DOI: 10.2507/31st.daaam.proceedings.xxx

STRAIN RATE INFLUENCE ON MECHANICAL CHARACTERISTICS OF FDM 3D PRINTED MATERIALS

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This Publication has to be referred as: Katalinic, B[ranko]; Park, H[ong] S[eok] & Smith, M[ark] (2020). Title of Paper, Proceedings of the 31st DAAAM International Symposium, pp.xxxx-xxxx, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-xx-x, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/31st.daaam.proceedings.xxx

Abstract

One of the rapidly growing additive technology for polymer-based products is Fused Deposition Modeling (FDM), which is used for prototypes, single-part production and also small series production. Today, this technology is increasingly used for engineering purposes, and it is of great importance to know the mechanical properties of materials used in FDM technology, which are commonly thermoplastic polymers. The mechanical properties of materials are obtained by standard mechanical testing, but problem is that there are no official standards that define the method of mechanical testing of FDM materials. The aim of this study is to analyse the influence of the strain rate on tensile properties. Three different materials, PLA, tough PLA and carbon PLA, are examined. Strain rate was varied from 0,5 mm/min to 100 mm/min. The test was performed according to ISO 527-2. All specimens are 3D printed with 100 % infill and same 3D printing parameters.

Keywords: Strain Rate; FDM; 3D Print; Tensile Testing; PLA

1. Introduction

Additive manufacturing (AM), or 3D printing, is a process that can join materials in an additive way (layer upon layer), and builds a three-dimensional object from a computer aided design (CAD) model. One of the key advantages of 3D printing is the ability to make complex physical parts from 3D digital models. Additive manufacturing technique can be categorised into three fundamental groups such as [1], [2]:

- Liquid based (Stereolithography, SLA),
- Solid based (Fused Deposition Modeling, FDM) and
- Powder based (Selective Laser Sintering, SLS).

The most frequently used 3D printing technique is Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF). This technology belongs to the family of additive manufacturing processes that generally uses thermoplastics polymeric materials, but today there is also FDM with metal materials (Markforged Metal X System). FDM is used to create prototypes, single-part-production and also small batch manufacturing for the medical, aerospace, architecture, electronics, and automotive industries. Despite being one of the most used AM processes, it is not completely industrialized yet. This is due to the large number of parameters that govern the process, as well as the lack of standardization, studies, and communication [3], [4], [5], [6].

FDM printers utilize three main software [7]:

- CAD, software that is required for forming the object as a format of STL file, defines a 3D object in various 3D views.
- Computer Aided Manufacturing (CAM), software that takes 3D model as STL file and converts it into G-code file that contains instructions for the printer to control the parameters.
- Firmware, a software which loads into the memory of the printer and activates when it is turned on with no further modifications.

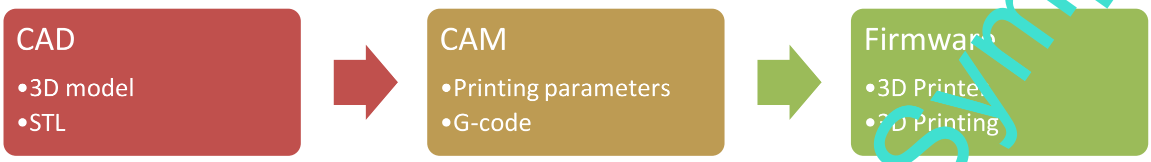

Fig. 1. Three main software for FDM printers

Process starts with part created in CAD software (Solidworks, Catia, Inventor etc.). The CAD model of the part is converted into a stereolithography (STL) file and uploaded into the slicer, a program used for cross sections the part into layers and prepare G-code with 3D printing parameters for 3D printer. In 3D printer, a thermoplastic filament is fed into a print head, with heated extrusion nozzle, using drive wheels in feeder, to deposit a molten polymer onto build plate. The nozzle translates in the x and y direction to create each individual layer. The build plate is then translated in the z direction to create each subsequent layer (Fig 2) [1], [8], [9], [10].

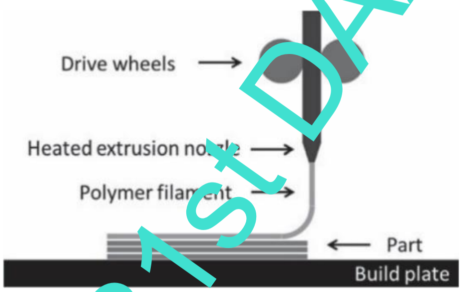

Fig. 2. Schematic of fused deposition modeling (FDM) 3D printing process [1]

The principle of the FDM technology offers great potential because, without any need of machining allows the fabrication of complex 3D parts directly from a computerized solid model. On todays market, there are many different materials for FDM such as thermoplastics, composites even metallic materials. Some of materials used today in FDM technology are presented on Fig 3 [8], [11].

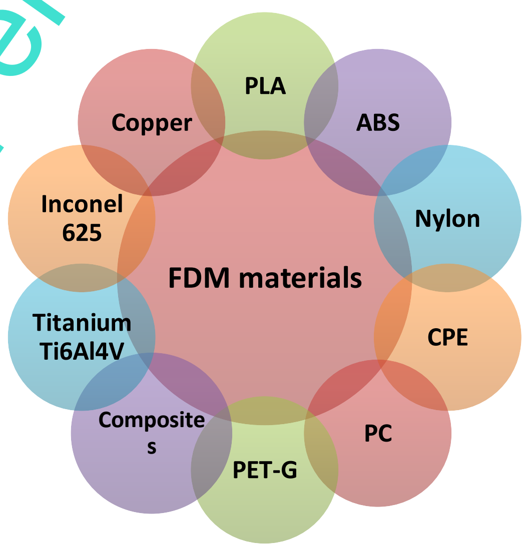

Fig. 3. Some of materials used in FDM 3D printing technology

As the application of FDM technology in engineering expands more and more, knowledge of mechanical properties of 3D printed materials is very important. Previous research shows that a large number of factors affect the mechanical properties of 3D printed materials (Fig. 4.) [8], [11], [12].

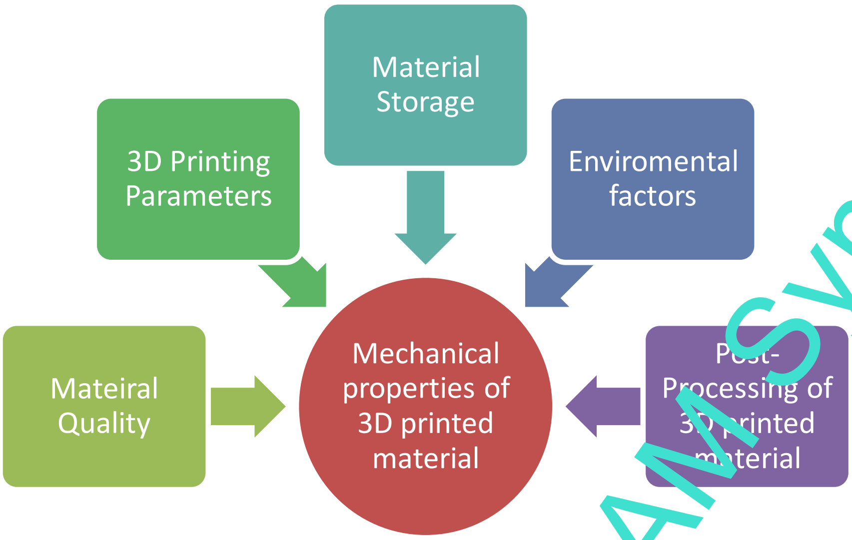

Fig. 4. Factors that affect the mechanical properties of 3D printed materials

By reviewing the literature it can be noticed that the accent is given to the influence of 3D printing parameters on mechanical properties of 3D printed material [3]. A large number of researches are based on mechanical testing (tensile, bending and pressure) of samples made with different 3D printing parameters. Aim of this study is to analyse strain rate influence on mechanical characteristics of FDM 3D printed materials. The test will be performed with five different strain rates on three different materials. Methods and results are presented in further text.

2. Methods

To determine the mechanical properties of 3D printed specimens and variability in these properties when different strain rate is used, this study looked at the relationship between strain rate and tensile mechanical properties of 3D printed materials. Three different types of material were used to make samples:

- Polylactic Acid – PLA (Ultimaker),
- Tough-PLA (Ultimaker) and
- Carbon fiber reinforced PLA - CFPLA (Proto-Pasta).

Today PLA became a popular print material, and thus also became a research topic. The PLA material is known as one of the favourite among the FDM 3D printing users. Polylactic acid is a natural polymer, derived from renewable sources, also it is renewable, compostable and biocompatible material [3], [12]. In this section, description from manufacturer technical data sheet will also be provided for all three materials:

- Ultimaker PLA – material that provides no-hassle 3D printing experience thanks to its reliability and good surface quality. Ultimaker PLA is made from organic and renewable sources. It is safe, easy to print with, and it serves a wide range of applications for both novice and advanced users. Good tensile strength and surface quality, easy to work with high print speeds, user friendly for both home and office environments, PLA allows the creation of high-resolution parts.
- Ultimaker Tough-PLA (T-PLA) – Is a technical PLA material with toughness comparable to Ultimaker ABS. Ideal for reliably printing technical models at large sizes. Ultimaker tough-PLA offers the same safe and easy use as regular PLA. With an impact strength similar and higher stiffness compared to Ultimaker ABS, tough-PLA is less brittle than regular PLA and gives a more matte surface finish quality. Heat resistance is similar to standard PLA material, so printed parts should not be exposed to temperatures above 60 °C. More reliable than ABS for larger prints, with no delamination or warping.
- Proto-Pasta CFPLA – Material is made from natureWorks 4043D PLA Resin compounded with 15% (by weight) chopped Carbon Fibers. It is more brittle than standard PLA in its filament form. This material is not "stronger", rather, it is more rigid. Increased rigidity from the carbon fiber means increased structural support but decreased flexibility, making CFPLA and "ideal" material for frames, supports, shells, propellers, tools, etc. The carbon fibers in this material are processed for an optimum size, short enough to print in PLA without clogging nozzles, but long enough to provide the added rigidity carbon fiber is famous for.

Materials came with wire (filament) diameter of 2,85 mm, also this is standard wire diameter size for Ultimaker FDM 3D printers. Tensile mechanical properties from manufacturer technical data sheet are presented in table 1.

Material	Yield tensile strength [MPa]	E-Modulus [MPa]	Strain at yield [%]	Strain at break [%]
PLA	49,5*	2346,5**	3,3*	5,2*
Tough-PLA	37*	1820**	3,1*	3,1*
CFPLA	Not defined	Not defined	Not defined	Not defined
* Tested according to ISO 527, with strain rate 50 mm/min. ** Tested according to ISO 527, with strain rate 1 mm/min.				

Table 1. Material mechanical properties from manufacturer technical data sheet.

CAD 3D model of specimen for tensile testing according to ISO 527-2 (Fig. 5.) is prepared in CAD software Solidworks 2020. Also 3D model of specimen is converted into a STL file, and prepared for slicer Cura to generate G-code for 3D printing.

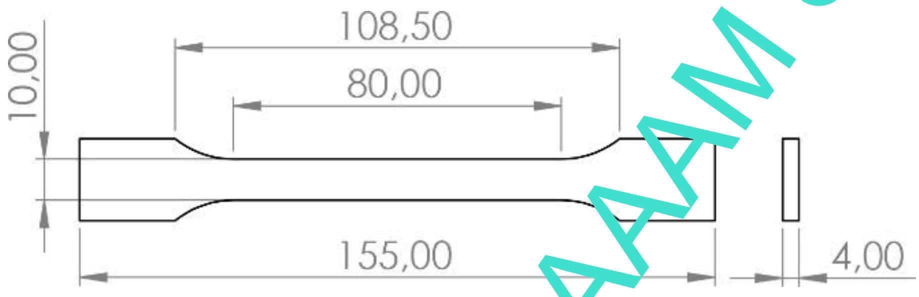

Fig. 5. Technical specification of specimen for tensile testing according to ISO 527-2

Ultimaker S5 with standard 0,4 AA print core is used for 3D printing specimens of PLA and tough-PLA materials. For CFPLA material it is recommended to use steel nozzle for less wear caused by fibers, so Ultimaker 2+, with steel nozzle 0,5 mm, was used for CFPLA material samples. 3D printing parameters for PLA and tough-PLA materials are predefined Cura profile “Engineering – Normal 0,15 mm”, but for CFPLA material, some parameters were changed as shown in the table 2. Also, all specimens are 3D printed with 100% infill.

3D printing parameters			
Material	PLA	Tough-PLA	CFPLA
Nozzle diameter	0,4 mm	0,4 mm	0,5 mm
Layer height	0,15 mm	0,15 mm	0,15 mm
Wall thickness	1,2 mm	1,2 mm	0,7 mm
Print speed	30 mm/s	30 mm/s	60 mm/s
Printing temperature	200 ˚C	200 ˚C	210 ˚C
Build plate temperature	60 ˚C	60 ˚C	60 ˚C
Fan Speed	100 %	100 %	20 %

Table 2. Main 3D printing parameters used for selected materials

Testing was performed with five different strain rates for every material: 0,5 mm/min, 1 mm/min, 5 mm/min, 50 mm/min and 100 mm/min. Trapezium-X software is used for monitoring tests and collecting data for drafting Stress-Strain diagrams. Experimental methodology is presented in Fig. 6.

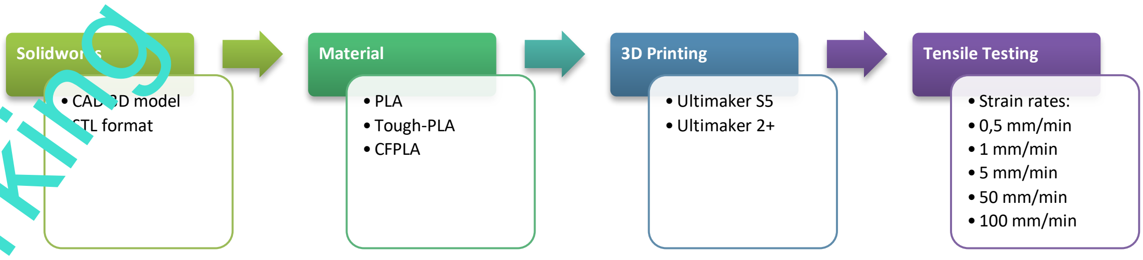

Fig. 6. Experimental methodology

All specimens are tested on Shimadzu AGS-X Std tensile machine with maximal capacity of 10 kN, but for this research 5 kN load cell was used (Fig. 7.).

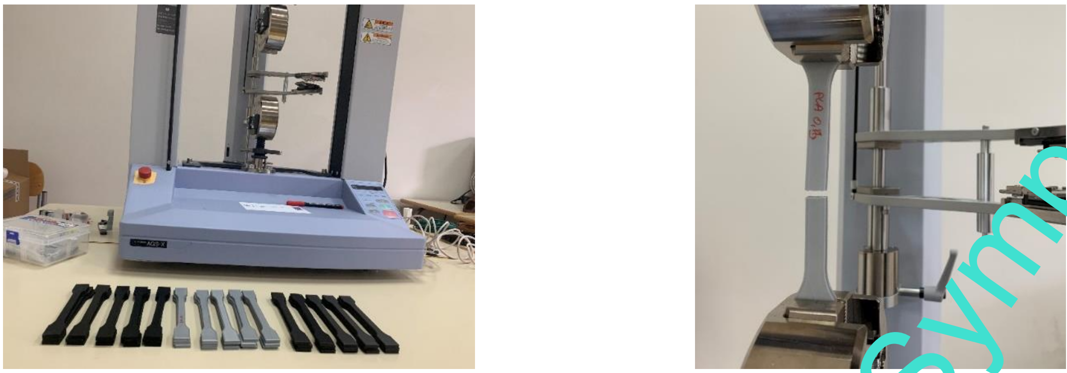

Fig. 7. Tensile tesitng on Shimadzu AGS-X Std machine

3. Results

Three different materials (PLA, T-PLA and CFPLA) are tensile tested with five different strain rates (0,5; 1; 5; 50 and 100 mm/min). Three identical tensile specimens were tested for each strain rate, and the mean values are presented as a results. The testing results data have been processed, analysed and for better visibility presented in diagrams bellow.

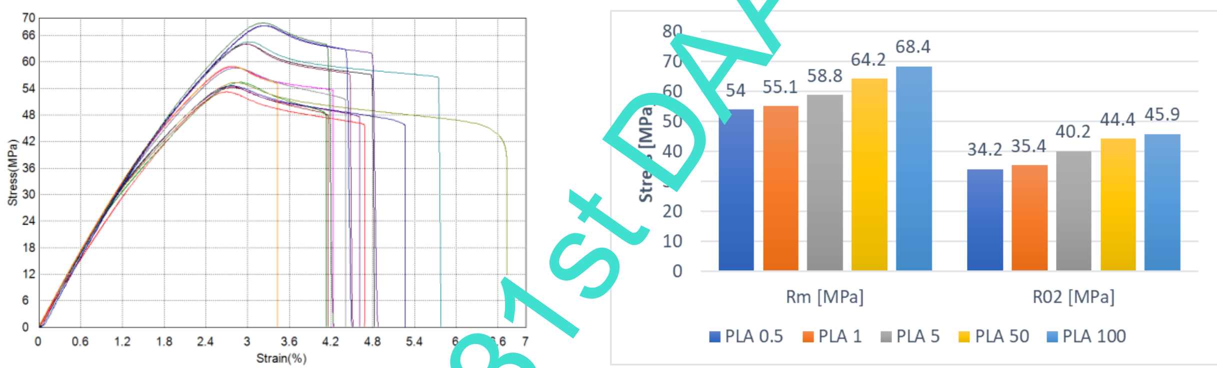

Fig. 8. Stress-Strain diagram for all tested PLA specimens, influence of strain rate on tensile (Rm) and 0,2% yield strength (R_{02})

Analysing the diagrams from Fig. 8. it can be seen that for PLA material the tensile and 0,2% yield strength are higher as the strain rate is increased. Fig. 9. showing T-PLA material behaviour and also higher tensile strength with strain rate increase, but R_{02} is increasing from 0,5 mm/min to 50 mm/min strain rate, and for 100 mm/min it was slightly decreased from 38,5 MPa to 36,9 MPa.

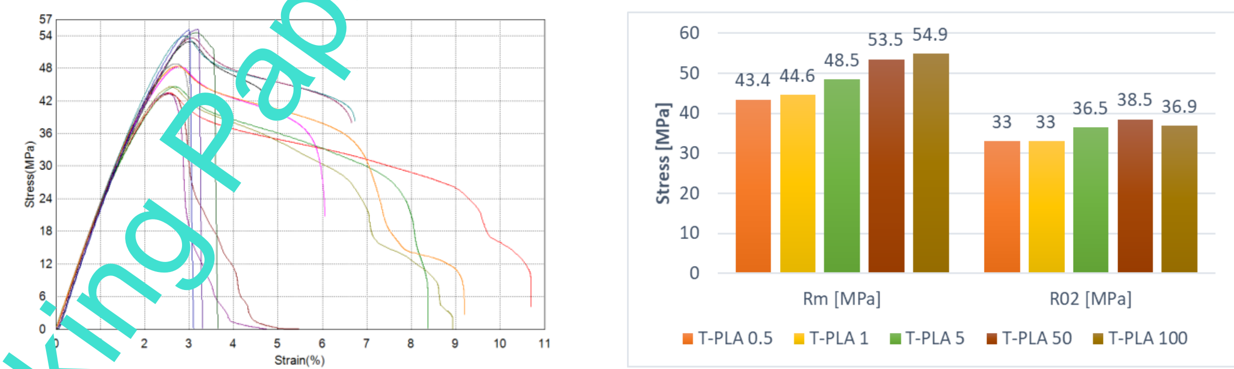

Fig. 9. Stress-Strain diagram for all tested T-PLA specimens, influence of strain rate on tensile (Rm) and 0,2% yield strength (R_{02})

Carbon fiber reinforced PLA material showed different behaviour, where with increasing strain rate there was not a constant increase in Rm and R_{02}, and diagram showing increases and decreases in strength while strain rate is increasing.

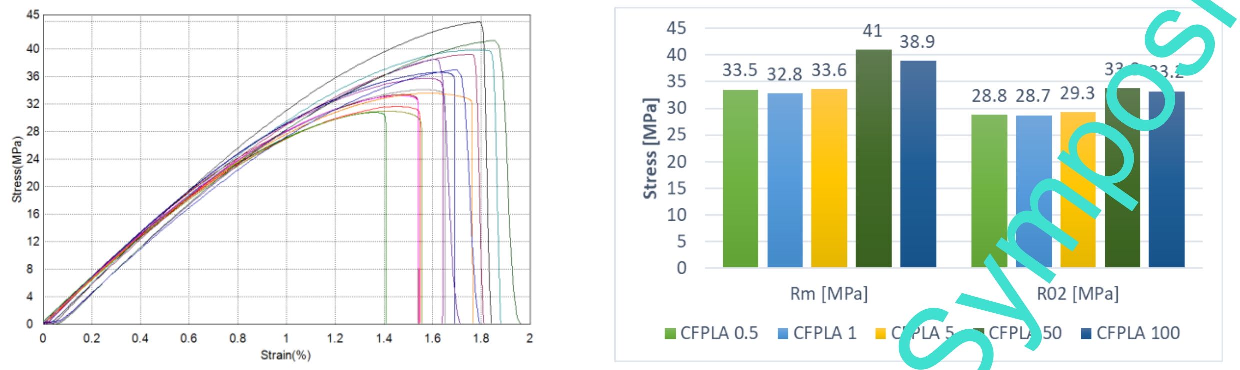

Fig. 10. Stress-Strain diagram for all tested CFPLA specimens, influence of strain rate on tensile (Rm) and 0,2% yield strength (R_{02})

Strain rate influence on Young modulus is presented on diagram bellow (Fig. 11.). PLA and T-PLA material with strain rate increase also showed increase of Young modulus. For PLA material it was increase up to 3,4 %, and for T-PLA increase was up to 4,2 %. CFPLA material showed similar behaviour as for strength, where there were decrease and increase of Young modulus.

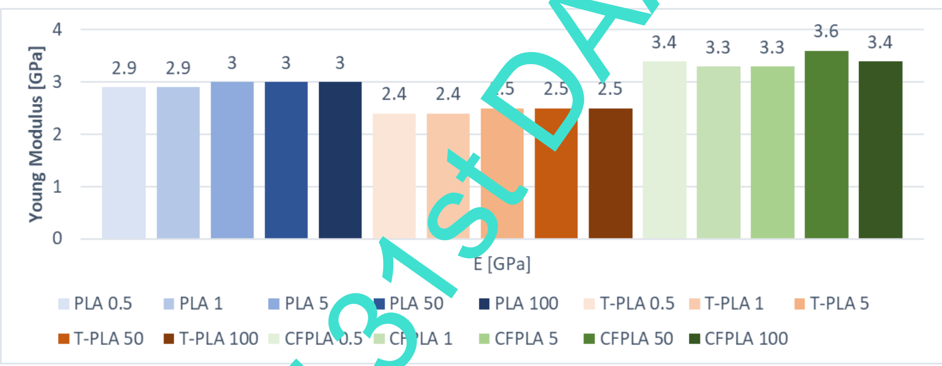

Fig. 11. Influence of strain rate on Young modulus (E) for, from left, PLA, T-PLA and CFPLA materials

Material T-PLA showed "natural" behaviour when analysing influence of strain rate on strain, and Fig. 12. showing linear decrease of strain with increasing strain rate. Other two materials, PLA and CFPLA, didn't show a linear decrease in strain with increasing strain rate, which was expected to happen.

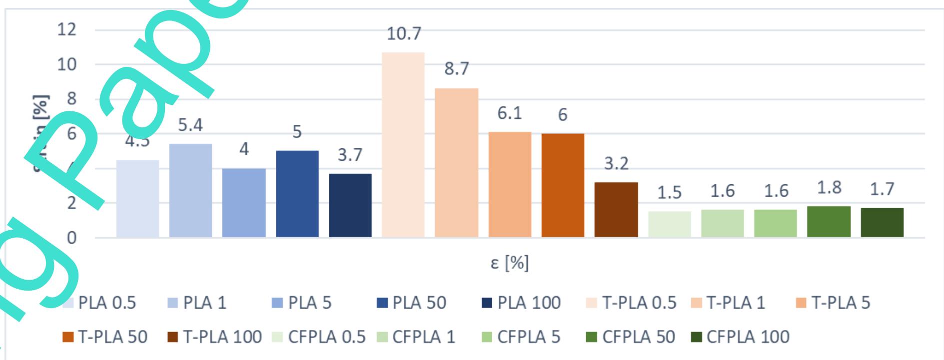

Fig. 12. Influence of strain rate on strain (ε) for, from left, PLA, T-PLA and CFPLA materials

Testing time showed what was expected (Fig. 13.), with an increase of strain rate, testing time was decreased. With strain rate increase from 0,5 mm/min to 100 mm/min, testing time for PLA material was decreased up to 99,58 %, for T-PLA up to 99,87 % and for CFPLA up to 99,41 %.

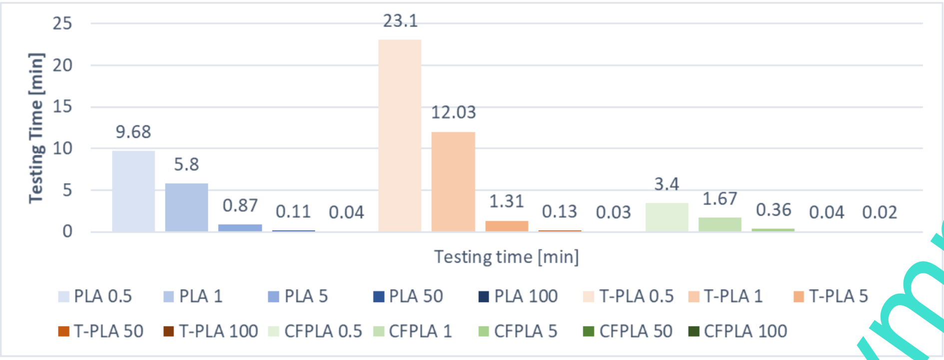

Fig. 13. Influence of strain rate on testing time for, from left, PLA, T-PLA and CFPLA materials

4. Conclusion

The FDM 3D printing process was used to create dog bone specimens for tensile testing according to ISO 527-2. Specimens are fabricated with a variety of material and studied influence of strain rate on tensile mechanical properties. Three different materials are analysed, namely PLA, tough PLA and carbon fiber reinforced PLA, and every material was tensile tested with five different strain rates. Three identical tensile specimens were tested for each strain rate, and the mean values are presented as a results. Influence of strain rate on tensile strength (Rm), 0,2% yield strength (R_{02}), Young modulus (E), strain (ε) and testing time was examined and conclusions are presented below:

- Tensile strength (Rm) – Analysing PLA and T-PLA materials, a linear increase in tensile strength with increasing strain rate is seen. While CFPLA material showed an increase and decrease in strength with increasing strain rate.
- Yield strength (R_{02}) – As the strain rate increase, the PLA material showed a constant increase in R_{02}. T-PLA also had a rise in R_{02} to a strain rate of 50 mm/min, then R_{02} decreased at a strain rate of 100 mm/min. For CFPLA material, with strain rate from 0,5 to 5 mm/min there were not significant change in R_{02}, but for 50 mm/min there was increase of 15% and then again a slight decrease at a strain rate of 100 mm/min.
- Young modulus (E) - PLA and T-PLA materials with strain rate increase showed increase of Young modulus. For PLA material, from 0,5 to 1 mm/min E was constant 2,9 GPa. For strain rate 5 mm/min,it was increase up to 3,4 %, Young modulus increase to 3 GPa and up to 100 mm/min it stayed constant. T-PLA material showed same behaviour like PLA material, only value of Young modulus was lower (min 2,4 and max 2,5 GPa). CFPLA material showed similar behaviour as for strength, where there were decrease and increase of Young modulus, but compared to PLA and T-PLA the Young modulus is up to 50% higher.
- Strain (ε) - Analysing influence of strain rate on strain, T-PLA material showed "natural" behaviour, what is expected, and that is linear decrease of strain with increasing strain rate. Other two materials, PLA and CFPLA, didn't show a linear decrease in strain with increasing strain rate, which was expected to happen. It happened that for those two materials, it can be seen and increase and decrease in strain with increasing strain rate.
- Testing time – As expected, with an increase of strain rate, testing time was decreased. With strain rate increase from 0,5 mm/min to 100 mm/min, testing time for PLA material was decreased up to 99,58 %, for T-PLA up to 99,87 % and for CFPLA up to 99,41 %.

Overall, influence of strain rate on tensile mechanical properties is confirmed on three different FDM 3D printed materials. It is important to understand and analyse influence of strain rate on mechanical properties, so that in the future mechanical testing of the FDM 3D printed materials can be standardized. For future research, it would be recommended to perform similar research, but use more than 3 samples per test, analyse a larger range of strain rates and do the test on more different materials, to get the better picture possible for the influence of strain rate on mechanical properties.

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