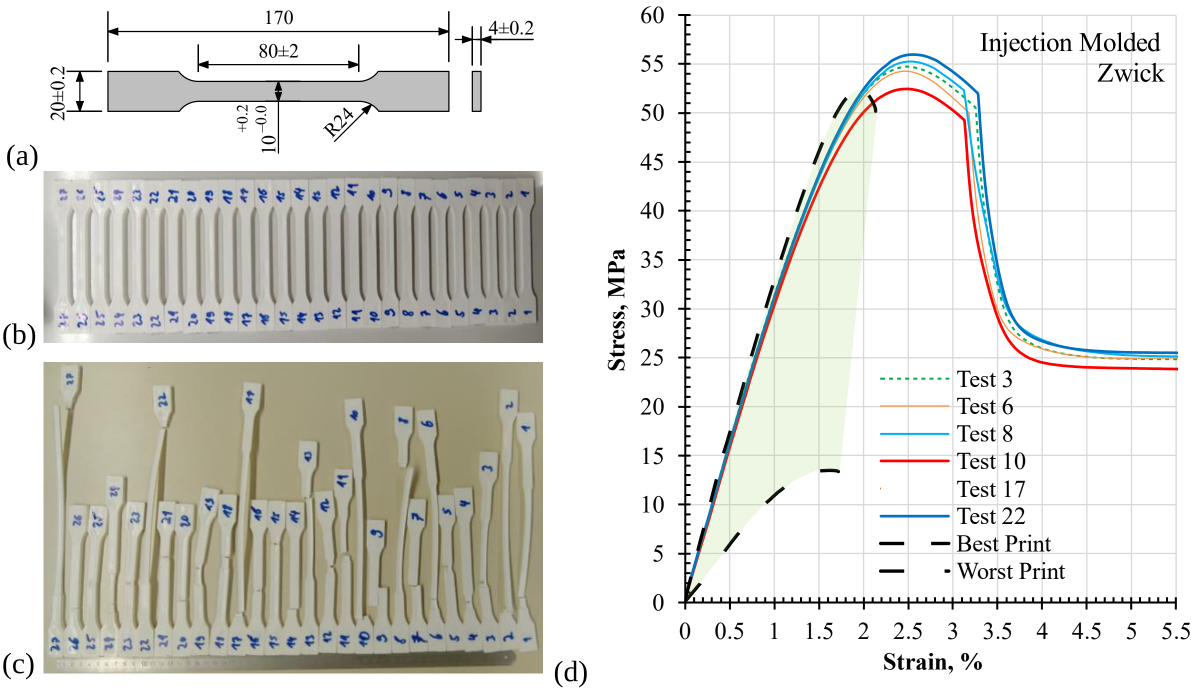


Fig. 4. **Injection moulded specimens:** (a) ISO 527-2 Type 1A specimen shape and size, mm; (b) Produced specimens; (c) Tested specimens; (d) Stress-strain curves

Six of the 27 achieved stress-strain curves are shown in Figure 4 (d). Averaged values for strength and stiffness are included in Figure 5 for comparison. Overall, the results are well-grouped, with a slight standard deviation of 60 MPa (1.9% of the mean value) for Young's modulus and 2.28 MPa (4.3% of the mean value) for strength. The tensile strength is 52.4 MPa, up to 4% higher than the raw PLA and practically equal to the best-printed specimens. The Young's modulus is 3120 MPa – almost equal to the raw material obtained by the second approach and the best-printed specimens.

Results and discussion

Averaged data from all the experiments performed are shown in Figure 5. In addition to the observations already made, the following generalisations can be made about the influence of the studied parameters on the experimentally obtained values of the PLA strength and stiffness:

- *Testing machine.* While the universal tensile testing machine with an extensometer is the best for testing flat specimens, smaller and more sensitive machines are preferable for small filament diameters. Accurate determination of Young's modulus requires precise strain measurement equipment. In our study, the MESSPHYSIK testing machine with laser speckle gave very good results. If the interest is only on the tensile strength and material behaviour under high loads, significantly simpler machines such as the MFC T-500 are also suitable.
- *Nominal length.* In the case of measuring engineering stress and strain, using a larger L_0 of 450 mm resulted in a smaller standard deviation and more accurate Young's modulus results than the L_0 of 150 mm. This reduced the Young's modulus difference from 28.2% to 14.1% compared to the values obtained by the third approach using injection-moulded ISO 527 specimens.
- *Clamps material.* Both metal and PLA clamps sometimes experience undesirable phenomena when testing cylindrical filament: premature failure due to stress concentration (more common with smaller diameters) or vice versa – slipping and even releasing without failure (more common with larger diameters). The current solution is to conduct more tests and ignore the unsuccessful ones. This way, the clamp material will not affect the final results. Further design improvements of the clamps should be considered.
- *Cross section.* As it can be seen from Figures 1 (b), 2, 3 (b), and 5, the Ø 1.75 mm filament exhibits slightly higher strength and stiffness, as well as greater brittleness than the Ø 2.85 mm filament, but the differences are generally not significant. These differences may be due to slight differences in material properties and undesirable effects in the clamps during testing.
- *Filament age.* The tests showed that an age of three months has no significant effect on the filament's strength and stiffness.
- *Processing technology.* The results obtained allow the mechanical properties of the raw PLA filament to be compared with those of finished parts made of the same material using two different technologies – injection moulding and 3D printing. It was found that the Young's modulus and tensile strength of the raw and injection-moulded materials are practically the same. This shows that remelting the filament once does not affect the Young's modulus or tensile strength. The same mechanical properties can be achieved through FDM, which requires a large amount of knowledge and an optimal combination of the process parameters. Otherwise, the mechanical properties of the 3D printed parts can be much worse than those of the starting material, as visible from the green areas in Figures 1 (b), 2, (b), and 4 (d).

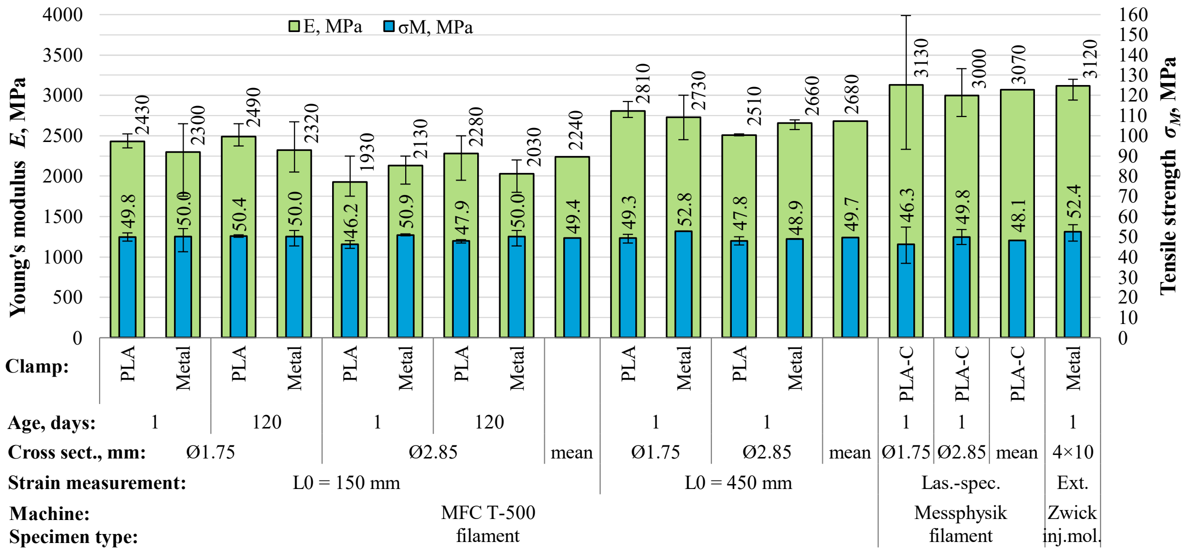


Fig. 5. **Tensile strength and Young's modulus of the tested groups of specimens**

Conclusions

Summarising the investigation shows that the tensile strength and the Young's modulus values from the injection-moulded specimens, the best 3D-printed specimens, and the raw filament are similar. The tensile strenghts from all tests varying only by about ± 3.3 MPa from the mean of 49.4 MPa. The Young's modulus values from the second and the third approaches are in the range of 3065 ± 65 MPa.

The results prove that re-melting the PLA once does not affect its mechanical properties. Also, the clamping material, filament diameter, and age difference of three months have no significant effect on the examined mechanical properties. The best approach to experimentally achieve stress-strain curves for numerical modelling is injection moulding of flat specimens and standard testing with universal machines. However, testing of FDM specimens cannot be avoided when the influence of printing parameters must be considered.

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Author contributions

Conceptualisation, N.N.; methodology, M.S. and N.N.; validation, M.S.; formal analysis, N.N and M.S.; investigation, M.S. and N.N.; data curation, M.S.; writing – original draft preparation, N.N.; writing – review and editing, M.S. and N.N.; visualisation, N.N. and M.S.; project administration, N.N.; funding acquisition, N.N. All authors have read and agreed to the published version of the manuscript.

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