

Strain Rate Sensitivity

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1. Introduction

Strain rate is a parameter related with dynamic loading phenomena, which are common in industrial applications ^{[1][2]}. Strain rate sensitivity is a measure that has been widely studied for polymers processed through many manufacturing technologies ^[3]. On the other hand, not enough research exists in the literature regarding the strain rate sensitivity of polymers processed through AM technologies and especially the FFF technology ^{[3][4]}. Strain rate sensitivity is an important parameter for end-use applications when polymers are FFF processed. Studying the behavior change due to the strain rate could provide information for fail-safe mechanisms and other dynamic analysis properties ^[5], such as the energy absorbed in crashes etc. ^[6].

A recent study provided critical information for the strain rate sensitivity of several different polymers processed with the FFF technology ^[3]. The increasing demand for FFF manufactured parts with engineering grade polymers such as polycarbonate (PC) and thermoplastic polyurethane (TPU) has further increased the necessity for a study on the strain rate sensitivity of these polymers, which has not been reported before in literature. PC is a well-known high mechanical performance polymer ^[7], widely used in many applications which require strong dynamical properties, such as automotive ^[8], medical ^{[9][10][11][12]} and optics ^[13] applications. In AM, PC applications are still limited in the literature, with research mainly related to acoustic applications ^[14] and heat pipes ^[15]. TPU is also an elastic material, employed in many industrial and other environmental parts ^{[16][17]}. Indicative applications of TPU material are in mechanical seals ^{[18][19]} or more advanced applications, such as flexible electronics ^[20], force sensors ^[21], pneumatic actuators ^[22] and pharmaceutical applications ^[23]. TPU thermal properties in 3D printing have also been reported ^{[24][25]}.

The strain rate of these materials has been studied either for homopolymers or for composites ^{[8][26][27]}, but not for parts built with AM technology. The manufacturing of parts through FFF technology requires the extrusion of melted-state polymer in shells, infills and, of course, in consecutive layers ^[28]. The interlayer and throughout layer fusion are prone to a wide range of process settings, such as number of shells, layer height, infill percentage, infill geometry pattern, extrusion temperature, extrusion speed etc. ^{[29][30]}. As mentioned above, AM built parts have an anisotropic behavior. These parameters are among others, responsible for the anisotropic behavior of the parts manufactured with the FFF process ^[31]. This anisotropy can create unpredicted behavior, especially when dynamic stresses are applied to AM processed parts.

2. Tensile Properties

Figure 1 shows representative graphs from the tensile tests conducted during the present study. Specifically, in **Figure 1a**, typical stress (MPa) to strain (mm/mm) curves are shown for PC material for the 10 mm/min strain rate. The layer thickness of the specimens, in this case, was 0.2 mm and curves shown are for the three different 3D printing temperatures studied in this work (one graph per temperature). Through this comparison, it can be observed that increasing the 3D printing temperature to 270 °C improved the mechanical performance of the material, probably due to increased inter and intra layer fusion. In **Figure 1b**, PC stress (MPa) to strain (mm/mm) typical curves for the different layer thicknesses studied are shown for the elongation speed of 10 mm/min and 3D printing temperature of 260 °C. The figure shows that varying the layer height had little effect on the strength of the specimen, as the difference was less than 10%. This difference could be plausibly attributed to the anisotropy of the process followed (AM). **Figure 1c** shows the effect of the strain rate on the PC polymer, at three different elongation speeds (10 mm/min, 100 mm/min and 300 mm/min), for specimens built with a 0.20 mm layer thickness at 260 °C. As it is shown, the strain rate had an effect on the

typical stress to strain curve of the PC polymer, although the maximum strength developed on the specimens was similar in the three cases shown.

Figure 1. Stress (MPa) to strain (mm/mm) typical curves for PC material for (a) different 3D printing temperatures, (b) different layer thicknesses and (c) different elongation speeds.

In **Figure 2**, the corresponding results are shown for the TPU polymer. In **Figure 2a**, a strong effect of temperature on the behavior of the materials is observed. Results shown could lead to the selection of the optimum 3D printing temperature among the three temperatures studied in this work. The temperature increase had an opposite effect on the TPU polymer, when compared to the PC polymer. When the temperature increased from 215 °C to 225 °C, a decrease of approximately 40% in the tensile strength was observed. It should be mentioned that these sharp drops shown by the stress graphs are caused by local breaks on the specimen, which occurred, during the test, either in its shell or in the infill structure. At higher 3D printing temperatures, TPU material developed smoother curves during the tensile tests. This could be probably attributed to a more isotropic behavior in this case. A better inter and intra layer bonding was possibly achieved, which had a clear effect on the properties of the material, as the specimen became stiffer.

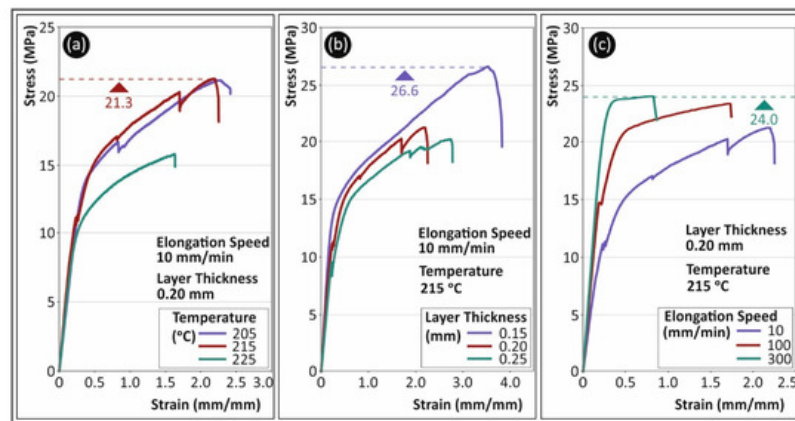


Figure 2. Stress (MPa) to strain (mm/mm) typical curves for TPU material for (a) different 3D printing temperatures, (b) different layer thicknesses and (c) different elongation speeds.

The effect of layer height on the tensile stress behavior is shown in **Figure 2b**. In this figure, typical stress (MPa) to strain (mm/mm) curves of the TPU specimens tested at 10 mm/min strain rate, with a 215 °C nozzle temperature are shown for the three different layer heights studied. Layer height exhibited a strong effect on the deformation (especially in the non-elastic area) and the tensile strength of TPU material, with lower layer heights developing higher tensile strength and deformation values. The 0.15 mm layer height developed approximately 30% higher tensile strength and almost 25% higher strain values than the 0.20 mm layer height. **Figure 2c** shows indicative graphs for the TPU specimens from tensile tests with three different strain rate values. Specimens in these three cases were 3D printed with a 0.2 mm layer thickness at a temperature of 215 °C. The strain rate had a strong effect on the brittleness of the material. The increase in the strain rate significantly increased the stiffness of TPU material. The tensile strength, on the other hand, was not affected in the same way, as the difference among the developed values for the three different strain rates was not higher than 10%.

Figure 3 shows a comparison between the parameters studied in this work. Specifically, **Figure 3a** shows, for PC material, the average tensile strength values and their deviation for the different strain rates and 3D printing temperatures studied in this work, for a 0.2 mm layer height. The nozzle temperature created a different trend regarding the tensile strength for the various strain rate values. This was probably due to the different inter and intra layer fusion of the material caused by the different 3D printing nozzle temperatures. The lower sensitivity of the strain rate to the tensile strength was observed for the highest nozzle temperature studied in this work. A similar trend was observed in PC material regarding the sensitivity of the material and the strain rate, when altering the layer height. In **Figure 3b**, it is shown that the tensile strength for the lowest layer height had a more consistent behavior at the different elongation speeds, when compared to the calculated tensile strengths for higher layer thicknesses. The calculated tensile modulus of elasticity (MPa) is shown in **Figure 3c** for the different 3D printing temperatures studied and, in **Figure 3d**, the corresponding values are presented for the different layer heights, for the five elongation speeds tested herein. It can be further assumed that 3D printing temperature constitutes an important parameter affecting the tensile properties of the material.

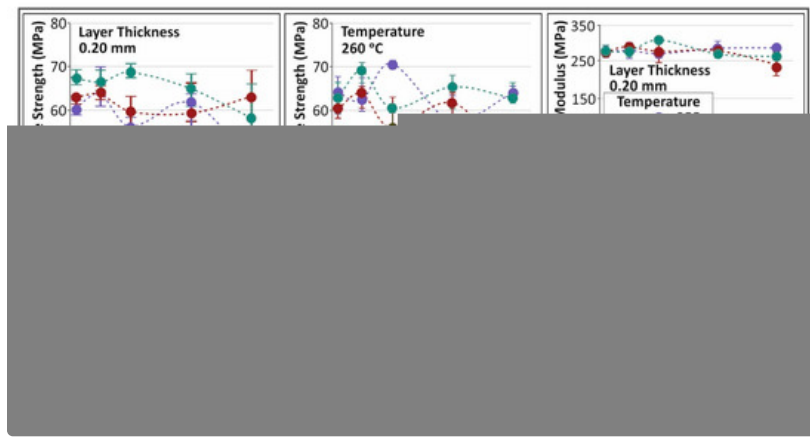


Figure 3. (a,b) Average tensile strength (MPa) and (c,d) average tensile elastic modulus (MPa) to elongation speeds (mm/min) for PC material as follows: (a,c) 3D printing temperatures; (b,d) layer heights.

References

1. Siviour, C.R. High strain rate characterization of polymers. *AIP Conf. Proc.* 2017, 1793, 8–13.
2. Rohbeck, N.; Ramachandramoorthy, R.; Casari, D.; Schürch, P.; Edwards, T.E.J.; Schilinsky, L.; Philippe, L.; Schwiedrzik, J.; Michler, J. Effect of high strain rates and temperature on the micromechanical properties of 3D-printed polymer structures made by two-photon lithography. *Mater. Des.* 2020, 195, 1–9.
3. Vidakis, N.; Petousis, M.; Velidakis, E.; Liebscher, M.; Mechtcherine, V.; Tzounis, L. On the strain rate sensitivity of fused filament fabrication (Fff) processed pla, abs, petg, pa6, and pp thermoplastic polymers. *Polymers* 2020, 12, 2924.
4. Vairis, A.; Petousis, M.; Vidakis, N.; Savvakis, K. On the Strain Rate Sensitivity of Abs and Abs Plus Fused Deposition Modelling Parts. *J. Mater. Eng. Perform.* 2016, 25, 3558–3565.
5. Hosur, M.V.; Alexander, J.; Jeelani, S.; Vaidya, U.K.; Mayer, A. High strain compression response of affordable woven carbon/epoxy composites. *J. Reinf. Plast. Compos.* 2003, 22, 271–296.
6. Mirmomeni, M.; Heidarpour, A.; Zhao, X.L.; Packer, J.A. Effect of elevated temperature on the mechanical properties of high-strain-rate-induced partially damaged concrete and CFSTs. *Int. J. Impact Eng.* 2017, 110, 346–358.
7. Bhadeshia, H.K.D.H. Additive manufacturing. *Mater. Sci. Technol.* 2016, 32, 615–616.
8. Krausz, T.; Serban, D.A.; Negru, R.M.; Radu, A.G.; Marsavina, L. The effect of strain rate and temperature on the mechanical properties of polycarbonate composites. *Mater. Today Proc.* 2020, 45, 4211–4215.
9. Lv, D.; Li, P.; Zhou, L.; Wang, R.; Chen, H.; Li, X.; Zhao, Y.; Wang, J.; Huang, N. Synthesis, evaluation of phospholipid biomimetic polycarbonate for potential cardiovascular stents coating. *React. Funct. Polym.* 2021, 163, 104897.
10. Park, S.J.; Lee, J.E.; Lee, H.B.; Park, J.; Lee, N.K.; Son, Y.; Park, S.H. 3D printing of bio-based polycarbonate and its potential applications in ecofriendly indoor manufacturing. *Addit. Manuf.* 2020, 31, 100974.
11. Kalkal, A.; Kumar, S.; Kumar, P.; Pradhan, R.; Willander, M.; Packirisamy, G.; Kumar, S.; Malhotra, B.D. Recent advances in 3D printing technologies for wearable (bio)sensors. *Addit. Manuf.* 2021, 46, 102088.
12. Hacıoglu, F.; Tayfun, U.; Ozdemir, T.; Tincer, T. Characterization of carbon fiber and glass fiber reinforced polycarbonate composites and their behavior under gamma irradiation. *Prog. Nucl. Energy* 2021, 134, 103665.
13. Mishra, V.; Sharma, R.; Khatri, N.; Garg, H.; Karar, V.; Khan, G.S.; Sarepaka, R.V. Processing of Polycarbonate by Ultra-Precision Machining for Optical Applications. *Mater. Today Proc.* 2018, 5, 25130–25138.
14. Liu, Z.; Zhan, J.; Fard, M.; Davy, J.L. Acoustic properties of a porous polycarbonate material produced by additive manufacturing. *Mater. Lett.* 2016, 181, 296–299.
15. Arai, T.; Kawaji, M. Thermal performance and flow characteristics in additive manufactured polycarbonate pulsating heat pipes with Novec 7000. *Appl. Therm. Eng.* 2021, 197, 117273.
16. Gul, J.Z.; Sajid, M.; Choi, K.H. 3D printed highly flexible strain sensor based on TPU-graphene composite for feedback from high speed robotic applications. *J. Mater. Chem. C* 2019, 7, 4692–4701.
17. Mistry, P.; Chhabra, R.; Muke, S.; Narvekar, A.; Sathaye, S.; Jain, R.; Dandekar, P. Fabrication and characterization of starch-TPU based nanofibers for wound healing applications. *Mater. Sci. Eng. C* 2021, 119, 111316.

18. Wang, C.; Hausberger, A.; Berer, M.; Pinter, G.; Grün, F.; Schwarz, T. An investigation of fretting behavior of thermoplastic polyurethane for mechanical seal application. *Polym. Test.* 2018, 72, 271–284.
19. Xiao, X.; Wang, J.; Cai, D.; Lou, L.; Xiao, F. A novel application of thermoplastic polyurethane/waste rubber powder blend for waterproof seal layer in high-speed railway. *Transp. Geotech.* 2021, 27, 100503.
20. Choi, J.; Moon, D.S.; Jang, J.U.; Yin, W.B.; Lee, B.; Lee, K.J. Synthesis of highly functionalized thermoplastic polyurethanes and their potential applications. *Polymer (Guildf.)* 2017, 116, 287–294.
21. Kim, K.; Park, J.; Suh, J.-h.; Kim, M.; Jeong, Y.; Park, I. 3D printing of multiaxial force sensors using carbon nanotube (CNT)/thermoplastic polyurethane (TPU) filaments. *Sens. Actuators A Phys.* 2017, 263, 493–500.
22. Hohimer, C.J.; Petrossian, G.; Ameli, A.; Mo, C.; Pötschke, P. 3D printed conductive thermoplastic polyurethane/carbon nanotube composites for capacitive and piezoresistive sensing in soft pneumatic actuators. *Addit. Manuf.* 2020, 34, 101281.
23. Verstraete, G.; Samaro, A.; Grymonpré, W.; Vanhoorne, V.; Van Snick, B.; Boone, M.N.; Hellemans, T.; Van Hoorebeke, L.; Remon, J.P.; Vervaet, C. 3D printing of high drug loaded dosage forms using thermoplastic polyurethanes. *Int. J. Pharm.* 2018, 536, 318–325.
24. Kang, K.S.; Jee, C.; Bae, J.H.; Jung, H.J.; Huh, P.H. Heat capacity variables of thermoplastic polyurethane for high-quality 3D printing resolution and their characteristics. *Mater. Lett.* 2019, 257, 126698.
25. Liu, J.; Li, W.; Guo, Y.; Zhang, H.; Zhang, Z. Improved thermal conductivity of thermoplastic polyurethane via aligned boron nitride platelets assisted by 3D printing. *Compos. Part. A Appl. Sci. Manuf.* 2019, 120, 140–146.
26. Wilberforce, S.; Hashemi, S. Effect of fibre concentration, strain rate and weldline on mechanical properties of injection-moulded short glass fibre reinforced thermoplastic polyurethane. *J. Mater. Sci.* 2009, 44, 1333–1343.
27. Walley, S.M.; Field, J.E. Strain Rate Sensitivity of Polymers in Compression from Low to High Rates. *DYMAT J.* 1994, 1, 211–227.
28. Vidakis, N.; Petousis, M.; Velidakis, E.; Mountakis, N.; Tzounis, L.; Liebscher, M.; Grammatikos, S.A. Enhanced mechanical, thermal and antimicrobial properties of additively manufactured polylactic acid with optimized nano silica content. *Nanomaterials* 2021, 11, 1012.
29. Johnson, G.A.; French, J.J. Evaluation of Infill Effect on Mechanical Properties of Consumer 3D Printing Materials. *Adv. Technol. Innov.* 2018, 3, 179–184.
30. Fernandes, J.; Deus, A.M.; Reis, L.; Vaz, M.F.; Leite, M. Study of the influence of 3D printing parameters on the mechanical properties of PLA. *Proc. Int. Conf. Prog. Addit. Manuf.* 2018, 547–552.
31. Vidakis, N.; Petousis, M.; Tzounis, L.; Maniadi, A.; Velidakis, E.; Mountakis, N.; Papageorgiou, D.; Liebscher, M.; Mechtcherine, V. Sustainable Additive Manufacturing: Mechanical Response of Polypropylene over Multiple Recycling Processes. *Sustainability* 2020, 13, 159.