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Fabrication and Characterization of Standard 3D-Printed Specimen under Various Printing Speeds and Infill Densities

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ABSTRACT

An entry level average priced 3d-printer, the maker bot replicator mini+, was used to print dog bone specimens to conduct ultimate tensile strength, hardness and surface roughness testing. Average priced, polylactic acid (PLA) material was used as material to print dog bone specimens. Specimens were printed at various printing speeds of 90mm/s, 110mm/s, 130mm/s and 150mm/s and with various infill density levels of 55%, 75% and 95% to test the effect of part strength.
Tensile testing of the 3d-printed specimens showed that for higher density level 95% the tensile strength was higher which is 5.334kgf/mm², while at the 55% and 75% density level, the tensile strength was not much less which is 3.7220kgf/mm² and 4.1412kgf/mm², similarly the printing speed also produced low effect on the tensile strength. A Micro Vicker hardness testing machine was used to conduct hardness testing on printed specimen. For this type of testing the 95% density produced higher hardness of the specimen as compared to 55% and 75% density levels while with increasing the printing speed also produced the higher hardness. For surface roughness testing it was clearly showed that the 55% density produced lower roughness parameters (Ra, Rz, Rq) as compared to 75% and 95% density levels, which mean that the 55% specimens' roughness values were less than that of 75% and 95%, while the highest printing speed, 150mm/s showed the lowest value of surface roughness.

Key Words- PLA material, 3d-printer, tensile strength, hardness, surface roughness, printing speed, density

Introduction

3d-printers have become affordable for the dedicated home user. There are many high

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quality low priced 3d-printers available for home user [1]. Many of average level 3d-printers have been sold as printer that prints using the material polylactic acid (PLA). Acrylonitrile Butadiene Styrene (ABS) material can also be used for printing, but it is difficult to print with ABS due to its strength etc. PLA is stronger than ABS and the melting temperature of PLA material is lower than ABS material. PLA does not have the same health risk as ABS when printing in an open environment and at room temperature, because PLA is mostly produced from the renewable sources, non-toxic, biodegradable and marked safe for food packing and medical industry [1]. The big disadvantage of PLA material is PLA material does not maintain its shape under load when deform in the warm environment. With this entire concept, so it is clear that why many manufacturers and engineers are producing and supporting 3d-printers that print the specimens using PLA material [1].

Many people will soon be able to understand the 3d printing technology and will also be able to print with their personal 3d printers at home by using PLA, especially, in the lock down of COVID-19 which faces the world from seven to eight months. The MakerBot Company alone has sold over 15000 3d-printers from 2009 to 2014 [3]. The material properties of PLA material, ABS material have been well studied and many studies related to printing speeds and densities.

The purpose of this study is to investigate and understand the mechanical characterization of 3d-printed PLA from the average level 3d-printer. Specimens were printed to investigate the ultimate tensile strength, hardness and surface roughness.

3D Printer

3d-printer also known as digital fabrication technology creates three dimensional objects by direct deposition of materials. 3d-printing technology prints an object directly from CAD model. It receives data from CAD model and creates 3d objects layer by layer deposition of material. Mostly there are two types of material are using in 3d printing technology; one is polylactic acid (PLA) and other one is Acrylonitrile Butadiene Styrene (ABS) material. There are three main steps for 3d-printers that we need to know, in order to create three dimensional objects [3].

3D Modeling/CAD Modeling Software

3d modeling software or CAD modeling is the first step of 3d printing process. For 3d printing process first we will have to design an object in CAD model because a printer can't guess that what we want to print. Some designs are very difficult to design for manufacturers that are why CAD software comes in. The 3d modeling software that are using in the 3d printing process are, solid works, Pro E, Auto cade etc. This modeling software are very important in many industries especially in medical industry, dentistry etc, where laboratories are using three dimensional software to design the human body parts. So the 3d modeling software is very important for the 3d printing process because without this step a 3d printer can't print an object [3].

Slicing The Model

Once a model is created in 3d CAD modeling, it's time to slice it in the slicing or MakerBot software. The slicing software tells the 3d printer that how to slice the model into layer in order to produce final object. When we design an object in CAD

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model, then we need to convert it into stl file, because the slicing or MakerBot software only runs stl files. The slicing software or MakerBot software takes the scan of each layer of the 3d CAD model and tells the 3d printer that how to scan its internal and external structure. Once the slicing software takes scan and sliced the object then it sent the object to the 3d printer for the actual printing process to produce final shape of the object [3].

3D Printing Deposition Process

When slicing of the object is completes, it's time for 3d printer to take action and create the three dimensional object. It takes the data from slicing software model and creates that type of model layer by layer deposition process. The nozzle move back and forth while dispensing the melted material layer by layer, waiting for the layer to dry then continuous the next level.

PLA Material

Polylactic acid (PLA) also known as polylactide is a 3d filament and thermoplastic material with formulae ($C_3H_6O_3$), when lactic acid is heated and condensate it so it will lose its water molecule produce the PLA material.

PLA is produced from renewable sources that are why it becomes most popular day by day for 3d printing process. PLA material is also called bio-plastic material because it provides positive response to the environment and also reduces the pollution. PLA has been marked safe for medical devices in human body. PLA is the most widely used material in 3d-printing. The molecular structure of PLA material is given below.

Some of the properties of PLA material are given in the following table

Table 1: PLA Material Properties

Properties of PLA Material	Units	Values in the range
Composition	---	PLA (Polylactic Resin) 98% — 99%
Color	---	Green
Diameter	Mm	1.70 — 1.78
Print Temperature	°C	190 — 230
Tensile Strength	Kgf/mm^2	1.40 — 11.0
Elongation at Break	%	4% —10%
Modulus of Elasticity	Kgf/mm^2	35 — 350
Hardness	Kgf/mm^2	10 — 250
Density	g/cm^3	1.21 — 1.25
Glass Temperature	°C	40 — 80
Melting Temperature	°C	150 — 180

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Figure 1: Schematic of Available PLA Material and 3d Printer

Experimental Procedure

The ultimate tensile strength, hardness and surface roughness property testing were conducted on PLA specimens that were 3d-printed using PLA material. Twelve specimens were printed on an average priced 3d-printer, the MakerBot Replicator Mini+. First I designed the dog bone sample in solid works then convert it into stl file and start the makerBot software which can run the 3d-printer, start the 3d-printer and control the 3d-printing parameters. Each specimen was printed separately and kept the size of each specimen same in order to produce all specimens similar in term of size and orientation. For all the specimens the two (2) perimeters were changed, one is the printing speed and other is the density, while the size and the orientation have been kept same. I took three density levels 55%, 75% and 95%, and took four printing speeds 90mm/s, 110mm/s, 130mm/s and 150mm/s. The PLA material was extruded at 215°C with different printing speeds and densities and with heated bed surface 65°C. All specimens were printed from 1-kg spools of PLA material. To check whether the size and orientation of each specimen are same or not, we checked and measured each specimen individually throughout the experiments.

AG-IS SHEMADZU model Universal Testing Machine was used to conduct the ultimate tensile strength, modulus of elasticity and elongation at break of each specimen. The stroke speed has been kept at 50mm/min. The Micro Vickers hardness testing machine was used to find out the hardness of each specimen and the Surface Roughness Tester was used to conduct the surface roughness of the specimens. All experiments were performed at room temperature.

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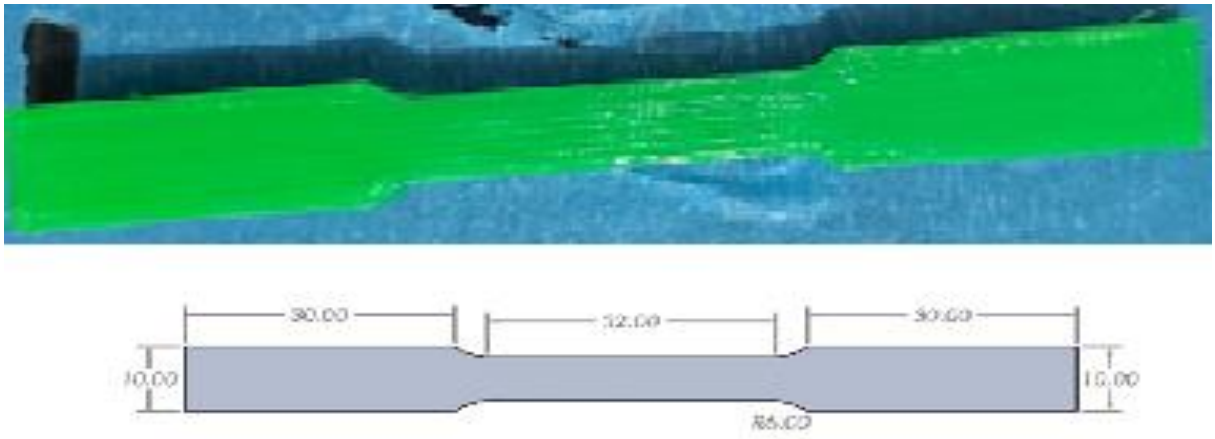


Figure 2: Schematic of Printed PLA Dog Bone Specimen and Standard Specimen

Ultimate Tensile Strength Testing of 3D Printed Specimen

Twelve specimens were tested for tensile properties of PLA printed material. AG-IS SHEMADZU model Universal Testing Machine was used to conduct the ultimate tensile testing. The universal testing machine (UTM) wedge grips were displaced at 50mm/min rate with data (applied force, displacement between grips and elongation) collected at 100Hz. An UTM model can directly measure the force, strain and tensile strength values. Twelve specimens were tested for different printing speeds and densities. Each specimen has the same length, width and thickness so we don't need to measure each specimen, just measure one specimen for the calculation of tensile strength and perform the experiments. Following figure shows the ultimate tensile strength testing of 3d printed PLA specimen by using UTM.



Figure 3: 3d-Printed Specimen Tensile Testing

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Hardness Testing of 3D Printed Specimen

Twelve specimens were tested to conduct the hardness of the 3d-printed specimen for different printing speeds and densities. A Micro Vicker Hardness testing machine was used to perform the test. The force was kept constant i.e 1kgf and dwell time was 5 seconds. The Micro Vicker hardness testing machine has high electronic microscope which is used to measure the diagonal distance of the deformed surface. When 1kgf force was applied on the specimen for 5 seconds of dwell time some deformation was produced, these deformation was measured on microscope in the form of L_1 and L_2, which was in millimeter and need to convert it into micrometer because this type of hardness machine measure the hardness in very low deformation on surface microscopically. The formulae used to find the hardness is given below.

Hardness = $1.854 * F/D^2$

Where,

F = applied force

D = diagonal length

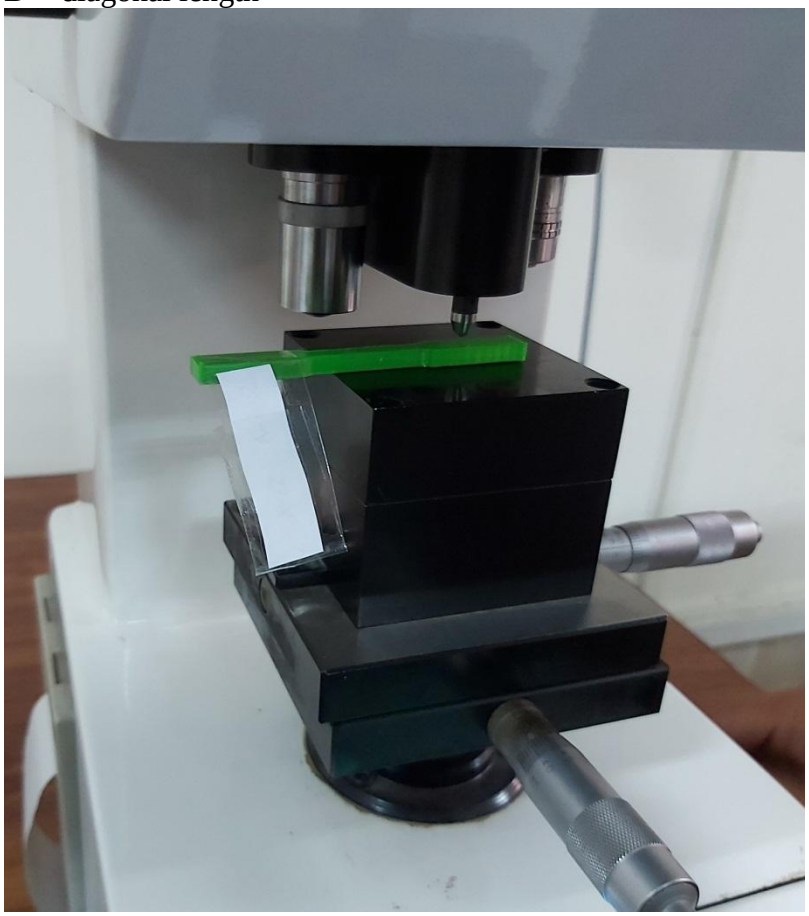


Figure 4: 3d-Printed Specimen Hardness testing

Surface Roughness Testing of 3D Printed Specimen

The surface roughness testing was conducted on Mitutoyo SJ-201 model of Surface Roughness tester. This type of model which is available in our Industrial laboratory was much calibrated and can measure three parameters of surface roughness, Ra, Rz

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and Rq. Ra is the called average roughness, is the area between highest roughness profile peak and its mean line. Rz is the average value of the five highest profile peaks and depth of five deepest valleys. Rq is the root mean square value between highest profile peaks and mean line**.**

The surface roughness tester measured the specimen at three points in order to find the roughness, and then I took the average of Ra between three points, average of Rz between these three points and average of Rq between these three points in order to calculate the total roughness for entire specimen.



Figure 5: Schematic of Surface Roughness Testing of 3d Printed Specimen.

II. Results

Ultimate Tensile Strength Testing of 3D Printed Specimen

Twelve specimens were tested having same length, width and thickness. The following table 2 shows the individual result of each specimen.

Table 2: Tensile Testing Data

Printing speed (mm/s)	Density percentage (%)	Force (Kgf)	Elongation at Break (%)	Ultimate Tensile Stress (Kgf/mm²)	Modulus of Elasticity (Kgf/mm²)
90	55	110.894	6.50	3.696	85.00
110	55	112.061	6.59	3.735	84.00
130	55	110.735	6.62	3.691	96.00
150	55	112.965	6.70	3.765	100.50
90	75	136.228	7.65	4.540	105.00
110	75	121.251	7.35	4.041	99.67
130	75	122.366	6.90	4.078	104.00

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150	75	117.108	6.85	3.903	112.00
90	95	164.748	7.55	5.491	120.00
110	95	159.809	8.10	5.326	118.00
130	95	151.683	7.20	5.056	113.00
150	95	163.951	8.99	5.465	121.00

The following table shows average values of all tensile tests. The average force, average elongation in percentage, average ultimate tensile stress and average modulus of elasticity values at each of the density level are given in the following table.

Table 3: Summary of Tensile Testing at each Density Level

Density percentage (%)	Average Force (Kgf)	Average Elongation at Break (%)	Average Ultimate Tensile Stress (Kgf/mm²)	Average Modulus of Elasticity (Kgf/mm²)
55	111.66	6.60	3.722	91.25
75	124.23	7.18	4.141	105.00
95	160.07	7.97	5.334	117.75

In case of density, the 95% density produced the strongest specimen because at 95% density the tensile stress was 5.334 kgf/mm² while at 55% and 75% density level the tensile stress were not much less, which is 3.722 kgf/mm² and 4.141 kgf/mm² respectively. In the case of printing speed, there is fluctuation between the values, as shown in the table 1, at 55% density, with increasing the printing speed some values increases while some values decreases but there is very low difference between them. As we can say that with increasing the printing speed the elongation, the ultimate tensile stress, and modulus of elasticity were almost the same because there is a very low difference or gape between the values. The following figures show the stress/strain curves from each of the density and printing speed.



Figure 6: 3d-Printed Specimen Tensile Loading

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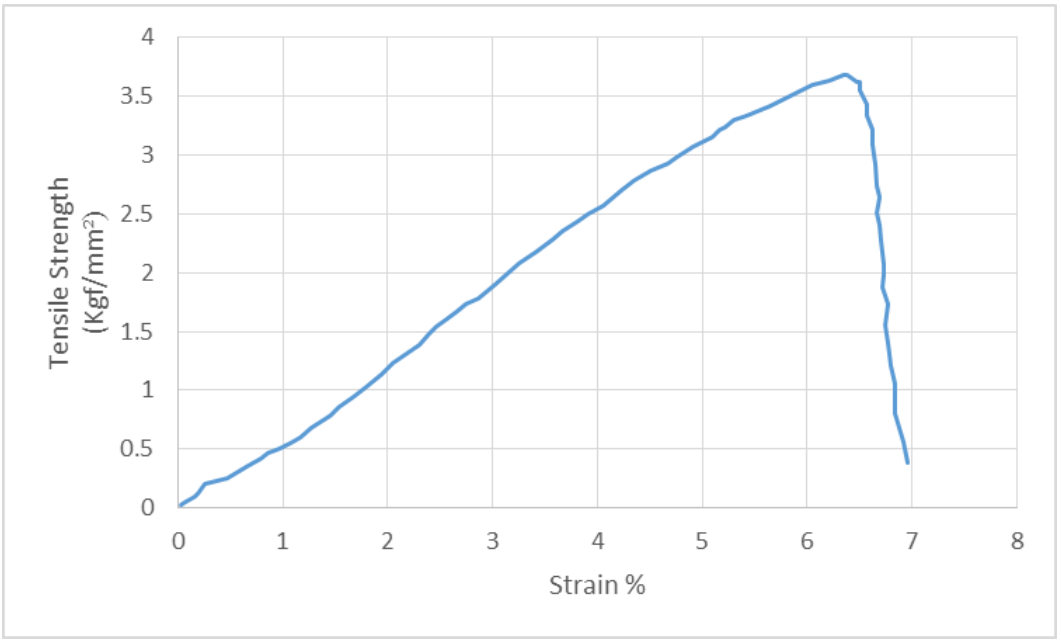


Figure 7: Stress/Strain curve for 90mm/s and 55% density

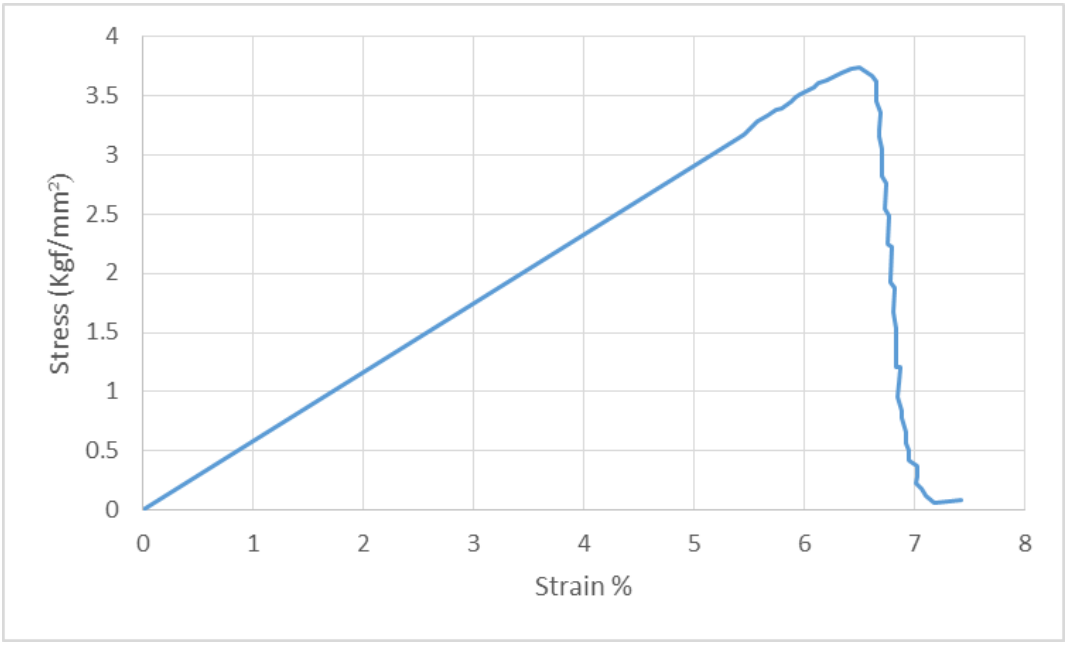


Figure 8: Stress/Strain Curve for 110mm/s and 55% density

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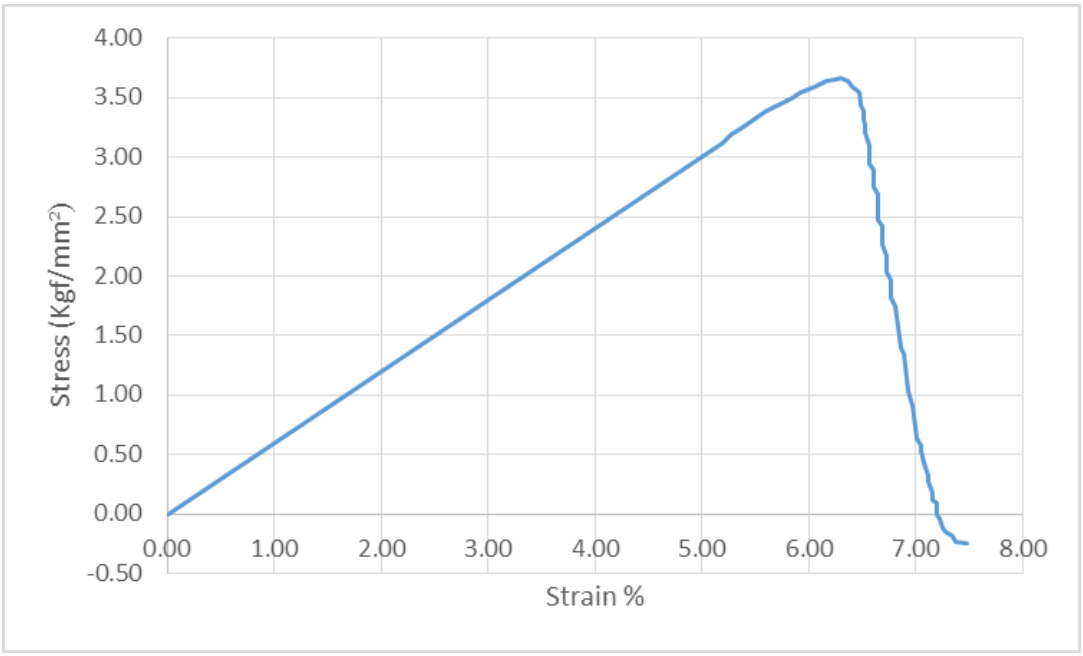


Figure 9: Stress/Strain Curve for 130mm/s and 55% density

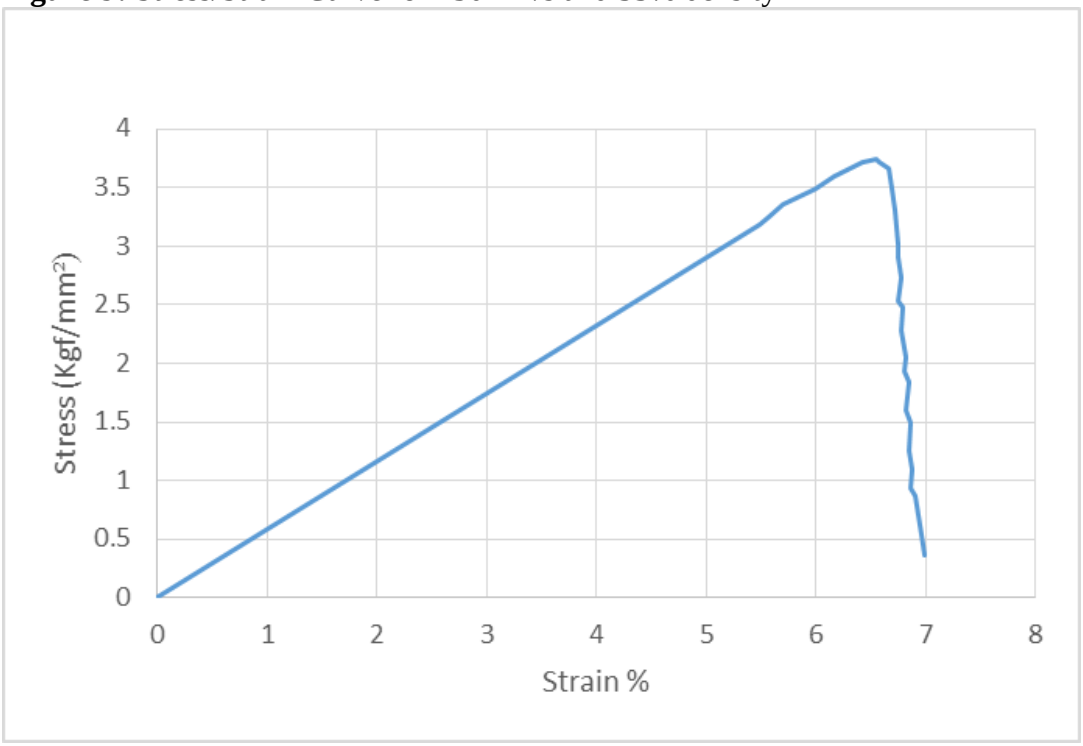


Figure 10: Stress/Strain Curve for 150mm/s and 55% Density

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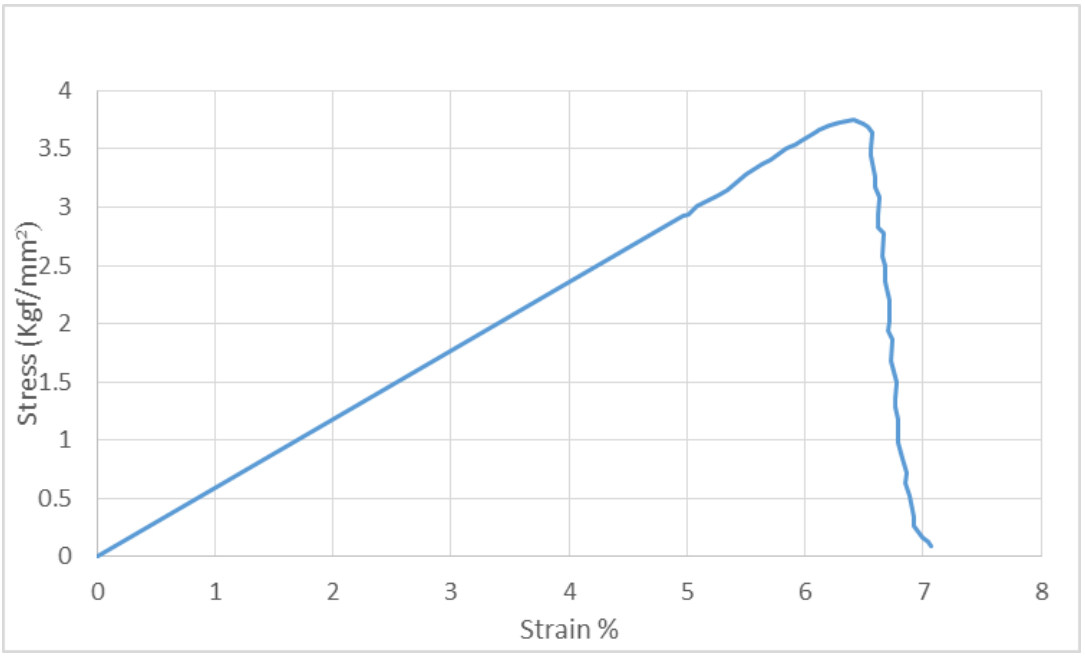


Figure 11: Stress/Strain Curve for 90mm/s and 75% Density

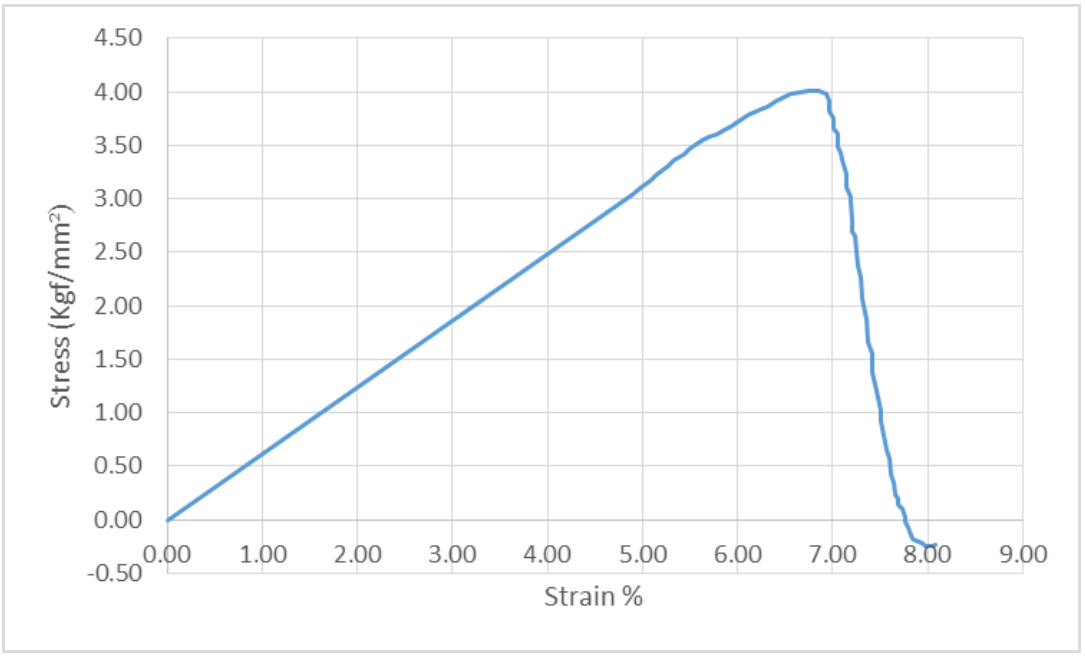


Figure 12: Stress/Strain Curve for 110mm/s and 75% density

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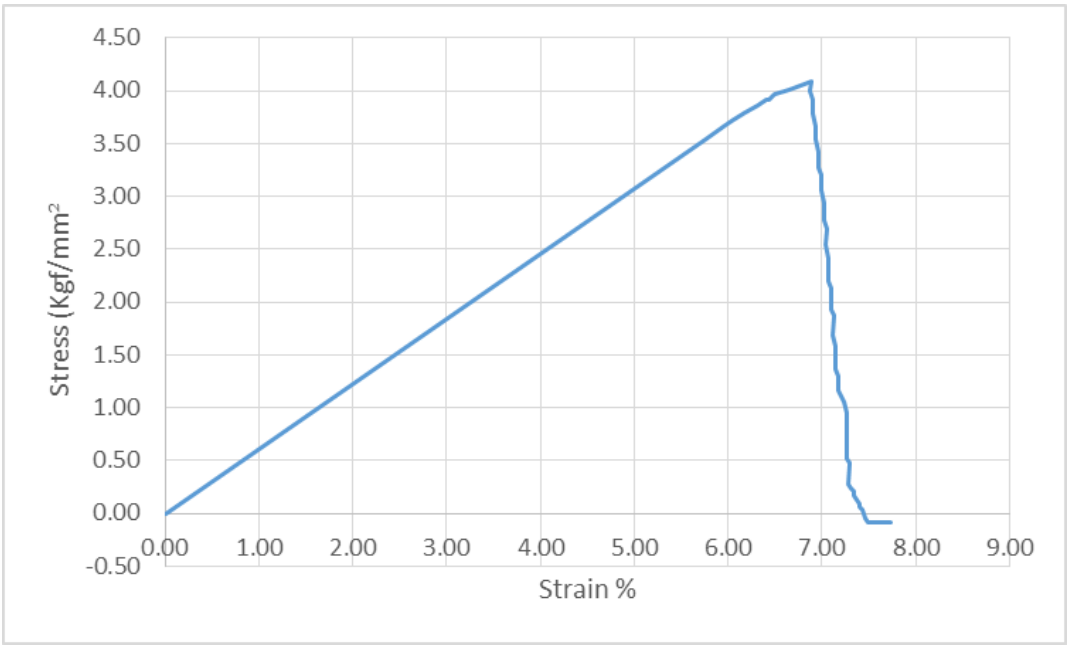


Figure 13: Stress/Strain Curve for 130mm/s and 75% Density

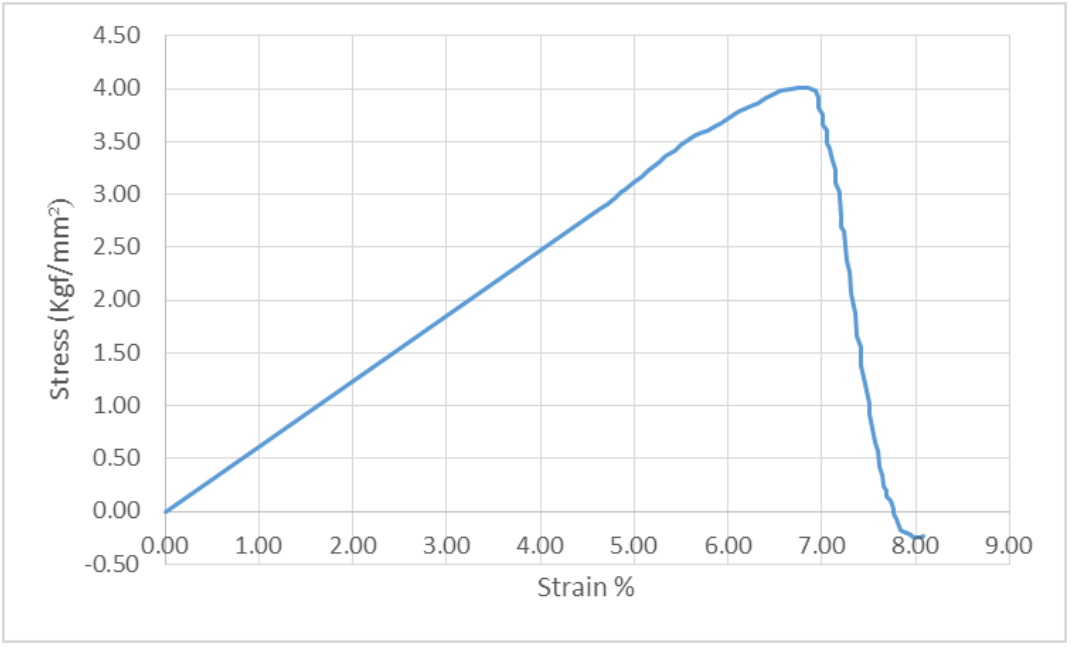


Figure 14: Stress/Strain Curve for 150mm/s and 75% Density

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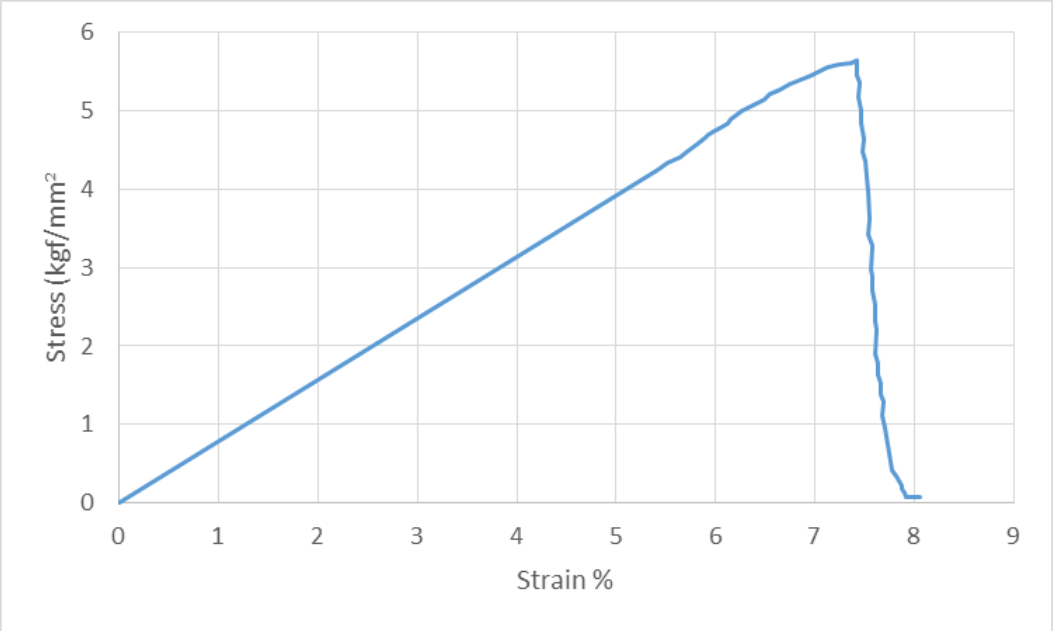


Figure 15: Stress/Strain Curve for 90mm/s and 95% Density

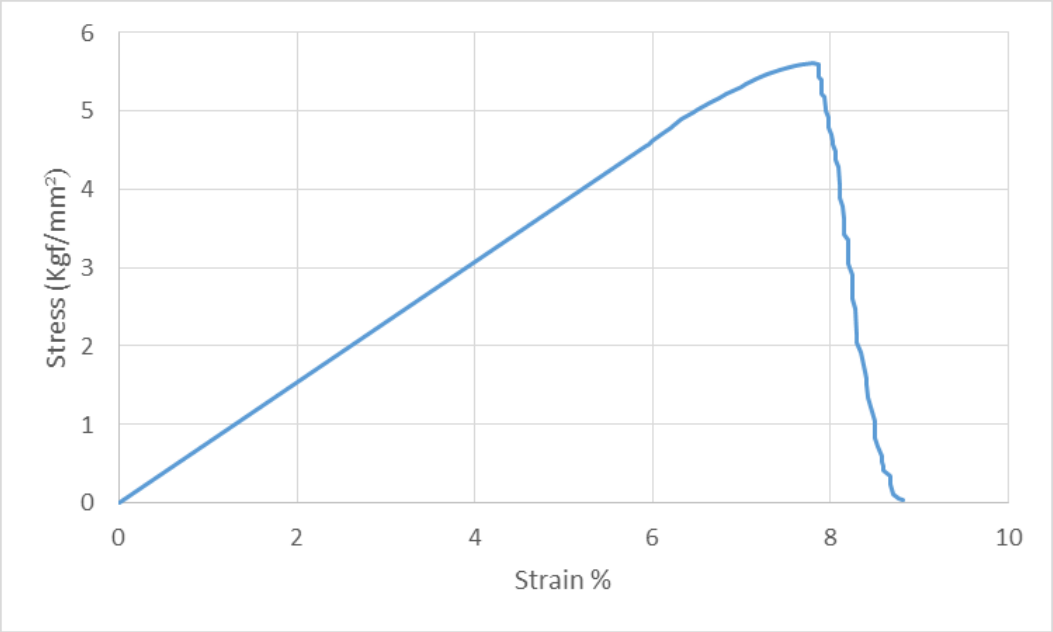


Figure 16: Stress/Strain Curve for 110mm/s and 95% Density

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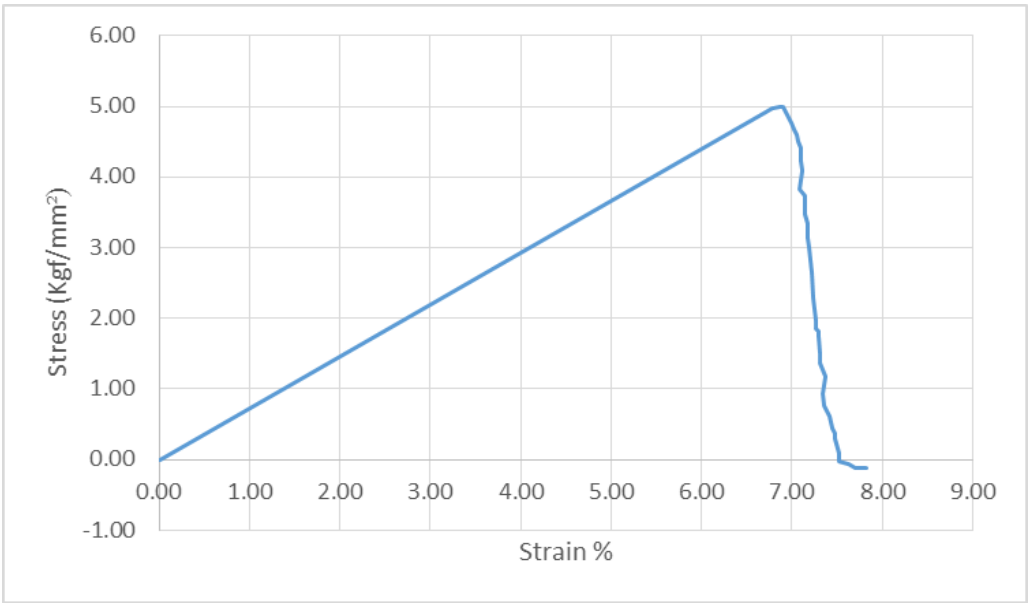


Figure 17: Stress/Strain Curve for 130mm/s and 95% Density

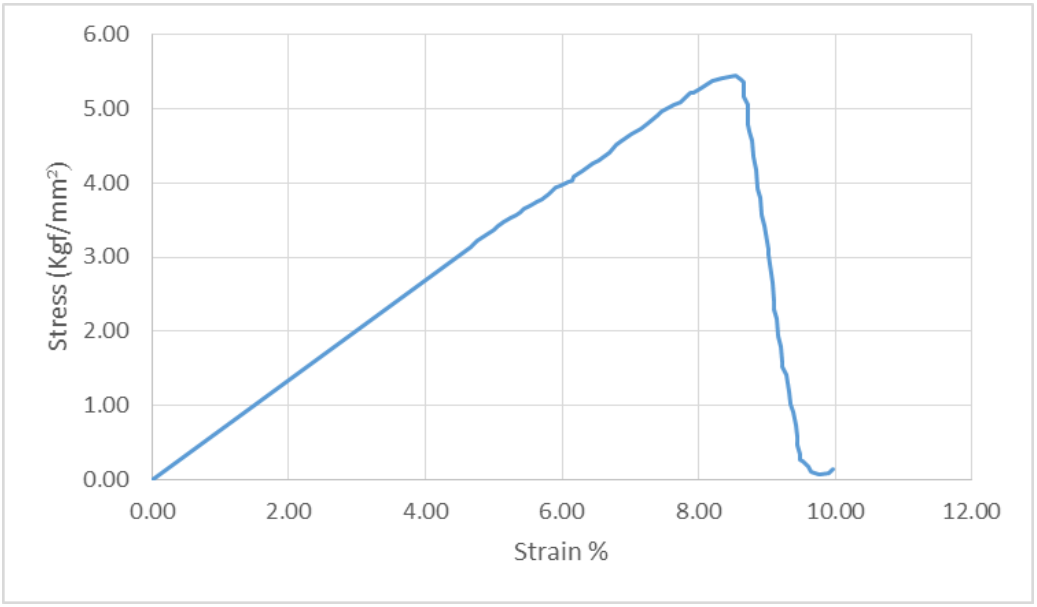


Figure 18: Stress/Strain Curve for 150mm/s and 95% Density

Hardness Testing of 3D Printed Specimen

Twelve specimens were printed and tested at each printing speed and its specified density. For this testing, a very low deformation was considered which we can measure it with the help of microscope. In some specimen the diagonal length was very low while in some specimens the diagonal length was high because of threads on the surface of specimens. Table 4 shows the individual results for each test and specimen.

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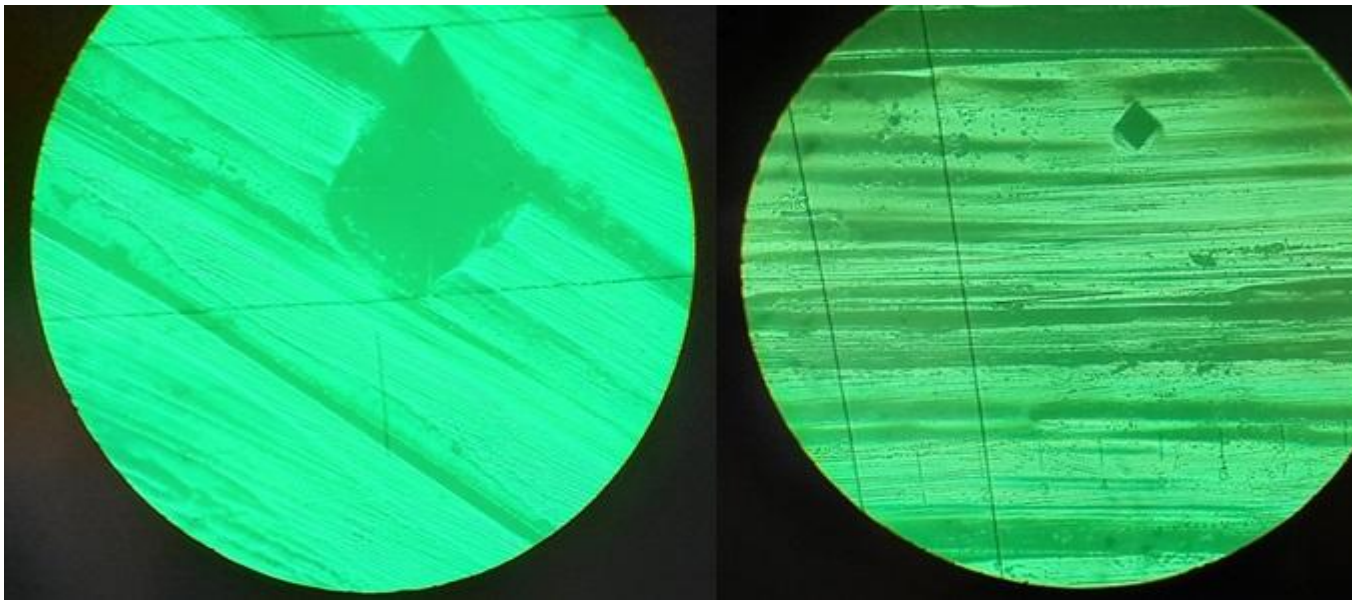


Figure 19: Microscopic View of Hardness of 3d Printed Specimen

Table 4: Hardness testing data at Each Density Level and Printing Speed

Printing speed (mm/s)	Density (%)	Hardness (HV)
90	55	21.8
110	55	42.2
130	55	62.56
150	55	82.34
90	75	51.31
110	75	65.2
130	75	79.25
150	75	120.82
90	95	61.7
110	95	71.6
130	95	91.35
150	95	162.85

For PLA printed specimen, the 95% density specimens produced the hardest specimens as compared to the 55% and 75% density specimens. When we look at the

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above table the 95% density specimens produced the hardest specimens while the 55% and 75% density specimens' hardness values were less than 95% density specimens.
While when we look at the table 4, when the printing speed increases from 90mm/s to 150mm/s the hardness also increases for specific densities.

Surface Roughness Testing of 3D Printed Specimen
Twelve specimens were tested on surface roughness tester to conduct the surface roughness of each specimen for various printing speeds and densities. The surface roughness tester calculates the roughness of the 3d specimen in terms of three parameters (Ra, Rz, Rq). Table 6 shows the individual results of surface roughness tests. Table 7 shows the summary of all surface roughness tests at each of the density level and printed speed

Table 5: Surface Roughness Testing

Printing speed (mm/s)	Density (%)	Ra (µm)	Rz (µm)	Rq (µm)
90	55	1.66	6.24	1.95
110	55	1.50	5.76	1.78
130	55	1.35	5.28	1.62
150	55	1.16	4.50	1.34
90	75	1.74	6.94	2.05
110	75	1.55	6.09	1.82
130	75	1.37	5.31	1.59
150	75	1.19	4.57	1.37
90	95	8.00	32.16	9.59
110	95	3.36	13.35	4.13
130	95	3.27	11.36	3.75
150	95	2.56	10.06	3.04

Table 6: Summary of Surface Roughness Testing

Density (%)	Average Values Ra (µm)	Average Values Rz (µm)	Average Values Rq (µm)
55	1.29	5.44	1.67
75	1.46	5.72	1.70
95	4.29	16.73	5.12

In the case of density, the 55% density material produce finer surface as compared to 75% and 95% specimens. The surfaces of 55% and 75% density specimens were almost produced same average values i.e Ra 1.29µm and 1.46µm, Rz 5.44µm and 5.72µm and Rq 1.67µm and 1.70µm, respectively, while the surface roughness values of 95% specimens were very high which has average values were, Ra 4.29µm, Rz 16.73µm and Rq 5.12µm.
While when we look at the table 5, the specimens with 150mm/s printing speed

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produced finer surface as compared to 90mm/s, 110mm/s and 130mm/s, because the surface roughness values at 150mm/s were comparatively low as compared to others printing speeds. Following are the few diagrams which are the graphical representation of the roughness parameters at each of the printing speed and density levels.

Conclusion

The PLA 3d printed specimen mechanical properties were tested. For tensile testing, it was determined that the 95% density specimens produced the strongest specimen as compared to 55% and 75% density specimens, so we can say that with increasing the density of the 3d-printed specimen the maximum tensile strength and the elongation (strain) increases. Similarly, in case of printing speed, the tensile strength from 90mm/s to 150mm/s were almost same, also the force and the strain values were almost same at specific density.

For hardness testing, it was determined that with increasing the density the hardness of the 3d-printed specimen increases, the 95% density 3d specimen showed the highest hardness as compared to 55% and 75% density specimens, similarly with increasing the printing speed the hardness of 3d specimen increases, the 150mm/s printing speed specimen showed the highest hardness values as compared to other printing speed.

For surface roughness testing, the higher printing speed and low density 3d specimens showed fine surface as compared to other 3d specimens because of low or low quantity of material is used. The 55% density 3d specimens showed the lower roughness values as compared to 75% and 95% density specimens, so 55% density 3d specimens will produce finer surface as compared to other specimens. Similarly, with increasing the nozzle printing speed the surface roughness parameters values decreases, so 150mm/s printing speed specimens produced lower roughness values as compared to lower printing speed, and will produce finer surface as compared to other printing speed.

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