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Mechanical Properties of Fused Deposition Modeling (FDM) 3D Printing Materials

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Zusammenfassung

This report contains the mechanical description of 8 material types, which were printed via Fused Deposition Modeling (FDM) and tested based on the standard EN ISO 527-1, in order to characterise the different materials from a mechanical point of view and compare the measured mechanical properties to the values given by the manufacturers. Special emphasis is placed on the manufacturing process of the testing specimens, thus providing insight into the best method for printing each filament material and enabling the exact replication of the different samples. As the tests were conducted complying with the standard EN ISO 527-1, the obtained results can be compared to other published results. It was observed, that printing with a polyamide (PA) filament generated the strongest material, while the stiffest material was produced by utilizing a filament made of polyethyleneterephthalate reinforced with carbon fibers (PET-C). All measured specifications were lower than the values given by the manufactures.

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1. Introduction

Among the numerous methods of 3D printing, fused deposition modeling (FDM) is probably the most popular due to its easy usability and low costs. FDM entails the extrusion of a melted filament through a 0.4 mm diameter nozzle, building up an object layer upon layer. In this fashion, objects exhibiting even complex geometries can be readily produced and utilized as mechanical parts in applications where the occurring forces are not exceedingly high. Furthermore, the 3D printed parts are oftentimes used for prototype test setups, to eliminated design errors before producing solid steel parts, for which manufacturing is much more time intensive and material costs are higher.

Disadvantages, concerning the strength or stiffness of the FDM materials in comparison to other conventional materials, as well as the long printing times of a single part in comparison to the swift process of injection molding, are obvious. However, FDM provides a good alternative for the production of prototypes or simple custom-made tools.

In this study, typical mechanical characteristics of tensile specimens of a standard geometry which were produced under clearly defined conditions with different filament materials for 3D printing were tested and evaluated. Thus, it was possible to compare the mechanical properties of the different materials with each other, as well as with the properties given by the manufacturers.

2. Methods

2.1. Study Design

The current experimental study gives an overview of the mechanical properties of 8 different filament material types. 4 specimens were produced per filament type. This is not completely corresponding to the testing standard EN ISO 527-1 which defines the minimum number of specimen as 5. The testing parameters, however, were done according to the standard. The results of this study can readily be replicated by closely following the taken steps during measurement and adjustments of the print settings.

2.2. Sample Geometry

The EN ISO 527-1 standard provides a definition of the specimen geometry which is to be used for testing. The application of this particular standard for mechanical testing of materials produced by FDM has previously been reported [1]. The tensile specimen is designed with Autodesk Inventor Professional 2017 (Autodesk, Inc.), exported as *.stl file and imported to the slicer 3D printer software Cura (Ultimaker).

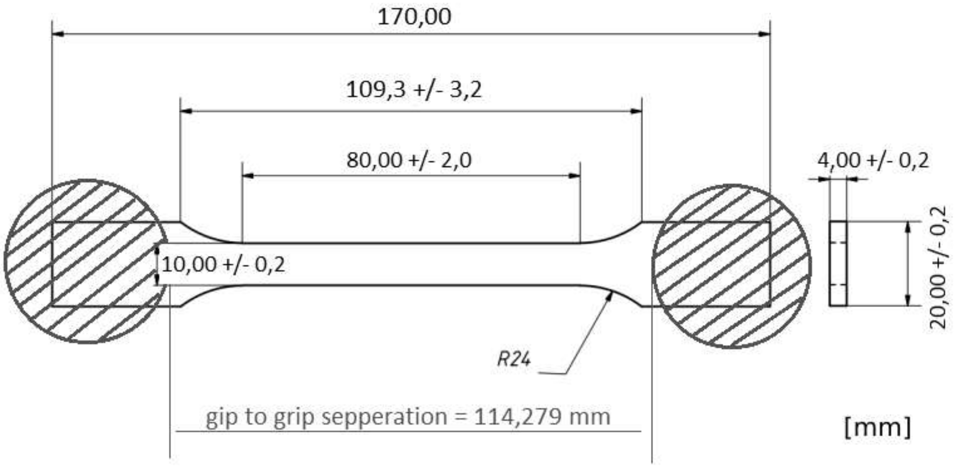

Figure 1: Specimen geometry: The blue hatched circles indicate clamping are in the testing machine

2.3. 3D Printing Materials

Table 2 supplies the mechanical properties as given by the manufacturers for the different materials which are listed in Table 1. In some cases, there was no data available from the manufacturer.

Table 1: Material abbreviations

Abbreviation	**Full Name**
PLA	Polylactide
ABS	Acrylnitril-Butadien-Styrol-Copolymer
PLA-H	Polylactide-HOLZ
PET-C	Polyethylenterephthalat-CARBON
PET	Polyethylenterephthalat

PA-C	Polyamide-CARBON
PA	Polyamide (Nylon (r))
TPE	(TPE-U) Thermoplastic-Elastomer-Urethane

Table 2: Material specifications as provided by the manufacturers

	Reference	**Young's Modulus (E) [MPa]**	**Yield Stress (σ) [MPa]**	**Strain at Break (ε_b) [%]**
PLA	[2][1]	3500	60	-
ABS	[3]	2000	44	-
PLA-H	[4]	3290	46	-
PET-C	[5]	3800	52,5	8
PET	[6]	2150	50	20
PA-C	[7]	6000	100	-
PA	[8]	-	45,574	34
TPE	-	-	-	-

Most manufacturers provide recommendations for appropriate printing conditions, depending on which filament is used. The nozzle temperature T_N is normally given within a small range. The exact value of the optimum temperature might also depend on which printer is utilized. At this point, the price of the different filaments is also noteworthy (see [Table 3]). The bed temperature is defined as T_B.

Table 3: Recommendations for printing different materials provided by the manufacturers

	T_N [°C]	**T_B [°C]**	**Second Material [%]**	**∅ [mm]**	**Brand**	**Price [€/Kg]**	**Part Name**	**Ref.**
PLA	190 - 220	60	non	1,75±0,03	Tianse	18,99	TS-3D-blue-1	[9]
ABS	210 - 260	90-120	non	1,75	Prima Fil.	23,90	PVABS175WT	[3]

PLA-H	190 - 220	60	20-30 wood shaves	1,75±0,03	Tianse	28,99	TS-3D-Wood-1	[4]
PET-C	230 - 265	80	~20% carbon fibre	1,75	ICE FIL.	35,57	ICEFIL1CRB138	[5]
PET	195 - 220	70	non	1,75	ICE FIL.	30,92	ICEFIL1PET153	[6]
PA-C	240	60	-	1,75	EUMAKERS	99	non	[7]
PA	250 - 255	30-65	non	1,75	Taulman	139,33	10523	[8]
TPE	195 - 210	-	non	1,75	FlexiSmart	64	ASIN:B018SMIIIM	[10]

2.4. Printing

The utilized printer for this study is a Anycubic i3 Mega 3D Printer (Shenzhen Anycubic Technology Co., Ltd) [11] with the following specifications:

model: Anycubic i3 Mega

certifications: CE, FCC, RoHS and EN

printing technology: FDM (Fused Deposition Modeling)

layer resolution: 0,05 - 0,3 mm

position resolution: X/Y 0,01 mm Z 0,002 mm

printing velocity: 20 - 100 mm/s (recommended velocity 60%)

driving speed: 150 mm/s

nozzle diameter: 0,4 mm

extruder numbers: 1

supplied printing materials: PLA, ABS, HIPS, HOLZ

max. building geometry: 210 x 210 x 205

temperature:

heating bed max.: 100°C

operational extruder temp. max.: 260°C

ambient temperature: 8°C - 40°C

software:

handled formats: STL, OBJ, DAE, AMF

slicer software: Cura

cura output format: gcode

connectivity: SD-card and USB supply

electric:

input max.: 100 - 240 V AC, 50/60 Hz, 1,5 A

printer size: 405 x 410 x 453 mm

In the open source 3D printing software Cura, it is possible to process the *.stl file and define the desired print settings like print quality, topology, speed and temperature. See [subsection 7.2] for the print settings of all utilized materials.

The structure of the printed sample consists of a 0,8 mm outer wall and an inner structure, which is printed in an alignment of 45° in regard to the wall (see [Figure 2]). Upon completion of one print layer, the next following layer has an alignment which is flipped by 90° compared to the previous layer. This method of printing is called ±45° printing and should reduce anisotropy. Of course the thus obtained materials exhibit lower mechanical strength when compared to materials with a print direction, parallel to the vector of force applied for testing, but the aim is to achieve results that are comparative to parts, which are actually used and are printed the same way.

A manual was established to define the print modes which describe optimal pre-print settings for each material. This manual was developed based on pre-tests and was used for the manufacturing of all tensile specimens. For example, a self-constructed layer provides additional support for the ABS tensile specimens at their base (see [Figure 3]), due to the fact that the support layers constructed automatically by Cura are frequently insufficient. It is important to support the edges of the specimen to avoid shrinking (warping) of the material [12]. To prevent the specimen from lifting off the print platform, a degree of 90° between the specimen's long axis and the edges between the strips of blue tape is advantageous [Figure 4]. While both the small, as well as the big clamps, securing the specimen (see [Figure 4] and [Figure 5]) provide adhesion between the specimen and the platform it is printed on, the big clamps predominantly support the mid-part of the specimen.

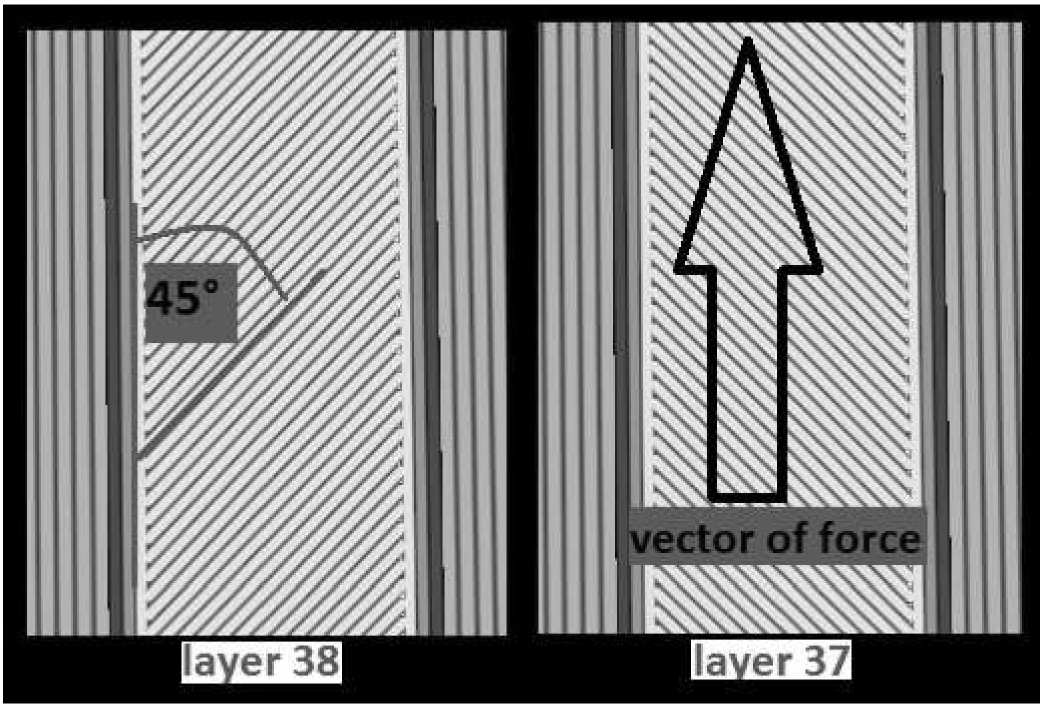

Figure 2: print structure: red= outer wall, green=whole wall thickness, yellow=inner structure

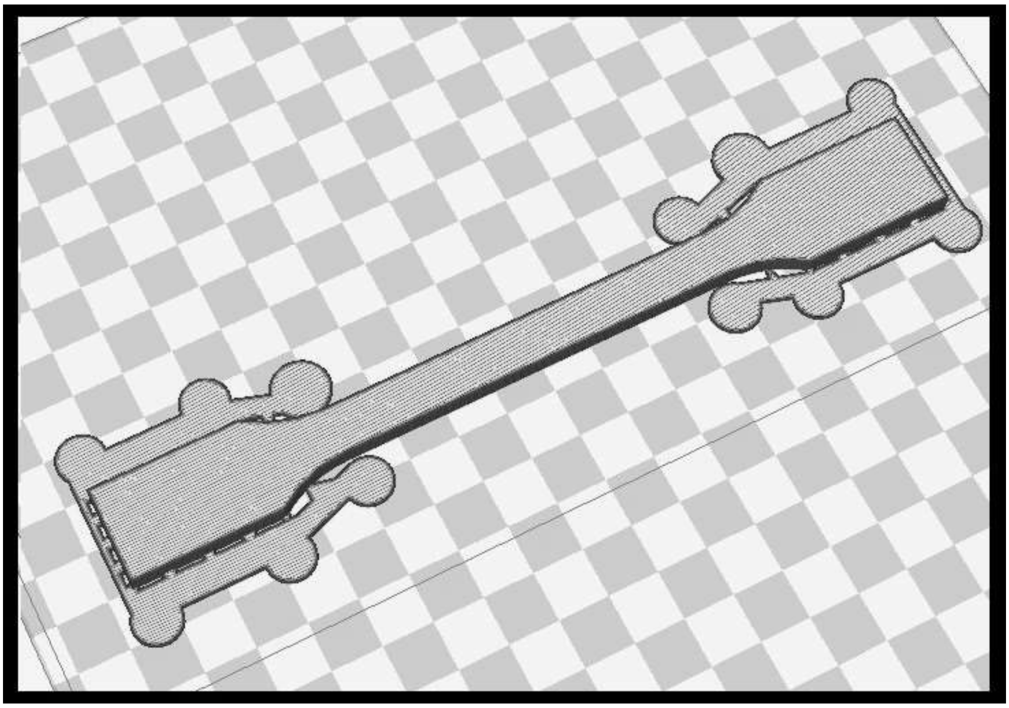

Figure 3: self-constructed additional support to avoid shrinking

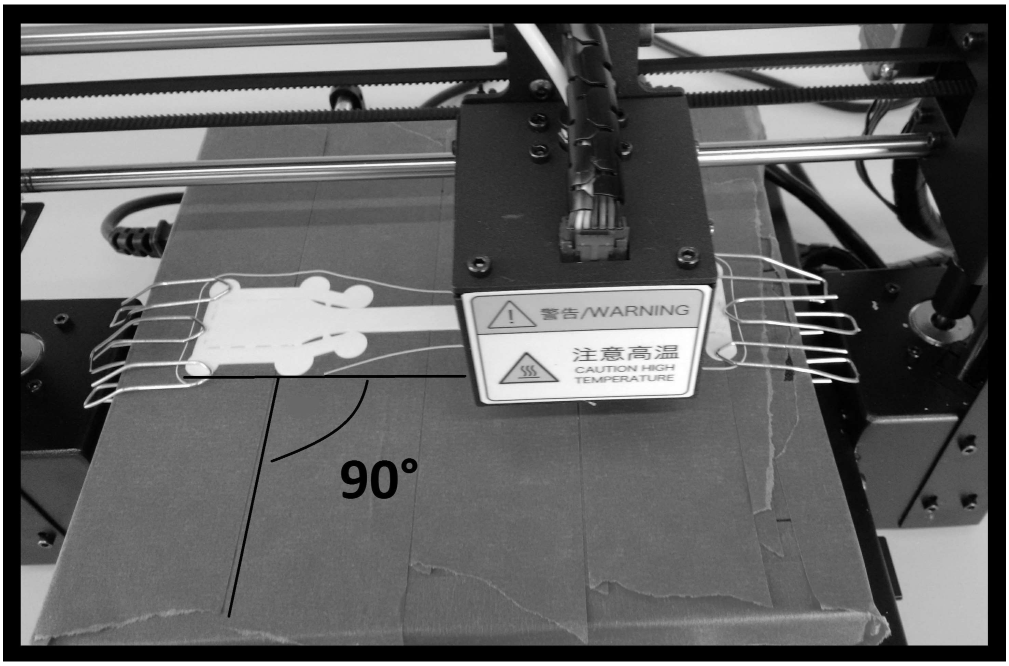

Figure 4: small clamps to provide adhesion to the platform and print orientation

Figure 5: big clamps to provide adhesion to the platform

A brim signifies the standard first layer constructed by the Cura software: It entails the printing of an 8 mm wide bottom layer surrounding the specimen. Glue is required for certain materials in order to avoid sample detachment, and adhesive tape provides additional adhesion (subsection 7.3). It depends on the tension within the specimen itself, whether glue or blue tape is needed. If the tension during the printing process is too high, which leads to the removal of blue tape from building plate, glue is needed. In the case of PLA for example, blue tape is sufficient, while PA requires the application of glue. Generally, glue is impractical (as it requires labour-intensive cleaning of the building plate) in comparison to blue tape, but in some cases is inevitable. See Table 4 for a summary of the printing requirements for the different materials.

Table 4: print modes: mechanical support of the specimen

	Small Clamps	**Big Clamps**	**Brim**	**Additional Support**	**Glue**	**Blue Tape**
PLA	NO	NO	NO	YES	NO	YES
ABS	YES	NO	NO	YES	NO	YES
PLA-H	NO	NO	NO	YES	NO	YES
PET-C	YES	NO	YES	YES	NO	YES
PET	YES	YES	YES	YES	NO	YES
PA-C	YES	YES	YES	YES	YES	NO
PA	NO	NO	YES	NO	YES	NO
TPE	NO	NO	YES	NO	NO	YES

The optimum temperature and flow adjustments were also defined over pre-tests. An appropriate print temperature is crucial for the strength of the cohesion between the layers, as well as suitable flow characteristics of the melted filament inside the nozzle. Better specimen stability is attained by increasing the initial layer temperature compared to the print temperature of the subsequent layers, due to the fact that the contact surface of the filament's cross section with the building bed is increased for the first layer. An appropriate bed temperature provides conditions protecting against warping, and the material has more time to cool down evenly. For some materials it is also necessary to decrease the print speed while increasing the flow rate, as is the case for TPE for example. Presumably, the reason for this is that TPE's high flexibility yields a higher resistance between the filament and the nozzle, leading to the requirement of more pressure (higher flow rates) to extrude the filament. See Table 5 for a summary of the temperature requirements for the different materials.

Table 5: print modes: temperature, speed, flow rate

	T_N [C]	Initial Layer T [°C]	T_B [C]	Flow [%]	Print Speed [mm/s]
PLA	200	200	60	100	60
ABS	255	255	120	100	60
PLA-H	200	200	60	100	60
PET-C	255	260	80	100	60
PET	240	255	80	100	60
PA-C	240	250	70	100	60
PA	255	260	60	100	60
TPE	215	220	60	130	45

2.5. Mechanical Testing

The utilized tensile testing machine Z030, produced by the company Zwick/Roell, enables a maximum load of 30 kN. For measuring loads, a 30 kN load cell was used (Xforce K by Zwick/Roell) alongside an extensometer with an initial length L_0 of 25 mm (BTC-EXICLEL.001 by Zwick/Roell).

All specimens were pneumatically clamped into the testing machine at the position signified by the blue hatched circles in [Figure 1] with a pressure of ~7.5 bar, leading to a clamping force of ~45 kN for each clamp. [Figure 6] depicts a standard testing situation

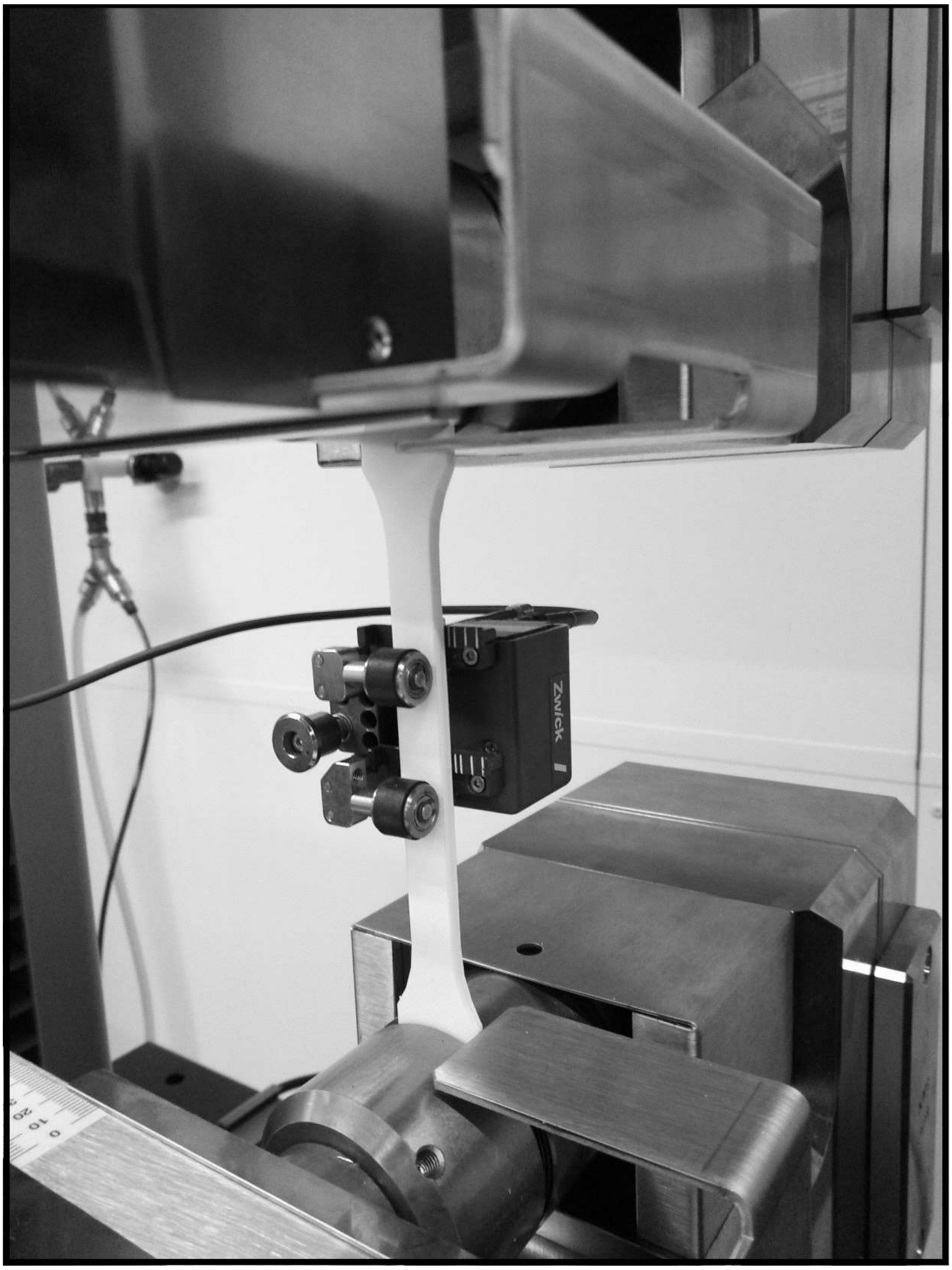

Figure 6: specimen in test position and extensometer applied

The temperature and humidity were not continuously reported throughout the testing period. The 3D printing and storing conditions were between 21°C and 25°C temperature and between 20% and 40% humidity. The tests themselves were done in the course of one day, the temperature being 24°C and relative humidity 20%. A pre-load of 0.5 MPa was applied at a speed of 5 mm/min. The test speed was also 5 mm/min with an initial grip to grip separation of 114.3 mm for each specimen.

Time, force, displacement and strain data were recorded at 100Hz. Nominal stress was calculated by the testing software by relating the force reading to the initial crossectional area of the respective specimen. The position for measuring the cross section of the specimen (whithin the 80 mm measuring length) was randomly selected (see [Figure 1]) and cross sections were recorded 5 times for each specimen. The results were well within the range of tolerance defined by the testing standard [13].

2.6. Data Analysis

To calculate the Young's modulus E as the slope of the measured stress versus strain curves, a range was defined in which the curve was sufficiently linear: 0.05% - 0.25% strain (see Figure 7) [13].

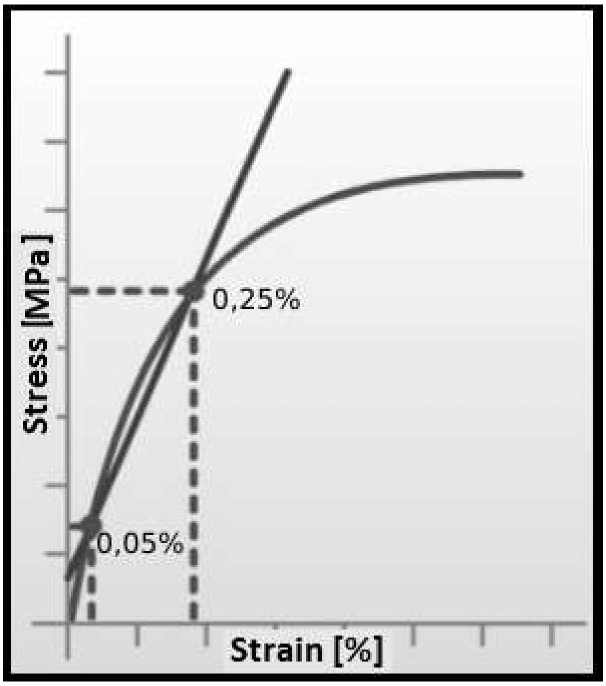

Figure 7: Young's modulus, blue line = measured data, black line = secant between 0.05% and 0.25% strain. (Image taken from Zwick TestExpert software)

The yield stress is described by the following two definitions for the test series:

- 1. According to the EN ISO 527-1 and other sources [14] [15] the yield stress for non-flexible materials is given by the maximum stress value of the specimen, while for flexible specimens the yield stress does not exist. This definition is based on Shah et al. (1998): "The first point on the stress-strain curve at which an increase in strain occurs without the increase in stress" [15]. In the Results section the thus defined yield stress is referred to as "Yield Stress ISO-527" (σ yISO).

- 2. Alternatively, the yield stress is defined at the point where the stress-strain curve intersects the linear function that has the Young's modulus as slope and a 0.2% strain offset [14]. In the Results section the thus defined yield stress is referred to as "Yield Stress 0.2% offset" (σ 0.2), [Figure 8].

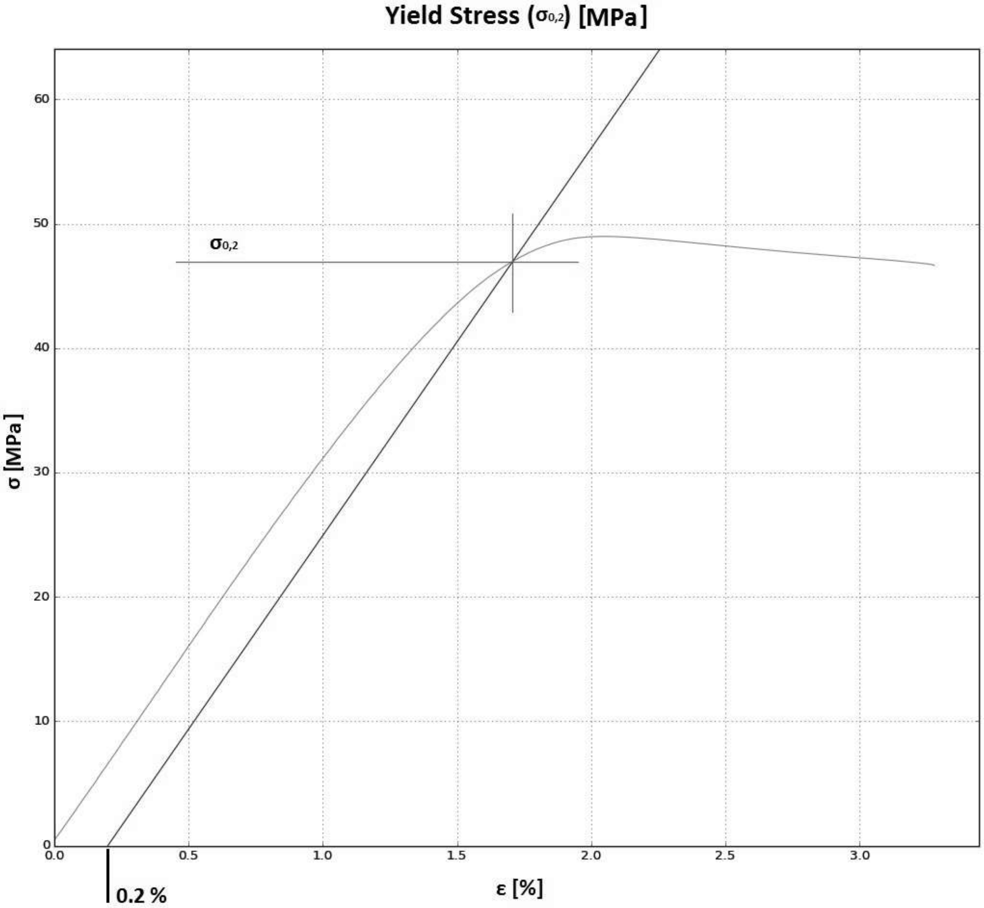

Figure 8: Stress-strain curve; explaination of "Yield Stress 0.2% offset"

The nominal stress at break σ_b, and the strain at break εb where specimen failure occurs, is evaluated under consideration of plastics, for which no clearly distinguishable breakage is observed; this is especially the case for the PLA-H material. The applied algorithm takes into regard the different mechanisms of breaking: the hard break observed for PLA and the soft break for the PLA-H material. σ_{max} describes the maximum measured nominal stress and the relative grip to grip length change is given by *Gb*.

3. Results

The graph Figure 9 shows the nominal stress on the y-axis while the x-axis displays the strain measured by the extensometer [15]. The amount of specimens for each material is 4. Table 6 and Table 7 list all measured mechanical properties for each

For PA and TPE no results for yield stress are available, because the "Yield Stress 0.2% offset" method is not feasible in their cases. Furthermore the "Yield stress ISO-527" method cannot be applied for the TPE material (due to their low stiffness).

In [Figure 9] the stress-strain curves for materials with low elongations are plotted, while [Figure 10] shows the curve for PA, which has a higher elongation, and in [Figure 11] the corresponding curve for TPE material with the highest elongation is plotted.

The elongation of PA and TPE exceeded the length of the extensometer. It was therefore neccecary to calculate the strain for PA and TPE by relating the cross-head displacement (*Gb*) of the Z030 to the initial sample length. PET-C exhibits the highest stiffness, PA the highest tensile stress, and TPE the greatest elongation. The carbon shaves makes the PA stiffer, but also weaker.

ABS is the weakest material tested. It can be concluded that the carbon shaves of the material PET-C (small carbon sticks, around 100 µm) provide the material with a higher stiffness and a higher tensile stress, compared to conventional PET[12]. Introducing wood shaves into the PLA filament, as is done for the material PLA-H, makes the material weaker (comparison of PLA to PLA-H), but the maximum elongation is increased.

Figure 10 shows how vast the difference in behaviour between the individual PA specimens is for the measurements. Furthermore, the TPE material also exhibits a high deviation in elongation and tensile strength among the individual specimens.

Table 6: Results for Young's modulus, yield (nominal) stress (according to two definitions), and maximum nominal stress obtained for the tested materials at defined print settings

	Settings	**E [MPa]**	$\sigma_{y\,ISO}$ **[MPa]**	$\sigma_{0.2}$ **[MPa]**	σ_{max} **[MPa]**
PLA	[Figure 19]	2940,5 ± 450,1	50,5 ± 1,6	48,6 ± 1,4	50,5 ± 1,6
ABS	[Figure 20]	1588,7 ± 3,6	24,3 ± 2,0	21,5 ± 4,2	24,3 ± 2
PLA-H	[Figure 21]	2393,4 ± 58,6	29,1 ± 0,7	26,1 ± 0,6	29,1 ± 0,7
PET-C	[Figure 22]	3523,4 ± 60,2	49,1 ± 0,8	36,9 ± 0,6	49,1 ± 0,8
PET	[Figure 23]	1629,9 ± 34,0	42,8 ± 2,9	37,2 ± 2,8	42,8 ± 2,9
PA-C	[Figure 24]	2325,9 ± 97,6	42,8 ± 2,6	25,7 ± 1,6	42,8 ± 2,6
PA	[Figure 25]	484,6 ± 52,8	51,3 ± 8,8	-	51,3 ± 8,8
TPE	[Figure 26]	15,3 ± 1,5	-	-	8,4 ± 1,8

Table 7: Results for nominal stress at break, strain at break, and relative length change between the grips for the tested materials

	σ_b **[MPa]**	E_b **[%]**	G_b **[%]**
PLA	47,4 ± 1,6	4,6 ± 1,1	2,8 ± 0,2
ABS	22,4 ± 1,2	4,5 ± 0,9	3,4 ± 0,5
PLA-H	24,2 ± 0,4	11,4 ± 1,7	5,8 ± 0,4
PET-C	46,5 ± 0,6	3,8 ± 0,5	3,0 ± 0,2
PET	40,1 ± 3,8	4,5 ± 0,9	3,9 ± 0,3
PA-C	39,5 ± 3,2	10,6 ± 6,1	7,1 ± 2,1
PA	40,1 ± 5,9		80,6 ± 45,6

		92,4 ± 52,3 2	
TPE	8,4 ± 1,8	497,1 ± 101,0 2	436,7 ± 89,2

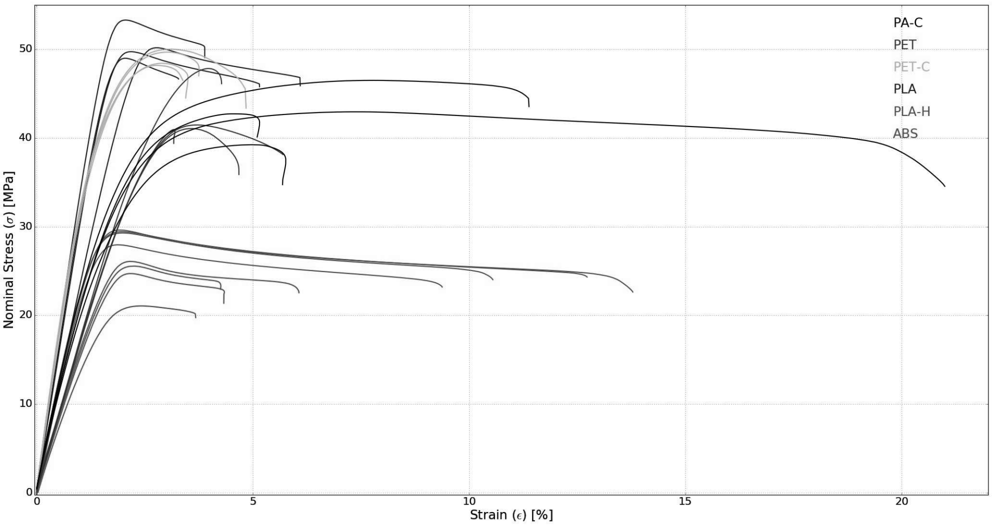

Figure 9: Nominal stress vs. strain for PA-C, PET, PET-C, PLA, PLA-H, and ABS

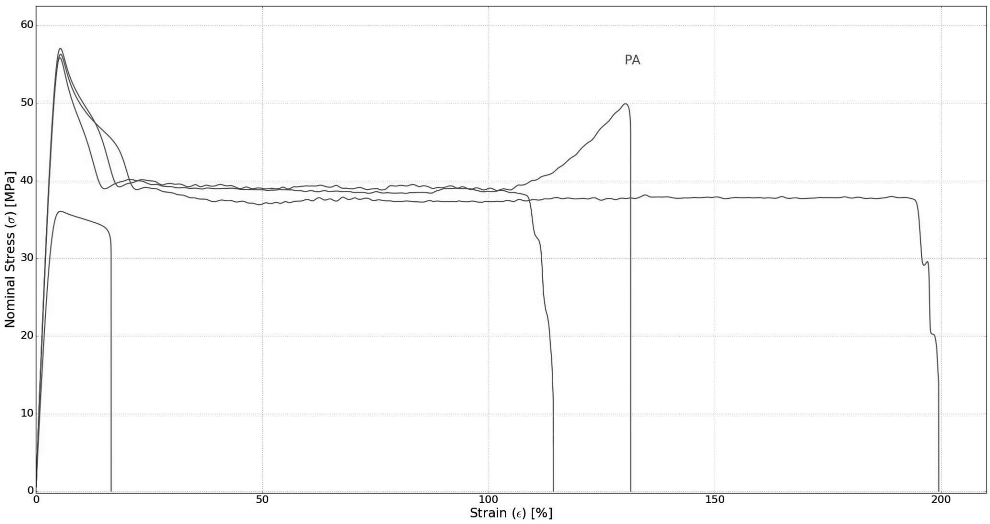

Figure 10: nominal stress vs. strain for PA

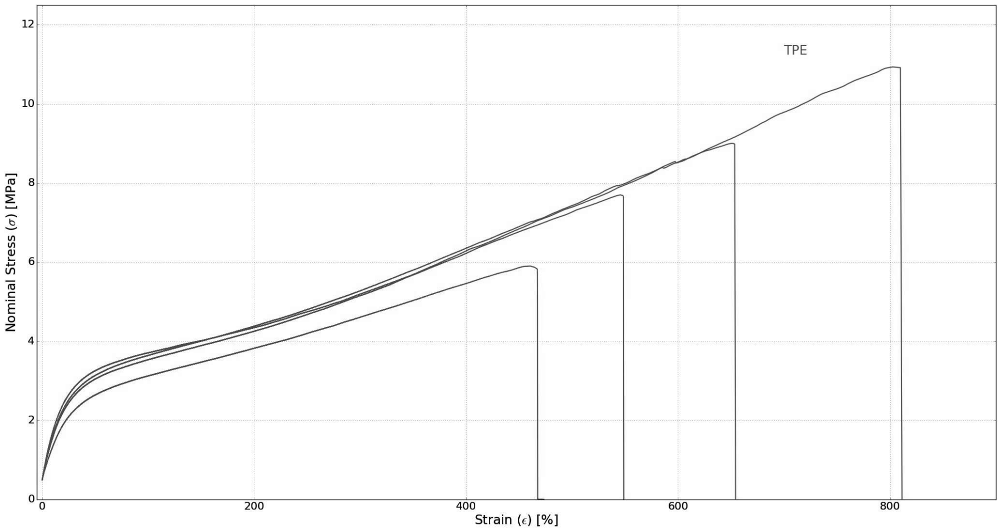

Figure 11: nominal stress vs. strain for TPE

Figure 12 and Figure 13 compare the values provided by the manufactures and the measured data. The PA and TPE materials are excluded from Figure 12 and Figure 13, due to the fact that their much lower values of Young's modulus and yield stress (compared to the other tested materials) would hinder a good illustration. PLA has the highest deviation for the measured values, concerning its Young's modulus (see Figure 12), and PA-C exhibits the highest difference between values according to the manufacturer and the measured values for the Young's modulus as well as the yield stress (see Figure 12 and Figure 13).

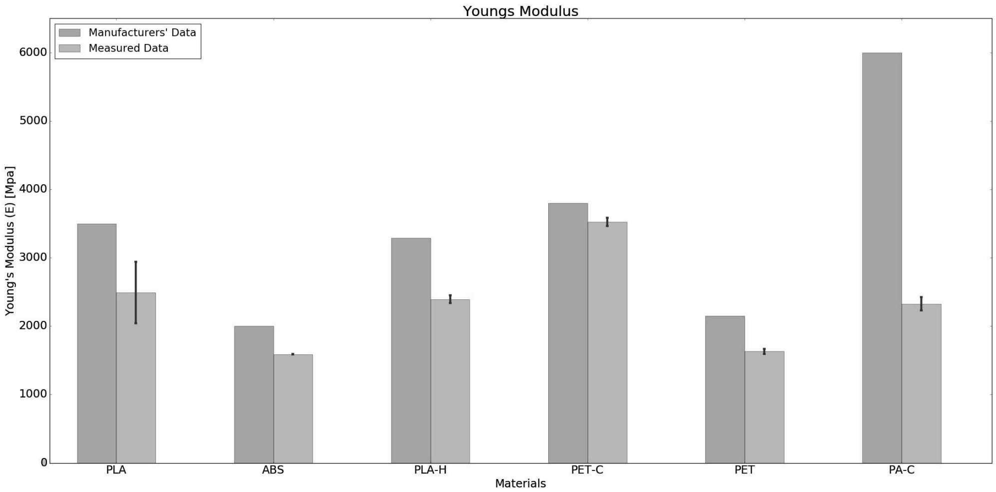

Figure 12: Young's modulus: blue = data given by the manufacturers, red = measured data complying with the standard EN ISO 527-1

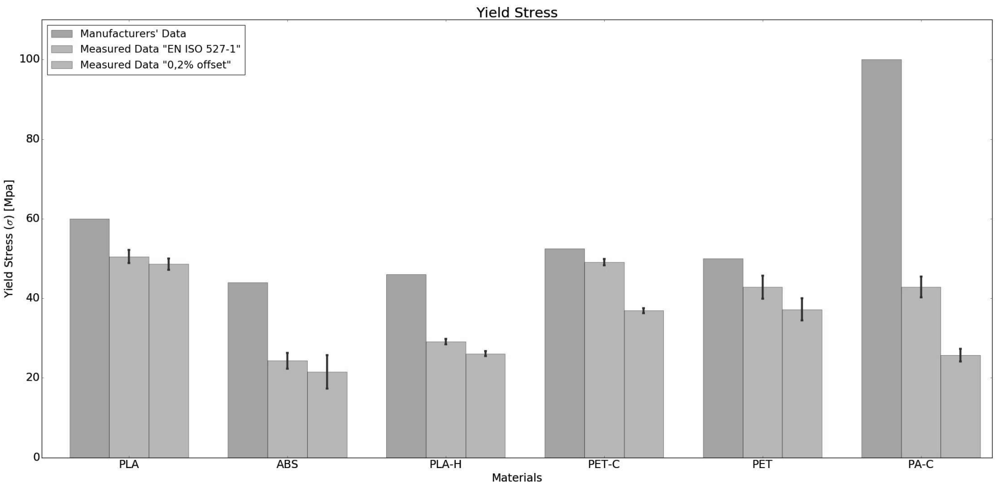

Figure 13: yield stress: blue = data given by the manufacturers, red = "Yield Stress ISO-527", green = "Yield Stress 0.2% offset"

4. Discussion

Generally, all manufacturers' specifications are higher than the measured values, as is seen when [Table 2] is compared to [Table 6]. One explanation for this mismatch could be that if the filaments were to be printed in a direction parallel to the vector of force of testing, the mechanical properties would increase and possibly correspond to the manufacturers' specifications.

The reason for the deviation between manufacturer and measured data, especially for PA-C could be explained if the manufacturer's data describes the properties of specimens made purely of filament material, i.e. test specimens that were produced by injection molding. The manufacturers do not providing any substantial information regarding this issue.

The high variability in [Figure 10] and [Figure 11] indicate that a sample size of 4 or 5 (as demanded in the EN ISO 527-1) specimens is not enough, to make a statement of good quality.

Due to the fact that the graph for the PA-C material exhibits no sharp, clearly definable, maximum for the "Yield Stress ISO-527-1", this method of defining yield stress does not seem well suited for this material.

The strength of PET-C is surprisingly low, indicating that the failure occurs in the PET matrix rather than in the high strength carbon fibers. In some publications the low adhesion between the matrix and the shaves is exposed by electron microscopy [12] [16] [17].

The mechanical possibilities are limited for low budget 3D printing. If stiffness or yield stress are to be increased, an entirely different approach to 3D printing must be employed. For example, reinforced endless carbon fibre filaments with a high proportion of carbon can yield a material with an ultimate stress of ~700 MPa [18]. Continious carbon fibres are mechancially advantageous, concerning strength, as opposed to incorperating short fibre shaves, which interrupt the matrix material and only provide limited strength and stiffness increase [19].

5. Conclusion

Overall, PLA is a good filament choice regarding its price-performance ratio, if its relatively poor resistance to high temperature can be neglected. For applications under very high temperatures (up to ~110°C), ABS is advisable.

The advantage of 3D printing is that various different materials can be processed. For the ideal print quality it is important to follow appropriate guide lines. Selecting the right settings for the printing process is the biggest challenge, particularly, considering that sample detachment and warping are undesired effects. When designing a 3D printed part, it is not sufficient to take the manufacturer's data for granted, but one must rethink the mechanical claims. Many influencing factors exists which can change the mechanical properties adversely. From a mechanical point of view, it makes a difference whether the material is printed or molded, as the printing alignment or the gradual of infill alter the mechanical properties. Furthermore, the printing temperature must be considered.

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8. Downloads

Appendix A: Specimens
Appendix B: Printing Settings
Appendix C: Printing Tools

Volltext

Lizenz

Empfohlene Zitierweise