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Simulation of uniaxial stress–strain response of 3D-printed polylactic acid by nonlinear finite element analysis

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Abstract

Accurate simulation of mechanical properties of 3D-printed objects can provide critical inputs to designers and manufacturers. Polylactic acid, a biodegradable polymer, is particularly important in this regard due to its excellent print quality and a wide range of applications. Herein, an accurate uniaxial stress–strain profile simulation of 3D-printed PLA is reported. Nonlinear Finite Element Analysis (FEA) was used to simulate the uniaxial tensile test and build a material model for the prediction of the stress–strain response. 3D model for this nonlinear FEA study was built in SolidWorks, and several measures were taken to simulate the nonlinear stress–strain response with high accuracy. Von Mises stress, resultant displacement, and strain plots were produced. Comparison with experimental data extracted from the literature was done to validate the FEA model. Fracture behavior was predicted by FEA stress distribution. Deviations between the stress–strain plot obtained by FEA from the experimentally obtained plot were minimal. The entire curve, except the failure zone, could be precisely simulated. Furthermore, the developed von Mises plasticity material model and the boundary conditions also captured the behavior of specimen under uniaxial tension load and the deviation between experimental results was minor. These results suggest that the developed material model could be useful in non-linear FEA studies on 3D printed PLA objects which are expected to withstand tensile stress.

Keywords: 3D printing, Finite Element Analysis, Biodegradable polymer, Polylactic acid, Validation

Introduction

3D printing allows the rapid development of complex objects of polymers, metals, and ceramics [1]. Though in the initial phase, applications of 3D printing were limited to prototypes for testing and experimental purposes; currently, 3D printing is being explored in a wide spectrum of industrial design education and medical research [2–4]. Notably, 3D printing has distinct advantages of high precision, customization, fast fabrication, lower waste, lower energy consumption, and lower cost over conventional manufacturing processes [5].

Polymers are the most commonly used material in 3D printing and can be processed using different 3D printing technologies. Fused deposition modeling (FDM) is one of the most promising 3D-printing technologies used for polymers. Polylactic acid (PLA) is a biodegradable thermoplastic made from renewable resources and offers good physical–mechanical properties and 3D printability by FDM [6–9]. Excellent biocompatibility and biodegradability coupled with good mechanical properties and processability make PLA a promising candidate for biomedical applications. PLA has been extensively explored for biomedical applications such as medical implants, scaffolds for tissue engineering, orthopedic and drug delivery devices and guided tissue regeneration. Indeed, 3D printed PLA structures are envisaged to play a key role in biomedical applications [10]. However, one of the concerns inherent in 3D printing of PLA is significant variations in the mechanical properties of 3D printed PLA objects in comparison to bulk PLA. Such issues are even more critical in 3D printed objects that are designed for load-bearing applications [11].

The infill density and internal shape have been reported to significantly affect the mechanical properties of 3D printed PLA specimens [7, 12]. It was found that the tensile strength and elasticity were directly proportional to infill density and that specimens with concentric internal-shaped specimens had the highest tensile strength and elasticity among specimens with internal shapes of line, lattice and crystal [13–15]. Song et al. performed tensile, compression and fracture tests on 3D printed PLA samples in different material orientations and found that specimens were tougher when loaded in the extrusion direction compared to the transverse direction [16]. After performing uniaxial tensile tests for PLA specimens, Noori et al. found that deposition height is a key parameter for the energy required for interlayer fracture [17]. It was also found that the tensile residual stress and interlayer contact area affect the fracture energy significantly.

A large variation in the mechanical properties of 3D printed PLA from the bulk PLA has promoted designers to develop simulation strategies for the prediction of mechanical properties of 3D printed objects. Several testing techniques are generally used to determine the mechanical properties of a material. The most common mechanical tests include a uniaxial compression test, a plane-strain compression test, and a uniaxial tensile test. The uniaxial tensile test is the most commonly used mechanical test, providing accurate values of key mechanical parameters such as Young's modulus, yield strength, ultimate tensile strength, elongation at break and Poisson's ratio. Provaggi et al. recently employed finite element analysis (FEA) to predict mechanical properties of 3D printed polymers under compression and concluded that inputs provided by FEA could be potentially useful for reducing product design and development time [18]. Their work, which was focused on the linear elastic region, suggested that in 3D printed PLA specimen with 100% infill density, maximum Von Mises stresses was considerably higher than the compressive yield strength. Pastor-Artigues et al., on the other hand, conducted FEA studies on 3D printed under tension, compression as well as bending condition [19]. However, they concluded that currently used procedures for the mechanical property evaluation of 3D printed objects do not guarantee a coherent set of results that could be effectively used in numerical simulations. Simulation of the mechanical test of 3D printed objects was also attempted by several other authors [20–22]. All these studies point out the challenges associated with the accurate simulation of mechanical properties of polymers, underscoring a need for more research in the direction of FEA based simulation for the prediction of non-linear behaviors under tension [23–26].

Herein, a nonlinear FEA model is devised to simulate the stress–strain response of 3D printed PLA. Mesh control and mess size sensitively analysis was conducted and von Mises stress, resultant displacement, and strain plots were also produced. Furthermore, the developed model was validated on the uniaxial stress–strain data of 3D-printed PLA reported in the literature.

Materials and methods

3D model for the specimen was built using SolidWorks® software to match the test specimen geometry (Fig. 1). As the 3D printed PLA specimen is thin-walled, a mid- surface model was used for simplification, reducing solution time and avoiding potential meshing problems. A curvature-based mesh, which has more nodes than a standard mesh, was assigned to get highly accurate results. The strain rate was set at 3 mm/min. The model was set to have the tension load applied to the specimen from the top and have the bottom section fixed to simulate the relative uniaxial motion between the upper and lower grips of a tensile testing machine. The numerical method with meshing and boundary conditions is presented in Fig. 2. A custom material model was created in SolidWorks Simulation® module. von Mises plasticity material model was used to define the nonlinear material behavior [27]. The material model was built by using the mechanical and physical properties listed in Table 1 and the stress–strain curve data extracted from literature [28]. The yield strength was determined based on a 0.2% offset strain. To account for large deformation and strain, a large-strain model was applied.

The experimental data published by Farbman and McCoy [28] was used for the validation of the Finite Element model developed in this work. Farbman et al. conducted a detailed tensile testing study on 3D printed PLA test specimens. Mechanical tests were conducted according to ASTM code B557-06 at a crosshead velocity of 3 mm/min at a maximum load of 1000 N. Data from the experimental stress–strain curve obtained in ref [28] was extracted using GetData Graph Digitizer [29].

Results and discussion

Finite element analysis

FEA was used to simulate the tensile load on the specimen up to the point just before the failure. Mesh sensitivity analysis was performed to evaluate the effect of mesh size on von Mises stress and resultant displacement. From the analysis summarized in Fig. 3, it can be observed that results for stress and displacement did not

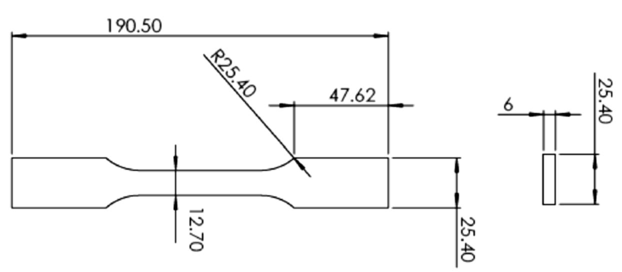

Fig. 1 The dimension of the tensile test specimen used in FEA (in mm)

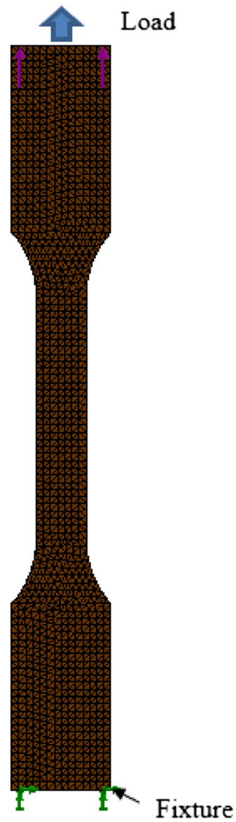

Fig. 2 FEA model showing mesh and boundary conditions

Table 1 Mechanical properties for PLA [34]

Property	Value
Density, ρ	1240 kg/m^3
Elastic modulus, E	973 MPa
Poisson's ratio, υ	0.36
Yield strength	15.7 MPa
Ultimate tensile stress	46.18 MPa

vary significantly within the mesh element range of interest, which means that results for both parameters are reliable. As expected, the maximum von Mises stress varied slightly over the resultant displacement results. Mesh parameters were determined and summarized in Table 2. To analyze the mesh quality, mesh plots (Fig. 4) were created and the results showed that the mesh quality was acceptable when the aspect ratio was less than 3. These results indicate that element edge lengths are close to each other. On the other hand, the Jacobian chart showed positive values, indicating that the analysis did not yield distorted elements. It can also be noted that the maximum stress point was located at the specimen centerline within the necking zone as

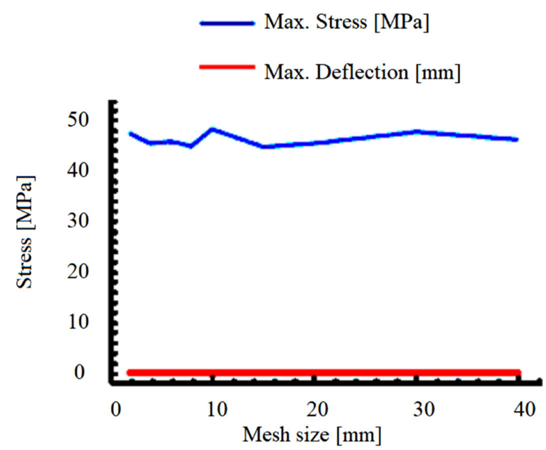

Fig. 3 Mesh sensitivity analysis results for maximum von Mises stress and maximum resultant displacement

Table 2 Mesh parameters used in FEA

Property	Value
Mesh size	1.85 mm
Mesh type	Curvature-based
Element type	Shell element
Mesh quality	High

shown in Fig. 5. As SolidWorks could not simulate the fracture behavior, expected fracture behavior shown in Fig. 6 could be predicted based on the maximum stress spot, which was expected to develop a crack initiation point. The model shows that the maximum resultant displacement and strain are 2.227 mm and 1.615e−2 respectively (Fig. 7a, b).

Validation

The experimental stress–strain curve and FEA simulated stress–strain curves are shown in Fig. 8. As expected, the uniaxial stress–strain curve of PLA started with an elastic zone wherein tensile stress has a linear dependence on the applied strain. The linear zone indicates the stress–strain range in which the material will regain its original shape after the removal of the applied stress or strain. The linear-zone continues to yield point, beyond which plastic deformation takes place in the specimen and it cannot regain original shape even after the removal of applied stress/strain [25]. The plastic deformation zone continues until the rapture of the specimen. Ultimate tensile stress was 46.18 MPa and the yield strength, which was evaluated using the 0.2% offset method, was 15.7 MPa. FEA simulated stress–strain profile and experimentally obtained stress–strain profile were almost overlapping and exhibited similar slopes and trends all over the range (Fig. 8). The yield and ultimate tensile strength values were very close to each other. To

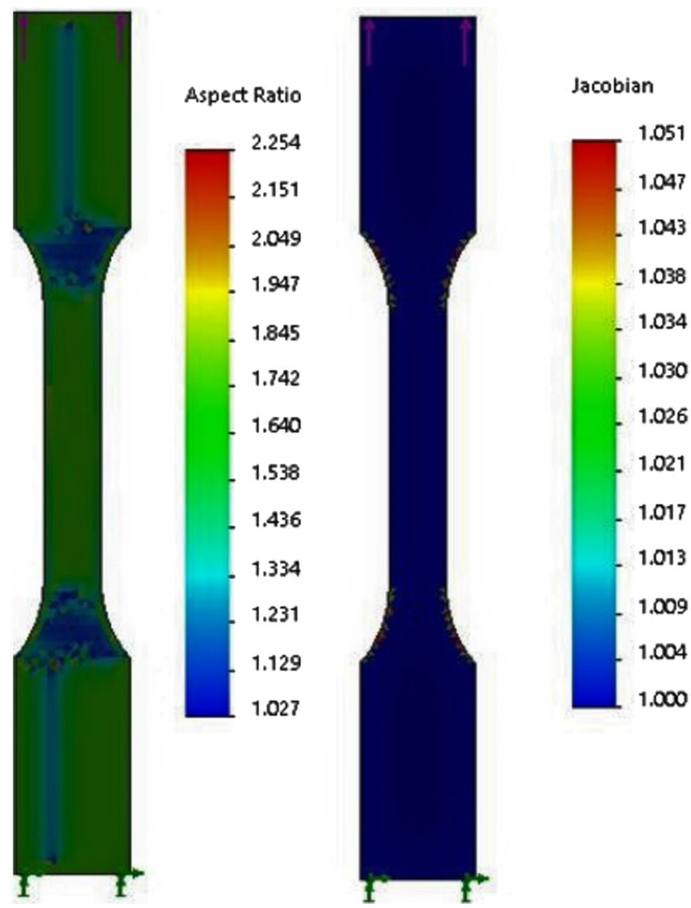

Fig. 4 Mesh control charts used in FEA: aspect ratio (left), Jacobian (right)

estimate the accuracy of FEA results, the deviation between FE and experimental results for yield and ultimate tensile strengths were computed (Table 3). It can be seen that there is only a ~ −2% error in the prediction of yield strength and the ultimate tensile strength has only error of ~7%. These results indicate validation of the FEA model [12, 16, 24, 30–33].

Conclusion

This study simulated a uniaxial tensile test for a 3D printed PLA using nonlinear FEA. FEA developed in this work could successfully capture the specimen behavior under uniaxial tensile load. Deviations between experimental and simulated results were minimal and the maximum error was 6.7%. The developed material model, therefore, could be used for the prediction of the uniaxial tensile behavior of 3D printed PLA parts covering the nonlinear region before failure.

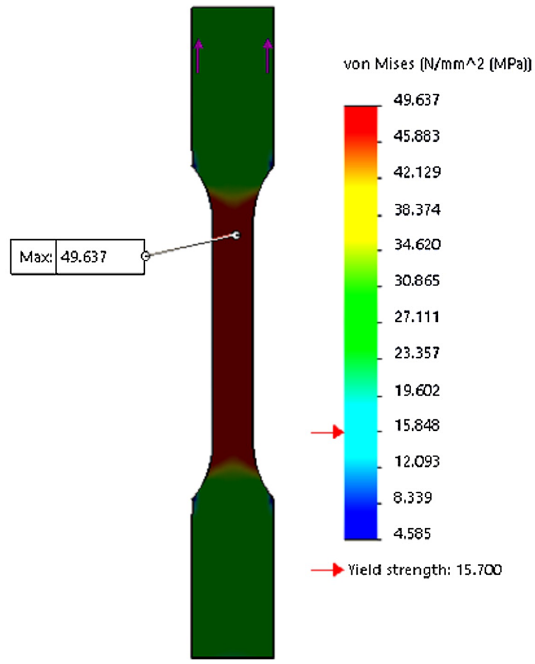

Fig. 5 von Mises stress distribution for the uniaxial tensile test (in MPa)

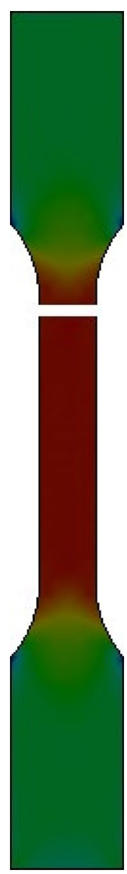

Fig. 6 Expected fracture response of specimen under uniaxial stress

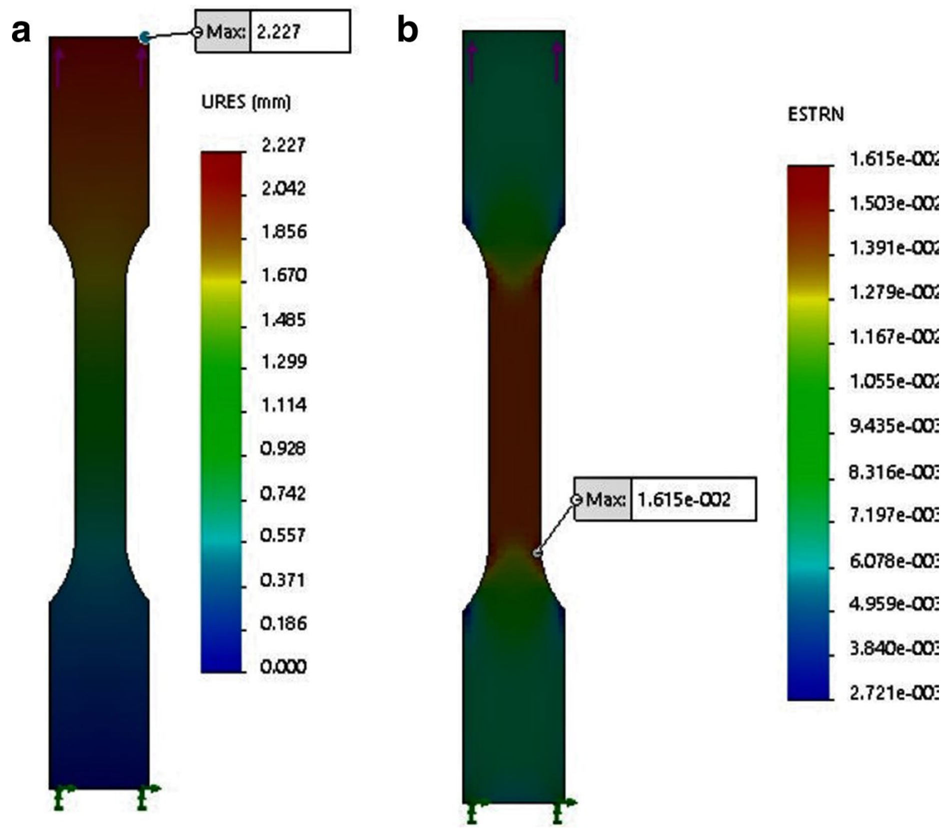

Fig. 7 Simulated (**a**) strain (**b**) displacement plots of the specimen

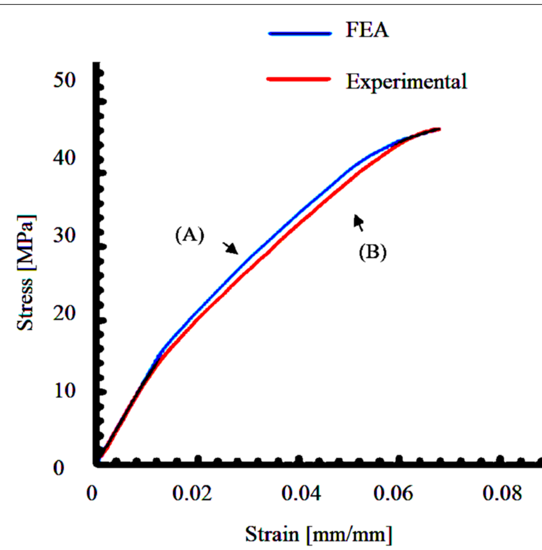

Fig. 8 Uniaxial tensile Stress–Strain plots of 3D printed PLA **(A)** FEA simulated profile, **(B)** Experimental profile

Table 3 Comparison between FEA simulated and experimental results

Property	FE result	Experimental result	Error (%)
Yield strength	15.4 MPa	15.7 MPa	− 1.91%
Ultimate tensile stress	49.3 MPa	46.18 MPa	+ 6.76%

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Authors' contributions
MA conducted study design, simulation studies, and manuscript writing; IK and VIP reviewed the manuscript and helped in improving the technical discussion. Both authors read and approved the final manuscript.

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References

1. Ngo TD, Kashani A, Imbalzano G, Nguyen KTQ, Hui D. Additive manufacturing (3D printing): a review of materials, methods, applications and challenges. Compos B Eng. 2018;143:172–96.
2. Hartings MR, Ahmed Z. Chemistry from 3D printed objects. Nat Rev Chem. 2019;3:305–14.
3. Ford S, Minshall T. Invited review article: where and how 3D printing is used in teaching and education. Additive Manuf. 2019;25:131–50.
4. Ventola CL. Medical applications for 3D printing: current and projected uses. P T. 2014;39:704–11.
5. Yao T, Ye J, Deng Z, Zhang K, Ma Y, Ouyang H. Tensile failure strength and separation angle of FDM 3D printing PLA material: experimental and theoretical analyses. Compos B Eng. 2020;188:107894.
6. Quan H, Zhang T, Xu H, Luo S, Nie J, Zhu X. Photo-curing 3D printing technique and its challenges. Bioactive Materials. 2020;5:110–5.
7. Sri-Amphorn P, Abeykoon C, Fernando A. Optimization of fused deposition modeling parameters for improved PLA and ABS 3D printed structures, Int J Lightweight Mater Manuf. 2020.
8. Liu J, Sun L, Xu W, Wang Q, Yu S, Sun J. Current advances and future perspectives of 3D printing natural-derived biopolymers. Carbohyd Polym. 2019;207:297–316.
9. Chaunier L, Guessasma S, Belhabib S, Valle G, Lourdin D, Leroy E. Material extrusion of plant biopolymers: opportunities & challenges for 3D printing. Addit Manuf. 2018;21:220–33.
10. Alam F, Shukla VR, Varadarajan KM, Kumar S. Microarchitected 3D printed polylactic acid (PLA) nanocomposite scaffolds for biomedical applications. J Mech Behav Biomed Mater. 2020;103:103576.
11. Petersmann S, Spoerk M, Van De Steene W, Üçal M, Wiener J, Pinter G, Arbeiter F. Mechanical properties of polymeric implant materials produced by extrusion-based additive manufacturing. J Mech Behav Biomed Mater. 2020;104:103611.
12. Lubombo C, Huneault MA. Effect of infill patterns on the mechanical performance of lightweight 3D-printed cellular PLA parts. Mater Today Commun. 2018;17:214–28.
13. Ligon SC, Liska R, Stampfl J, Gurr M, Mülhaupt R. Polymers for 3D printing and customized additive manufacturing. Chem Rev. 2017;117:10212–90.
14. Rodríguez-Panes A, Claver J, Camacho MA. The influence of manufacturing parameters on the mechanical behaviour of PLA and ABS pieces manufactured by FDM: a comparative analysis, materials. J Manuf Mater Process. 2018;11:64.
15. Dey A, Yodo N. A systematic survey of FDM process parameter optimization and their influence on part characteristics. J Manuf Mater Process 2019;3:64.
16. Song Y, Li Y, Song W, Yee K, Lee KY, Tagarielli VL. Measurements of the mechanical response of unidirectional 3D-printed PLA. Mater Des. 2017;123:154–64.
17. Noori H. Interlayer fracture energy of 3D-printed PLA material. Int J Adv Manuf Technol. 2019;101:1959–65.
18. Provaggi E, Capelli C, Rahmani B, Burriesci G, Kalaskar DM. 3D printing assisted finite element analysis for optimising the manufacturing parameters of a lumbar fusion cage. Mater Des. 2019;163:107540.

19. Pastor-Artigues M-M, Roure-Fernández F, Ayneto-Gubert X, Bonada-Bo J, Pérez-Guindal E, Buj-Corral I. Elastic Asymmetry of PLA Material in FDM-Printed Parts: Considerations Concerning Experimental Characterisation for Use in Numerical Simulations. Materials. 2020;13(1):15.
20. Ali MH, Yerbolat G, Amangeldi S. Material Optimization Method in 3D Printing, in. IEEE Int Conf Adv Manuf. 2018;2018:365–8.
21. Calneryte D, Barauskas R, Milasiene D, Maskeliunas R, Neciunas A, Ostreika A, Patasius M, Krisciunas A. Multi-scale finite element modeling of 3D printed structures subjected to mechanical loads. Rapid Prototyping J. 2018;24:177–87.
22. Mahshid R, Hansen HN, Højbjerre KL. Strength analysis and modeling of cellular lattice structures manufactured using selective laser melting for tooling applications. Mater Des. 2016;104:276–83.
23. Bhandari S, Lopez-Anido R. Finite element modeling of 3D-printed part with cellular internal structure using homogenized properties. Progr Additive Manuf. 2019;4:143–54.
24. Bhandari S, Lopez-Anido R. Finite element analysis of thermoplastic polymer extrusion 3D printed material for mechanical property prediction. Additive Manuf. 2018;22:187–96.
25. Muhammad S, Jar PYB. Determining stress–strain relationship for necking in polymers based on macro deformation behavior. Finite Elem Anal Des. 2013;70–71:36–43.
26. Geng L, Wu W, Sun L, Fang D. Damage characterizations and simulation of selective laser melting fabricated 3D re-entrant lattices based on in situ CT testing and geometric reconstruction. Int J Mech Sci. 2019;157–158:231–42.
27. Gómez-López LM, Miguel V, Martínez A, Coello J, Calatayud A. Simulation and modeling of single point incremental forming processes within a solidworks environment. Procedia Eng. 2013;63:632–41.
28. D. Farbman, C. McCoy, Materials Testing of 3D Printed ABS and PLA Samples to Guide Mechanical Design, in: ASME 2016 11th International Manufacturing Science and Engineering Conference, 2016.
29. H. Zein, V. Tran, A. Abdelmotaleb Ghazy, A.T. Mohammed, A. Ahmed, A. Iraqi, H. Nguyen, How to Extract Data from Graphs using Plot Digitizer or Getdata Graph Digitizer, 2015.
30. Li C, Denlinger ER, Gouge MF, Irwin JE, Michaleris P. Numerical verification of an Octree mesh coarsening strategy for simulating additive manufacturing processes. Additive Manuf. 2019;30:100903.
31. Kiendl J, Gao C. Controlling toughness and strength of FDM 3D-printed PLA components through the raster layup. Compos B Eng. 2020;180:107562.
32. Bhandari S, Lopez-Anido RA, Gardner DJ. Enhancing the interlayer tensile strength of 3D printed short carbon fiber reinforced PETG and PLA composites via annealing. Additive Manuf. 2019;30:100922.
33. Raj SA, Muthukumaran E, Jayakrishna K. A Case Study of 3D Printed PLA and Its Mechanical Properties. Materials Today: Proceedings. 2018;5:11219–26.
34. Torres J, Cotelo J, Karl J, Gordon AP. Mechanical property optimization of FDM PLA in shear with multiple objectives. JOM. 2015;67:1183–93.

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