Tensile Testing and Evaluation of 3D Printed PLA Specimens as per ASTM D638 Type-IV Standard

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S. Anand Kumar and Yeole Shivraj Narayan

Abstract Additive Manufacturing is playing a major role in the manufacturing of parts by providing an alternative to the existing processes. However, strength of such 3D-printed parts using specific materials is still an area of current research. Polylactic acid, a biodegradable material, is one of the compatible materials in fused deposition modelling-based 3D printing process. Researchers have primarily focused on testing of PLA material as per ASTM D638 Type I standard. In this research ASTM D638 type IV specimens printed on FDM printer using PLA material are subjected to tensile testing and then compared relatively with the simulated results. Process involves preparation of ASTM specimens in Solidworks software followed by printing using PLA material in a Makerbot 3D printer, conditioning the printed specimens and then subjecting it to tensile testing in AutoGraph AG 15 universal testing machine. CAD model of the test specimens is then subjected to tensile loads in ANSYS software to obtain simulated tensile strength and maximum deformation.

Keywords Tensile testing · Polylactic acid · ASTM D638 Type IV 3D printing

1 Introduction

FDM is one of the most popular additive layer-by-layer manufacturing technologies capable to deliver or duplicate unsupported modern structures in one piece [1]. Additive manufacturing permits programmed creation of complex shapes with a critical decrease in assembling cost, contrasted with conventional subtractive manufacturing methods [2]. In the most recent years, the utilizing additive manufacturing has developed generously equally in volume and extension [3, 4]. Independent of the particular strategy, additive manufacturing producing brings

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about segments with a layer of microstructure; inside each of the layers, the direction of layers in 3D-printed parts effects the mechanical properties [5, 6]. Main principle of FDM technology is to produce parts directly from three-dimensional computer-aided design (CAD) data by using material extrusion process [7]. Three-dimensional CAD model is saved as *.stl* file configuration and later exported to a 3D printer. The plan is then printed by the FDM printer layer-by-layer structuring a genuine product. 3D printing enables creators and designers to go from level screen to correct part [8]. FDM is an unpredictable procedure with number of parameters that impact material properties and quality of the product, and also, the mix of these parameters is frequently hard to understand [9, 10]. Printing parameters like layer thickness, feed rate, infill pattern and density, raster width and angle, orientation of the part show a substantial effect on performance and quality of the FDM-printed parts [10–15].

2 Polylactic Acid

Polylactic acid (PLA) is a thermoplastic polyester which can be produced from renewable resources. It is presently considered a substitute for synthetic plastic materials in food packing marketplace as its cost is moderately low and possesses superior process-ability. PLA is likely to reduce the impact on the environment due to the production and use of petrochemical polymers [16]. PLA has a larger strength and lower ductility than the traditional acrylonitrile butadiene styrene (ABS) material. PLA is a sustainable thermoplastic alternative which addresses the problem of added waste from end-users manufacturing components at home and has similar characteristics as ABS. PLA parts produced via FDM have also been of high interest to the medical field, due to its biocompatibility in applications such as tissue engineering and custom-made patient-specific implants [17]. PLA may be

Table 1 Material properties of PLA [23–28]

Property	Unit	Value
Elongation at break	%	7.0
Melting temperature, T_m	°C	130–230
Shear modulus, G	MPa	1287
Elastic modulus, E	MPa	3500
Rockwell hardness	Hr	88
Yield strength, σ_y	MPa	70
Flexural strength, σ_x	MPa	106
Poisson's ratio, v		0.360
Ultimate tensile strength, σ_{usd}	MPa	73
Tensile modulus	GPa	2.7–16
Crystallinity	%	37
Unnotched Izod impact	J/m	195

stronger over ABS, yet more fragile. PLA has a lower effect of warping due to its lower coefficient of thermal expansion, which increases the adhesion of part to the printed surface and reduces cracking of the part while printing [18]. Table 1 shows the material properties of PLA material.

3 Specimen Design

ASTM D638 standard procedure is adopted for evaluating the tensile behaviour of 3D-printed PLA test specimens. Solidworks software is used for modelling the geometry of the specimens as per the dimensions specified in ASTM D638 standard as shown in Fig. 1 and Table 2, respectively. Models are then saved in *.stl* file format as shown in Fig. 2 and then imported to the 3D printing software [19].

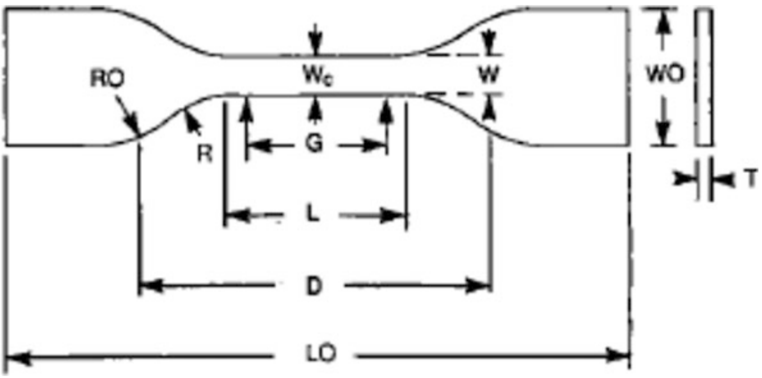


Fig. 1 ASTM D638 Type IV specimen [22]

Table 2 ASTM D638 Type IV specimen dimensions [22]

Dimensions	Type IV (mm)
L—Length of narrow section	33
W—Width of narrow section	6
LO—Length overall	115
WO—Width overall	19
R—Fillet radius	14
RO—Outer radius	25
D—Distance between grips	65
G—Gage length	25

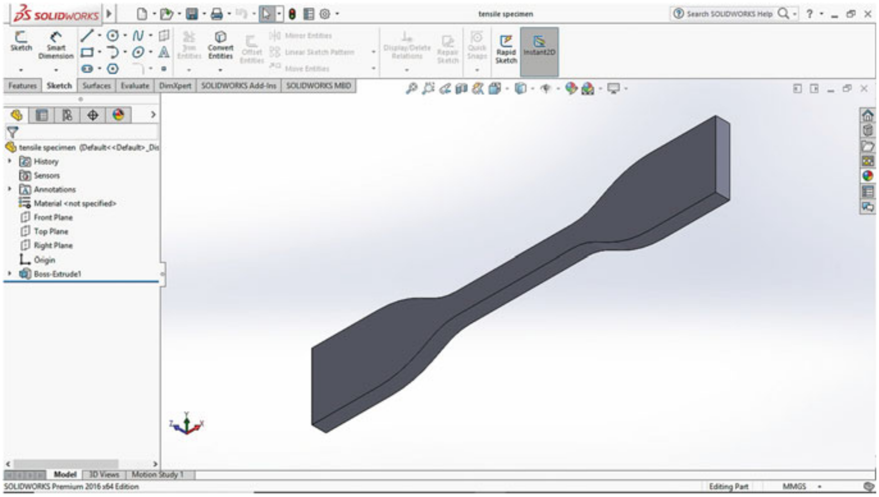


Fig. 2 Modelled tensile specimens

3.1 Tensile Specimen with Detailed Dimension

Figure 3 displays a schematic of tensile specimen with detailed dimensions based on the ASTM standard. A tensile specimen has augmented finishes or shoulders for grasping. The critical piece of the example is the gage area. The cross section of the gage area is reduced so deformation and distress will be restricted in this area. The gage length is the area over which estimations are made and is focused inside the decreased segment. Separations amongst finishes of the gage area and shoulders must be sufficiently extraordinary so that bigger closures do not oblige deformity within the gage length, and the gage length ought to be perfect with respect to its distance. Rather, the anxiety state will be more mind-boggling than straightforward pressure. Portrayals of standard example shapes are given in detail on malleable testing of particular materials.

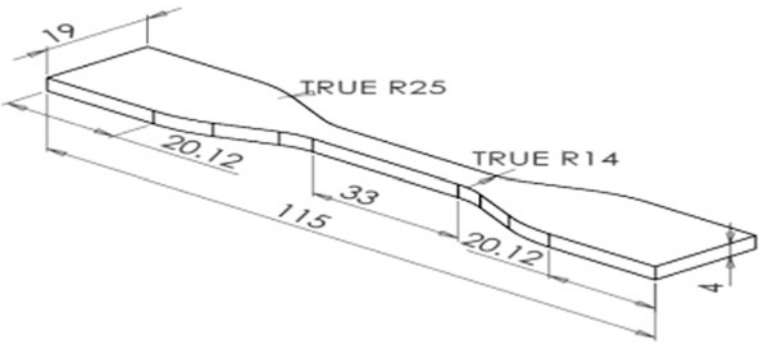


Fig. 3 Tensile specimen with detailed dimension

There are different methods for holding. For example, screwing the samples into a grasp handle, it can be stuck, butt closures can also be utilized, or the hold segment may be held amid wedges. Determination of a grasping approach is made by assuring the greatest load of the specimen that is held without any slippage in the hold area, and the twisting has to be limited.

3.2 STL File of Tensile Specimen

The created 3D model using Solidworks software is saved in *.stl* format. Figure 4 shows the *.stl* file of tensile specimens. As depicted in Fig. 5, this format is

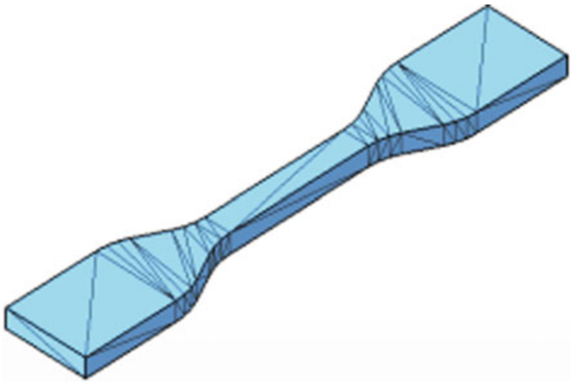


Fig. 4 .stl file of tensile specimens

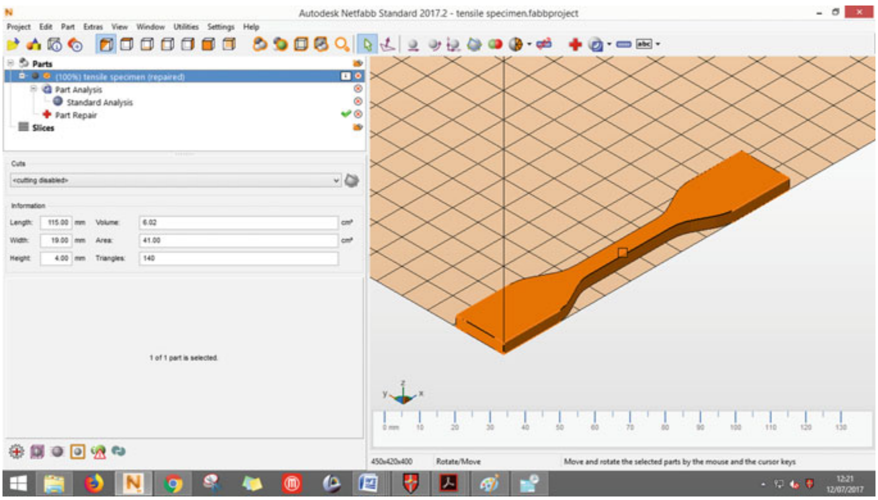


Fig. 5 .stl file of tensile specimens imported to Netfabb

imported into software called Netfabb, which sorts out any errors that are present in the sliced layers of the 3D model. The output is the new *.stl* file with minimum or no errors in the model.

4 Fabrication of Specimen

4.1 Makerbot Replicator Z18

Makerbot Industries has an online platform "Thingiverse", where clients can transfer 3D printable records, report plans, and team up with 3D printing ventures. The site is a synergistic storehouse for configuration documents utilized as a part of 3D printing, laser cutting and other DIY producing forms.

Additive Manufacturing (AM) makes a 3D model in which the filament is combined in a layer form using codes generated by the software to make a part, with material being included, (e.g. fluid particles or powder grains) being intertwined. Different geometry or profile can be delivered utilizing computerized data from a 3D display source, for example additive manufacturing file (AMF) file (typically in successive layers). Stereolithography (.stl) is a standout amongst the most well-known document sorts that is utilized for 3D printing. Most of the fifth-generation Makerbot 3D printers use a document type of *.makerbot* to send the guidelines to printer for model to be built. Makerbot desktop software naturally changes any type of 3D printable format to *.makerbot* file for its convenience, which contains the guidelines for the print like extruder path, rasters and temperature. *.stl* and *.obj* are file sorts utilized for 3D printable models in Makerbot 3D printers. *.thing* documents are a method for sparing courses of action and settings for 3D models (Figs. 6 and 7).

4.2 STL

A standard tessellation language (STL) is a generally utilized 3D model file format. It comprises of surfaces which are composed of triangles. Every triangle has an inward side and an external side. External side is known as 'normal'. In an all-around framed stl, everyone of the normal's confronting outward and the surface is nonstop, without any gaps. At the point when these guidelines are met by a model, it is alluded to as complex .stl's containing normal's that face inwards (modified normals) might be able to print; however, complex models are commonly viewed as obligatory for 3D printing.

.stl is now compatible with most of the 3D modelling software's and became a standard for 3D printing models. Table 3 shows the parameter values that are used in 3D printing and Fig. 8 shows the 3D printed specimens.

Fig. 6 Makerbot Replicator Z18

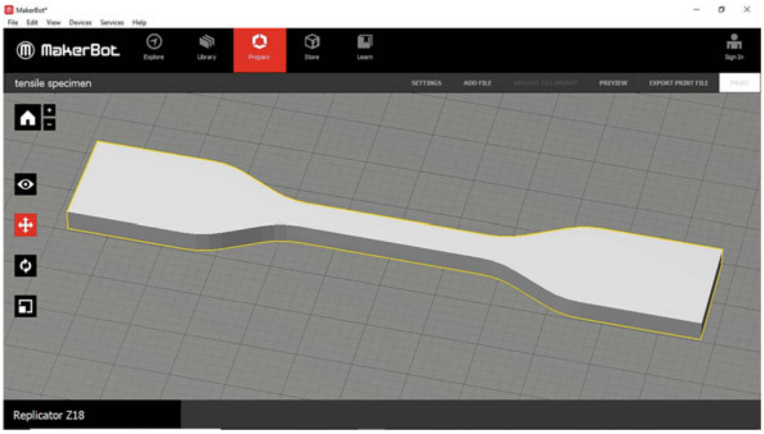


Fig. 7 .stl file imported to makerware software

Table 3 3D printing parameter values

Parameters	Values
Layer height (mm)	0.3
Feed rate (mm/s)	150
Extruder temperature (°C)	230
Bed temperature (°C)	110
Number of shells	2
Infill density (%)	100

Fig. 8 3D-printed tensile specimen

Makerbot Replicator Z18 3D printer with Makerbot PLA material is used to print the specimens for conducting tensile tests.

5 Experimental Procedure

3D-printed PLA specimens conditioned as per ASTM D618-13 [29] are tested experimentally for tensile strength on a universal testing machine (UTM) in specimen preparation laboratory at Central Institute of Plastic Engineering and Technology, Hyderabad. Figure 9 depicts UTM used for testing specimens. Tensile properties measurement is carried out on Shimadzu Japan make UTM machine whose specifications are given in Table 4.

AutoGraph AG 15 UTM has a grip attachment distance of 33 mm. A load of 5.0 kN at a constant speed of 5 mm/min is applied. Test specimens are prepared in compliance with ASTM D638 Type IV standard. Sample width and thickness are measured for individual specimens [20].

Specimens are placed in the UTM with the help of grippers, and a gradual load is applied on the specimens until failure, and the resultant loads are noted down for every single specimen thus obtaining the tensile loads for every specimen.

Fig. 9 Universal testing machine. *Source* CIPET, Hyderabad

Table 4 Specifications of UTM

Identification	CHYD/PTC/UTM/3
Model no.	AutoGraph AG 14
Range	0–50 kN
Accuracy	0.01 N
Location	Specimen preparation laboratory
Make	Shimadzu Japan
Applicable test	Tensile, compressive, flexural, tear, shear, elongation and modulus

6 Analysis of Specimens

Simulations are carried out in static structural analysis mode with one end fixed in ANSYS 16.2 software.

6.1 Stress Analysis of Tensile Specimen

Stress analysis is carried out on the tensile test specimen with different loads acting on the specimen as shown in Fig. 10.

The stress is induced in the specimen after the application of tensile load. Minimum and maximum values are obtained. Gauge length has high stress values when compared to the other regions of the specimen due to plastic flow or slippage

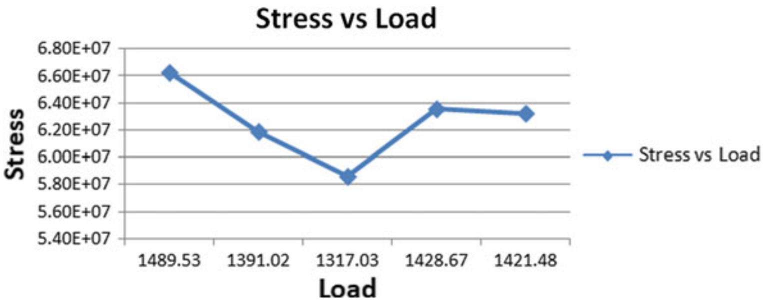


Fig. 10 Stress versus load graph of the analyzed tensile specimens

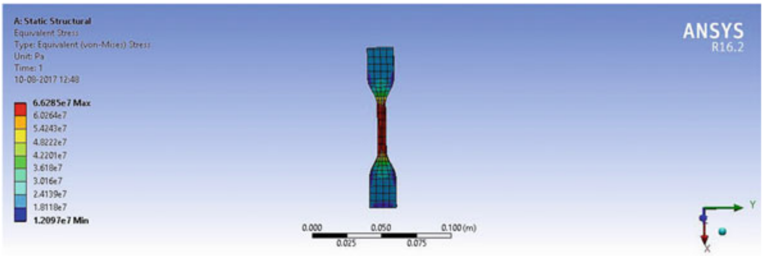


Fig. 11 Maximum stress obtained in the tested tensile specimens

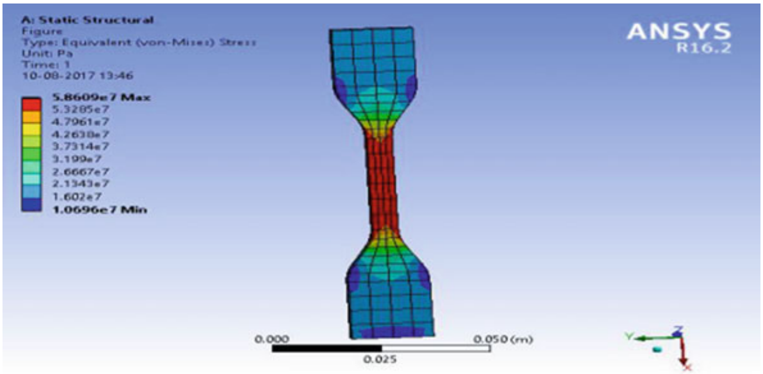


Fig. 12 Minimum stress obtained in the tested tensile specimens

along molecular slip planes when load is applied beyond elastic limit shown in Figs. 11 and 12, respectively. Table 5 shows the maximum and minimum equivalent stress obtained when the relevant load is applied on the specimen.

Table 5 Results of stress analysis of tensile specimens

Load (N)	Minimum equivalent stress (N/mm^2)	Maximum equivalent stress (N/mm^2)
1489.53	$1.2097e^7$	$6.6285e^7$
1391.02	$1.1297e^7$	$6.1901e^7$
1317.03	$1.0696e^7$	$5.8609e^7$
1428.67	$1.1603e^7$	$6.3577e^7$
1421.48	$1.1544e^7$	$6.3257e^7$

The minimum equivalent stress is observed for the load of 1317.03 N, and maximum equivalent load is observed for load of 1428.67 N.

The von-misses stress values of tensile specimen at various loads are as shown in Fig. 10. As different loads are applied on the specimen, different behaviour is observed. The graph gives a clear variation of stress versus load behaviour for particular loads acting on the specimen.

6.2 *Deformation Analysis of Tensile Specimen*

Deformation analysis is carried out on the tensile test specimen with different loads acting on the specimen as shown in Fig. 13.

The deformation is induced on the specimen after the application of tensile load. Minimum and maximum values are obtained. Table 6 shows various maximum and minimum deformation values for different loads acting on the specimen. Due to the applied load and work done by external forces acting on the specimen, large deformation is observed as shown and is indicated in red colour shown in Figs. 14 and 15, respectively. Maximum deformation is observed for the load of 1428.67 N. The deformation values of tensile specimen at different loads are as shown in Fig. 13.

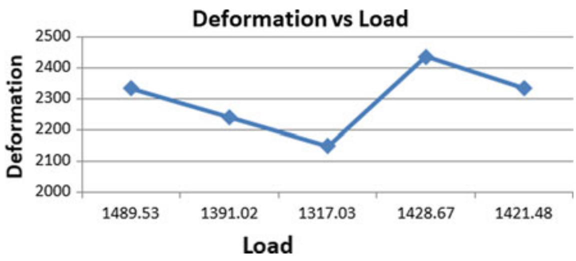


Fig. 13 Deformation versus load graph of the analyzed tensile specimens

Table 6 Result of deformation analysis of tensile specimens

Load (N)	Minimum deformation (mm)	Maximum deformation (mm)
1489.53	0	2336.2
1391.02	0	2241.1
1317.03	0	2149.5
1428.67	0	2438
1421.48	0	2282.6

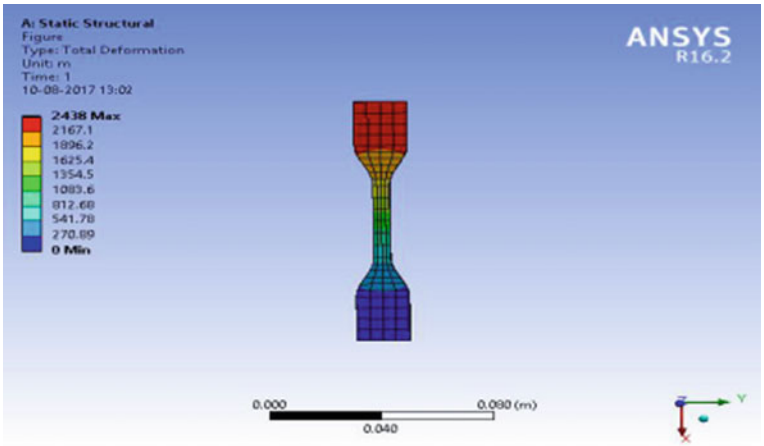


Fig. 14 Maximum deformation obtained from the tested tensile specimens

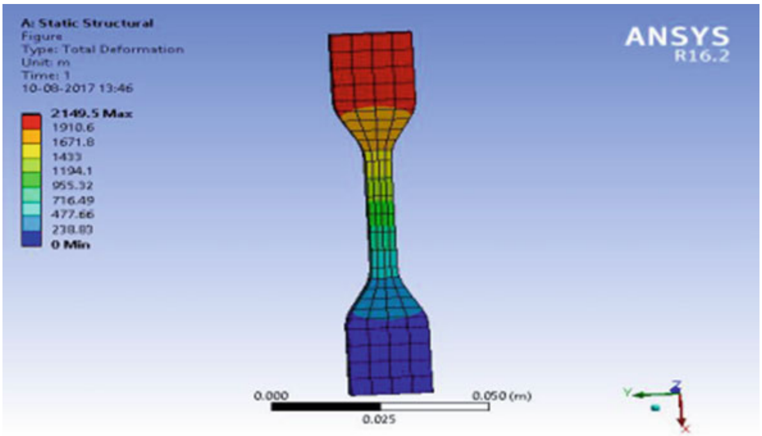


Fig. 15 Minimum deformation obtained from the tested tensile specimens

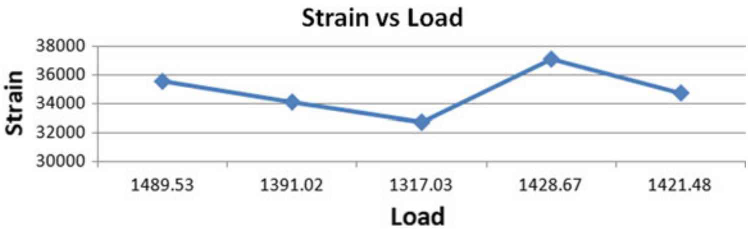


Fig. 16 Strain versus load graph of the analyzed tensile specimens

Table 7 Result of strain analysis of tensile specimens

Load (N)	Minimum elastic strain	Maximum elastic strain
1489.53	6641.5	35,534
1391.02	6371.1	34,087
1317.03	6110.6	32,693
1428.67	6930.9	37,082
1421.48	6489	34,718

6.3 Strain Analysis of Tensile Specimen

Strain analysis is carried out on the tensile test specimen with different loads acting on the specimen as shown in Fig. 16.

The strain is induced in the specimen after the application of tensile load. Minimum and maximum values obtained of the specimen at different loads are shown in Table 7. Strain at 1428.67 N is high in gauge length when compared to the other regions of the specimen due to reason that there is an increment in the length of specimen and decrease in the cross-sectional area of the specimen as shown in Figs. 17 and 18. Minimum elastic strain is seen for load of 1317.03 N, and maximum elastic strain is observed for load of 1428.67 N.

7 Results

As seen in Fig. 19, the behaviour of specimens under different loading conditions on the universal testing machine is depicted. It is observed that all the specimens except specimen 3 followed a similar pattern. Specimen 3, when subjected to a load of 1317.03 N, failed abruptly due to the fragility of the material. Figure 20 shows the failure of tensile specimens when subjected to different on AutoGraph AG 15 Universal Testing Machine.

Maximum displacement, maximum stress, maximum strain and modulus obtained under tensile testing are illustrated in Table 8.

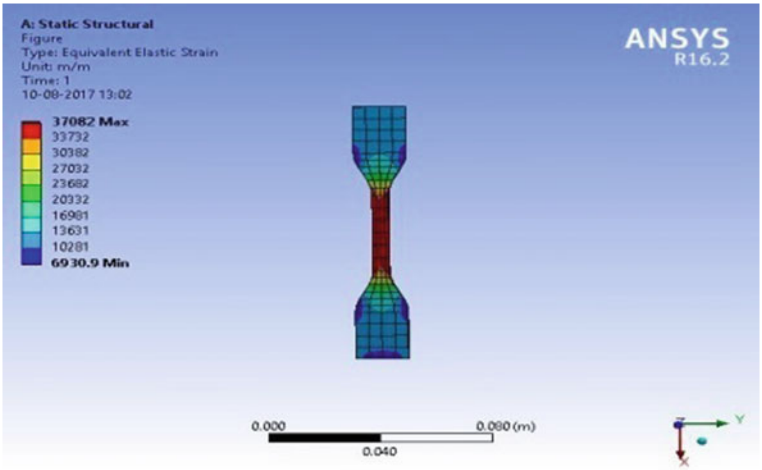


Fig. 17 Maximum strain obtained from the tested tensile specimens

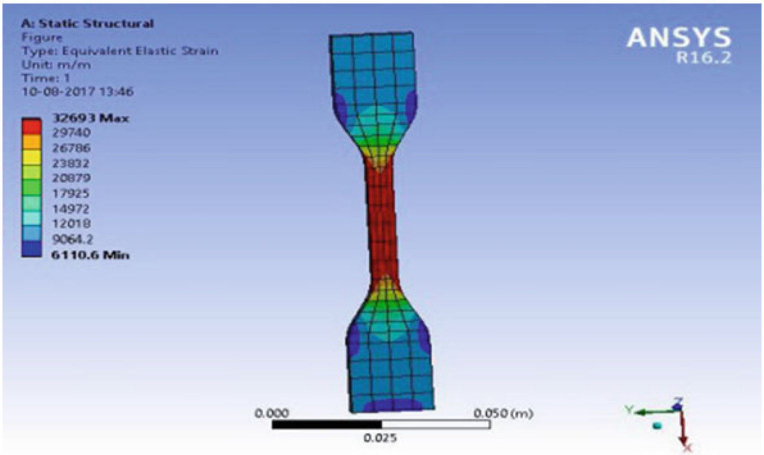
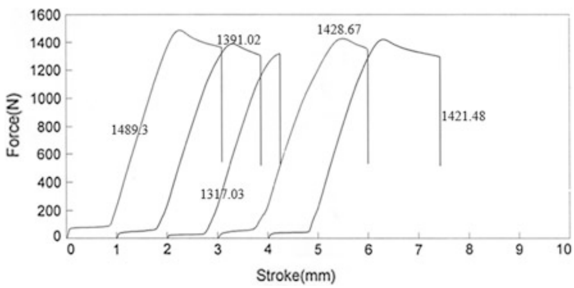


Fig. 18 Minimum strain obtained from the tested tensile specimens

Fig. 19 Force versus stroke graph of the tested tensile specimens



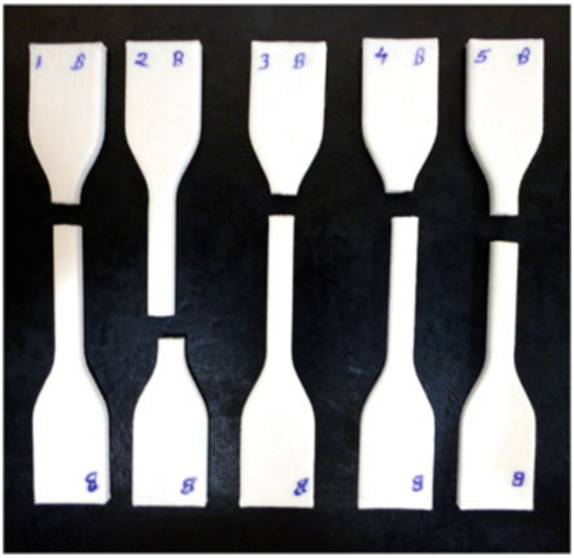


Fig. 20 Tested tensile specimens

Table 8 Tensile test values

Parameters	Max force	Max displacement	Max stress	Max strain	Modulus
Units	(N)	(mm)	(N/mm^2)	(%)	(N/mm^2)
1	1489.53	2.2600	54.4634	5.6500	1865.52
2	1391.02	2.3100	51.5430	5.7750	1816.07
3	1317.03	2.2430	48.7638	5.6075	1792.79
4	1428.67	2.49400	52.6486	6.2350	1714.58
5	1421.48	2.3050	52.7970	5.7625	1822.14
Mean	1409.55	2.3224	52.0432	5.8060	1802.22

8 Conclusion

This paper presents the evaluation of tensile strength of ASTM D638 Type IV specimens of PLA material additively manufactured using FDM-based Makerbot desktop 3D printer and its simulation in ANSYS software. Following results are observed:

- Maximum stress of 63.577 and 54.46 N/mm^2 is observed for a load of 1489.53 N under simulated and UTM testing, respectively.
- Maximum deformation of 2.336 and 2.4940 mm is attained for a load of 1428.67 N under simulated and UTM testing, respectively.

- Maximum elastic strain of 4.06 and 6.23% is observed for load of 1428.67 under simulated and UTM testing, respectively.
- The obtained tensile strength of 54.46 N/mm^2 is similar to that of the results obtained by other researchers reported in [18] and [21].
- Behaviour of specimen 3 is found to be different with respect to other specimens due to the fragility of the material which caused it to fail before reaching yield point, failing at a load of 1317.03 N.

As the strength of the 3D-printed PLA specimens are almost similar to the conventionally used ones, they can be used in almost all applications ranging from packaging, agricultural, sanitary, consumer products like trays, boxes, packaging, seeding pots, boxes, containers, dinnerware, dairy containers, meat trays and many more.

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