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Process Parameter Variation and its Impact on the Mechanical Characteristics of 3D-Printed Structures

R Aneela[1], Sivanagi Reddy Emani[2], Ummar Pasha Shaik[2*], K. Bullibabu[3], K. Veeranjaneyulu[4]

[1]*Assistant Professor, Department of Physics, B. V. Raju Institute of Technology, Narsapur, Medak District – 502313, Telangana, India.*
[2]*Assistant Professor, Department of Physics, Anurag Engineering College, Ananthagiri (V & M), Suryapet District– 508206, Telangana, India.*
[3]*Assistant Professor, Department of Mechanical Engineering, Sri Chaitanya Institute Of Technology & Research, Ponnekal, Khammam-507170, Telangana, India.*
[4]*Assistant Professor, Department of Mechanical Engineering, Anurag Engineering College, Ananthagiri (V & M), Suryapet District– 508206, Telangana, India.*
Email: Pasha.u123@gmail.com

Additive manufacturing is generally known as 3D printing, is capable in range of potential in the manufacturing industry. 3D printing was primarily developed in purpose of developing prototypes of experimental testing. But, recently 3D printing applications have increased in a widespread range. Although this has been a promising technology there are some drawbacks too. One of the main drawbacks in 3D printing is weaker mechanical properties of products when comparing with the products manufactured by conventional manufacturing methods. Since 3D printing has gained a new demand in manufacturing industry, there is a requirement of increasing the strength and durability of 3D printed products to an optimum level.

This paper work is analysis of mechanical properties of 3D printed objects by varying process parameters such as layer thickness and printing temperature. In the work two sets of specimens numbering each 1-6 were manufactured for both tensile and flexural testing. All the specimens were manufactured by varying their layer thicknesses through fused deposition modeling technique. Finally testing will doing on the specimens with the help of universal testing machine

Keywords: Additive, 3D print, universal.

1. Introduction

There are a lot of similar definitions and terminologies used to describe 3D printing such as: additive manufacturing, and rapid prototyping. However, all of them describes the main distinguishing idea from ordinary subtractive methods which is Additive manufacturing. Generally speaking, 3D printing: is a process by which 3D solid objects of any shape or geometry can be created from a digital file. The creation is achieved by laying down successive layers of a specific material until the entire object is created. Each of these layers represents a thinly sliced horizontal cross-section (similar to the output of an ordinary printer, this is why it is called printing) of the eventual object, in contrast to traditional subtractive manufacturing methods which relies upon the removal of material to create something.

3D printing is a new technology, the birth of 3D printing was in 1984 at the hands of Chuck Hull who invented a process known as stereo lithography, in which layers are added by curing photopolymers with UV lasers, after that, 1990 layer by layer technology used each layer has 0.1mm depth, in 1999 the first use in medicine, in 2000 the first parts of human such as ears, fingers was done, 2005 3D printing technology became open source, in 2006 the first SLS (selective laser sintering) machine become variable, in 2008 the first self-replication printer which made the printer able to print the majority of its own components also at the same year 3D technology developed to do a very hard shapes and artists for designers ,in 2009 Atom by atom printing were done which allows for Bio3D printing, in 2011 the first 3D printer Robotic Aircraft at the same year the world's first 3D-printed Car and it became commercially available at the next year, at the same year the first gold and silver jewelry were done using 3D printer.

2. Literature Review

3D printing has increasingly progressed from a strictly prototyping technology to one used for the production of final products intended for everyday use (Berman 2012; Chulilla Cano 2011; Espalin et al. 2014; Chua et al. 2003). 3D-printing has increasingly been used for advanced applications including the printing of adaptive structures utilizing shape memory polymer (SMPs) filaments and even printing cell structures in a granular gel medium (Ge et al. 2014; Ge et al. 2013; Raasch et al. 2015; Yang et al. 2015; Bhatta charjee et al. 2015). This explosion in popularity has come with a proportionate increase in the study of 3D-printed techniques as it is vital to comprehend the properties and characteristics of the parts which are created. Several previous studies utilized ASTM standard tensile test methods to determine the tensile properties as a function of the build and raster orientations the specimens were printed (Bellini & Guceri 2003; Giannatsis et al. 2012; Hill & Haghi 2014; Tymrak et al. 2014; Wittbrodt & Pearce 2015; Torrado Perez et al. 2014; Torrado et al. 2015; Es-Said et al. 2007; Ahn et al. 2003; Ahn et al. 2002; Montero et al. 2001). It has been widely publicized that in tension the road-to-road and layer-to-layer adhesion, shrinkage of the roads and higher porosity in some orientations influence the material properties of the printed parts and causes anisotropy (Es-Said et al. 2007; Rodrıguez et al. 2003; Torrado Perez et al. 2014). Several publications have worked to develop methods to reduce anisotropy including the creation of polymeric blends and other blended materials or postprocessing the parts via radiation (Torrado Perez 2015; Shaffer et al. 2014; Torrado Perez et al. 2014; Torrado et al. 2015). Creating polymeric blends and other blended materials did tend to reduce anisotropy but at the cost of the overall material strength. Radiation tended to have mixed results as some temperature/radiation combinations resulted in the weakening of the parts while others did reduce anisotropy. Other studies did offer a more in-depth look at the anisotropic properties of 3D-printed materials and included the impact, flexural, or compression properties (Ziemian et al. 2012; Lee et al. 2007; Sood et al. 2010). However, most studies on the anisotropy of 3D-printed materials generally give Young's modulus, yield strength, and ultimate strength using extensometers and loads from a universal testing machine. Some publications did attempt to characterize compression properties of 3D-printed materials. This approach assumes an isotropic relationship exists in the material on certain planes, which is somewhat of an oversimplification. If the assumption is that the material is anisotropic, which is why such tests are performed, this approach neglects to take into consideration the independence of the shear stress/strain behaviour from the normal stress/strain behaviour. Since the elastic module in all orientations doesn't vary significantly the assumption provides reasonably accurate module values. However, the strength as a function of orientation cannot be determined by tensile testing. This, however, cannot be utilized in this study because the specimen geometry is based on a cylindrical coordinate system whereas the printed material is oriented in a Cartesian coordinate system.

This methodology has been used on composites and plastics including PLA and ABS; however, the studies on plastics were of injection moulded specimens rather than 3D- printed parts (Fang et al. 2006; Fang et al. 2008; Daiyan et al. 2012; Qin et al. 2012). Using this experimental technique, it is critical to measure the average strain in the test section rather than the compression strain at the centre of the test section. This is because even though the specimen is designed to provide a uniform strain distribution in the test section, in reality, the distribution is not perfectly uniform.

Since the load path in the Iosipescu specimen must be transferred through the test section and since the shear strain is measured in the test section and not globally (displacement of one side of the fixture with respect to the other) any yielding of the stress-strain diagram is representative of the material behavior. Thus even if the specimen ultimately fails outside of the test section, the compression stress-strain diagram is representative of the material behavior to that point. However, the stress/strain response is cut short and the actual ultimate strength and per cent elongation may be higher.

3. Materials and Methodology

3.1 MODELLING

3D printable models can be created with the help of CAD design packages or via 3D scanner. The manual modeling process of preparing geometric data for 3D computer graphics is similar to method sculpting. 3D modeling is a process of analyzing and collecting data on the shape and appearance of an object. Based on this data, 3D models of the scanned object can be produced. Both manual and automatic creations of 3D printed models are very difficult for average consumers. That is why several market-places have emerged over the last years among the world. The most popular are Shape ways, Thing verse, My Mini Factory, and Threading.

3.2 PRINTING

Before printing a 3D model from .STL file, it must be processed by a piece of software called a "slicer" which converts the 3D model into a series of thin layers and produces a G-code file from. STL file containing instructions to a printer. There are several open source slicer programs exist, including, Slic3r, KISSlicer, and Cura. The 3D printer follows the G-code instructions to put down successive layers of liquid, powder, or sheet material to build a model from a series of cross-sections of a model. These layers, which correspond to the virtual cross sections from the CAD model, are joined or fused to create the final shape of a model.

The main advantage of this technique is its ability to create almost any shape or geometric model. Construction of a model with existing methods can take anywhere from several hours to days, depending on the method used and the size and complexity of the model. Additive systems can typically reduce this time to very few hours; it varies widely depending on the type of machine used and the size and number of models being produced.

3.3 FINISHING

Although the printer-produced resolution is sufficient for many applications, printing a slightly oversized version of the object in standard resolution and then removing material with a higher-resolution process can achieve greater precision. As with the Accucraft iD-20 and other machines Press Release. International Manufacturing Technology shows some additive manufacturing techniques are capable of using multiple materials in the course of constructing parts.

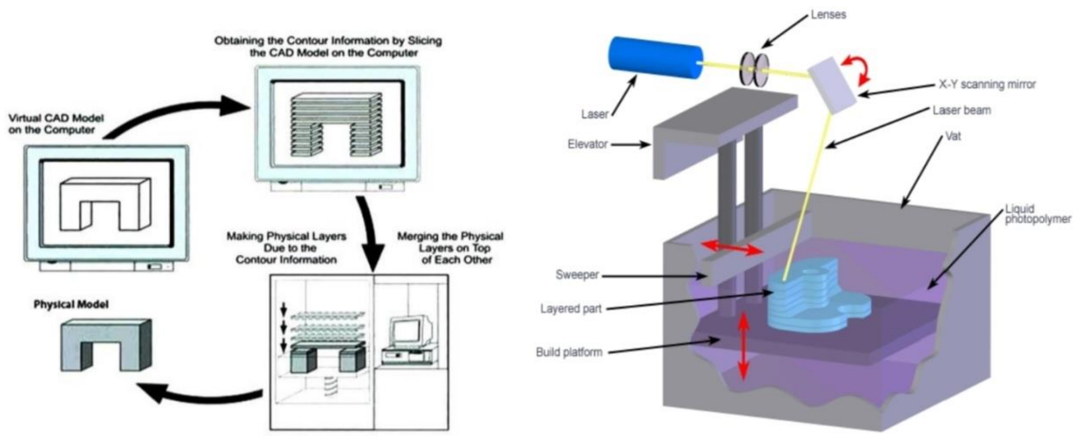


Fig: Printing Procedure

3.4 PROCESSES

Many different 3D printing processes and technologies have been invented from late 1970. The printers were originally very large and expensive in what they could produce. A large number of Additive manufacturing processes are now available. Some of the methods melt or soften material to produce the layers, e.g. selective laser melting(SLM), selective laser sintering (SLS), fused deposition modeling (FDM), while others cure liquid materials using different other technologies, e.g. stereolithography (SLA) and with laminated object manufacturing (LOM).

4. Fabrication Methods

4.1 MATERIALS AND SPECIMEN FABRICATION

The materials tested in this study were polylactic acid (PLA) and Acrylonitrile butadiene styrene (ABS) which was used to produce samples in a creality ender-3 pro 3D-printer. The specimen geometries followed specifications outlined in ASTM for the Type VI tensile specimens and ASTM for the bending specimens (ASTM International 2004; ASTM International 2011). These specimens and select dimensions for specimens types are shown in Figure. Tensile Specimen type were printed at a thickness of 7mm (0.275 in) and Bending specimens were printed at a thickness of 4mm (0.157). The tensile and bending specimens were first created in Solid Works®, exported in stereolithography (STL) format, and then imported into each 3Dprinter's respective slicer software to create the G-code used to print each specimen type.

The specimens printed on the Creality Ender-3 pro used an extrusion width (the width of each layer of deposited material, also known as the road width) of 0.45 mm (0.017 in) and a slice height (the height of an individual layer of deposited material) of 0.15 mm (0.005 in). The Creality Ender-3 pro used a default slice height of 0.2 mm (0.007 in) and an extrusion width of 0.5 mm (0.019 in). The Creality Ender-3 pro used a default slice height of 0.25 mm (0.009 in) and an extrusion width of 0.55 mm (0.021 in). The slice height, extrusion width, air gap (the space between the bead of material), printer environmental temperature (the temperature of the air around the part and the bed temperature), build temperature (the temperature of the liquefier), nozzle size (width of the hole through which the material is extruded), and colour (white & black) were all held to constant values.

4.2 COORDINATE SYSTEM FOR FDM PRODUCT

Specimens for testing by FDM technique are prepared according to ASTM dimensions. They are designed in designing software DS solid works. Then they are converted to.STL format for further processing in slicing software. Then setting parameters generates G-codes. Connecting to FDM machine, printing is done. Similarly, for testing samples of automated injection moulding process are prepared by using corresponding moulds. Before the testing, surface roughness values of specimens were also noted. Let us define the coordinate system for the FDM product. X direction is the strip direction in which nozzle moves to lay down each strip. Y-direction is perpendicular to strip direction, where successive strips are laid down. Z axis is per-perpendicular to printing layers, where layers are built up.

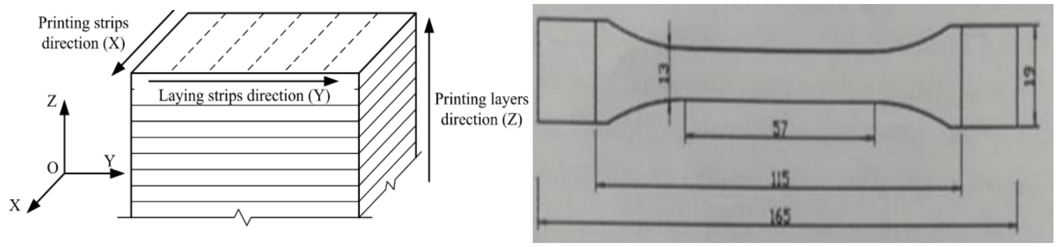


Fig: The coordinate system for FDM product

4.3 DESIGN OF 3D PRINTER SPECIMENS

3Dmodeling or CAD (Computer Aided Design) allows engineers and designers to build realistic computer models of parts and assemblies. These models can be then 3DPrinted or CNC machined as well as used to run complex simulations. A wide range of parameter s can be simulated such as strength or temperature resistance before any physical models have been created, enabling a much faster and cheaper work flow.

4.4 SOLID MODELING

Solid modeling creates solid 3d models as if they are actual parts, with a logical workflow which is similar to the processes which would be used to manufacture the part. Some of these operations include extruding, drilling and threading operations. Solid models can intersect, join and subtract objects from one another to create the desired part. Another advantage of solid modeling is that it is usually parametric, meaning that changes, or parameters are saved at every stage of the modeling processes and can be edited at any time during the design. This is very useful as it allows features of the model to be quickly modified without needing to create the part from scratch.

Assembly modeling is also an important stage in solid modeling, allowing individual parts to be assembled to get her, forming complex models. Assemblies can be used to insert standard components such as fasteners or bearings, which have been downloaded directly from the manufacturers. Motion elements can also be applied to assemblies, allowing detailed motion analysis to be used to evaluate the mechanical performance of the design.

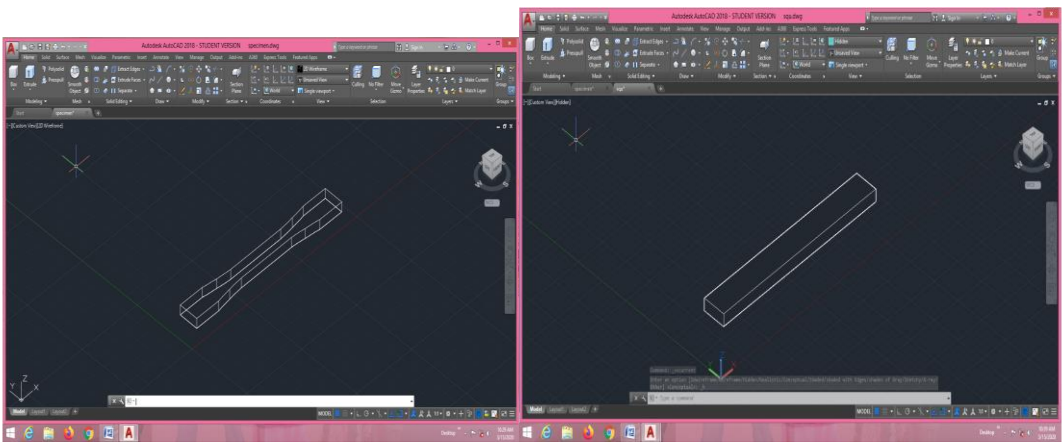


FIG: Design Of Solid Modeling In Cad Software

5. Results and Analysis

5.1 MECHANICAL TESTS

While analyzing and characterizing 3D printed components, results obtained should be treated as structural properties instead of material properties. It is because of the fact that, 3D printed samples areanisotrpic. PLA material samples as well as ABS material samples were undergone tensile test and flexural test.

5.2 TENSILE TEST

Tensile properties are most widely used and specified properties and are used as an indication of strength of polymers. It measures the ability of a material to withstand the forces that tends to pull it apart and extend of deformation before breaking. Tensile test data such as tensile strength, elongation and tensile modulus are useful for the selection of polymeric materials for particular application from a large group.

Fig: Tensile Test System

Fig: Specimens are PLA (a) And ABS (b) Materials for Tensile Testing

5.3 SPECIMENS

Dumbbell shaped specimens are used for tensile test. The shape and size of specimen shall conform to the dimensions as prescribed by particular test method specification i.e. ASTM. The specimens were divided into 2 groups, PLA and ABS materials samples of 0.15mm layer thickness, 0.2mm layer thickness, 0.25mm layer thickness, each loaded in X direction. Each group containing 3 samples each of PLA and ABS materials. PLA and ABS materials samples are shown in the above figure.

5.4 TESTING OF SPECIMENS

Tensile test followed the test procedure prescribed in ASTM. The tensile testing machine of a constant-rate-of crosshead movement is used. Machines can be operated at different constant speed. It was operated at 50 mm/min. It is fitted with load cell and extensometer to record the test load and extension accurately. Tensile strength is defined as the maximum tensile stress sustained by a test piece during the tension test or ultimate strength of material subjected to tensile loading. In other words, it is a measure of the ability of material to withstand forces that tends to pull it apart and to determine to what extend the material stretches before breaking. The ratio of tensile stress to corresponding strain at the maximum load within its proportional limits is the Tensile Modulus or Young's Modulus. It is an indication of the relative stiffness of the material.

6. Results and Analysis

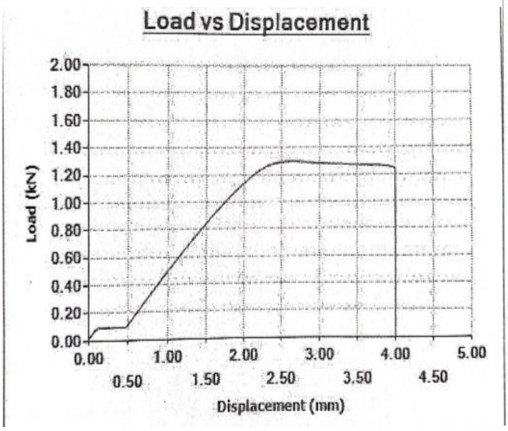
Tensile strength, yield load, yield stress and percentage elongation of the specimens are listed in table. Specimens prepared by ABS material process have the highest tensile strength at ultimate load 1.53KN (at 0.25 thickness) and at yield load 1.42KN (at 0.25 thickness) compared with PLA material 3.22KN (at 0.25 thickness) and at yield load 2.81KN (at 0.25 thickness) and . Considering elongation, specimens created by PLA material have the greatest performance. Considering elongation at break trend was converse, ABS material samples have better result. . The summarized values in tensile strength and elongation at break indicate that ABS samples provided the highest Ult tensile strength at 19.52N/mm^2 and PLA samples highest Ult tensile strength is 34.29N/mm^2 .It can be concluded that ABS samples have low Ult tensile strength than PLA samples. When ultimate load is increases then also an yield load increases by vice versa. Breaking area are shown in Fig of both ABS and PLA materials.

Fig: After Testing the Breaking Areas of a Specimens Both Materials

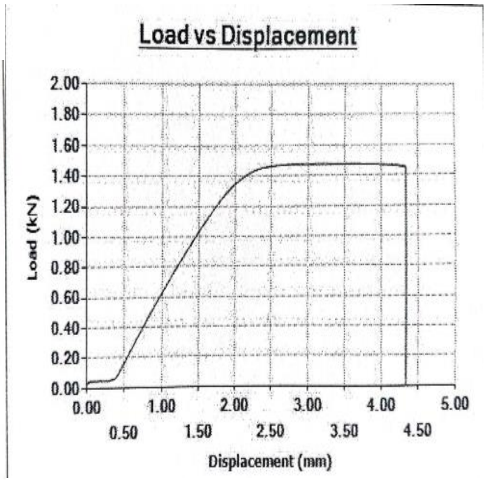
TENSILE TEST RESULTS OF ABS MATERIAL

Parameters	Units	0.15mm Layer thickness	0.2mm Layer thickness	0.25mm Layer Thickness
Original Gauge Length	Mm	50.00	50.00	50.00
Final Gauge Length	Mm	51.54	53.25	52.30
Ultimate Load	KN	1.3	1.48	1.53

Ult Tensile Strength	N/mm^2	15.88	18.25	19.52
% Elongation	%	3.08	6.5	4.6
Yield load	KN	1.2	1.31	1.42
Yield stress	N/mm^2	14.68	16.21	18.1



For 0.20mm Layer Thickness



For 0.25mm Layer Thickness

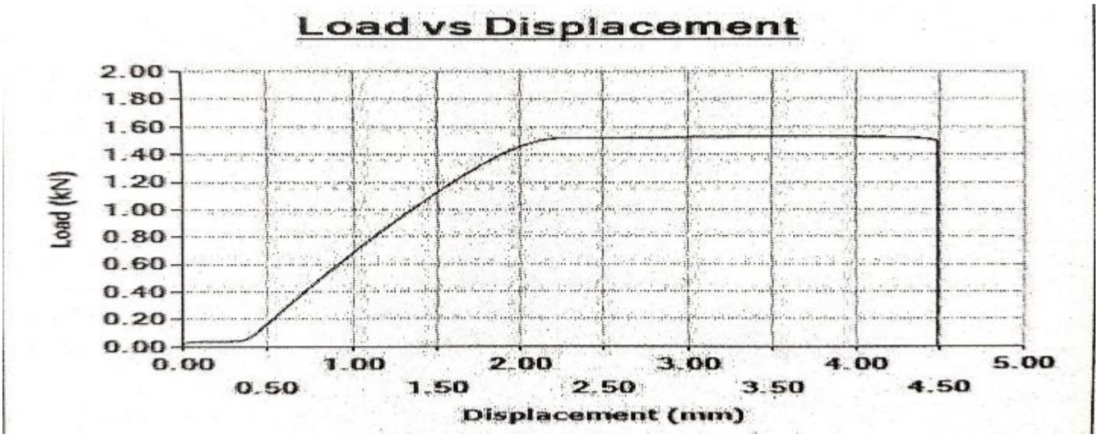
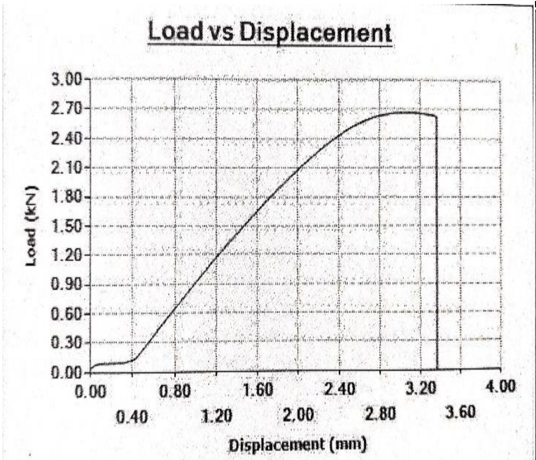


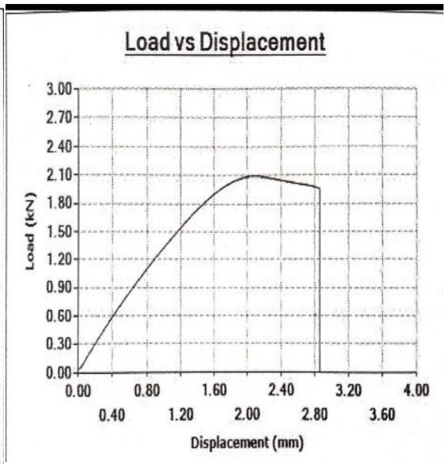
Fig: Load v/s Displacement Diagrams Of ABS Material.

TENSILE TEST RESULTS OF PLA MATERIAL

Parameters	Units	0.15mm Layer thickness	0.2mm Layer thickness	0.25mm Layer Thickness
Original Gauge Length	mm	50.00	50.00	50.00
Final Gauge Length	mm	51.62	51.11	51.43
Ultimate Load	KN	2.67	2.09	3.22
Ult Tensile Strength	N/mm^2	29.92	22.47	34.29
% Elongation	%	3.24	2.22	2.86
Yield load	KN	2.27	1.83	2.81
Yield stress	N/mm^2	25.47	19.67	29.96

For 0.15mm Layer Thickness For 0.20mm Layer Thickness





For 0.25mm Layer Thickness

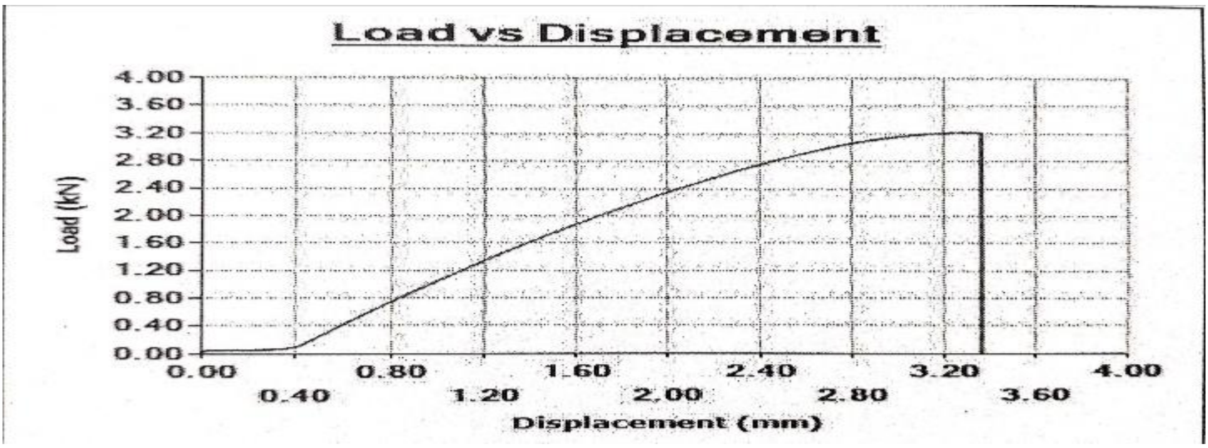


Fig: Load v/s Displacement of PLA Material.

6.1 FLEXURAL TEST

Flexural properties are largely specified properties for 3D printed products. Flexural strength is the ability of a material to withstand bending forces applied perpendicular to its longitudinal axis. The stress induced due to flexural load is combination of compressive and tensile load. The flexural properties are calculated in terms of maximum stress and strain that occurs at outside surface of test bar. And Flexural modulus is a measure of the stiffness during the first or initial portion bending process. 3-point flexural loading as shown in the fig is done in this research work. A bar of rectangular cross section rests on two supports and is loaded by means of a loading nose midway between the supports. The maximum axial fiber stresses occur on a line under the loading nose.

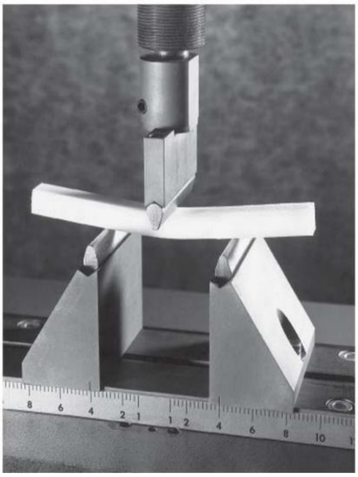


Fig: Flexural Test System

Fig: Specimens Are ABS(A) And PLA(B) Materials For Flexural Testing

SPECIMENS

Flexural tests were conducted with 10mm X 4mm X 10mm specimens. The specimens are made in accordance with Procedure of ASTM methods. The specimens were divided into 2 groups, of 0.15mm layer thickness, 0.20mm layer thickness and 0.25mm layer thickness of ABS and PLA materials. Each group containing 3 samples each.

TESTING

Flexural tests were conducted following ASTM standard Universal testing machine having flexural test fixture such as specimen support and loading nose is used. Machine should be fitted with a load cell and internal extensometer for recording the load and deflection of specimen at any point accurately. The surface of specimen support and loading nose had a surface radius of approximately 3.2 mm. Specimen was placed on support centrally with load axis perpendicular to the loading nose. The test was initiated by applying the load to the specimen at the specified crosshead rate. The deflection was measured either by a gauge under the specimen in contact with it in the center of the support span. Flexural strength Fs is calculated from the peak loads in the flexural tests, using the following formula, Fs= 3PL/2bd2 Where P is the peak load in N , L is the distance of supports in mm , b is width of specimen in mm and d is thickness of test specimen in mm.

Results obtained from flexural test are tabulated in table. When load is acting the flexural strength obtained is maximum. For ABS material samples compared to PLA material samples. The molecular orientation in the specimen has a significant influence on the test results. The sample having a high degree of molecular orientation perpendicular to the applied load will show higher flexural values.. The strain rate, which depends upon testing speed and specimen thickness, can affect the results. While focusing on the ABS samples, it is obvious that sample with 0.25mm layer thickness have maximum flexural strength =150.55 N/mm^2. And for the PLA samples flexural test is done on 0.25 mm samples by loading. Then flexural strength = 203.03N/mm^2. Comparing both ABS and PLA materials are to be PLA materials have better strength than ABS materials at same thickness.

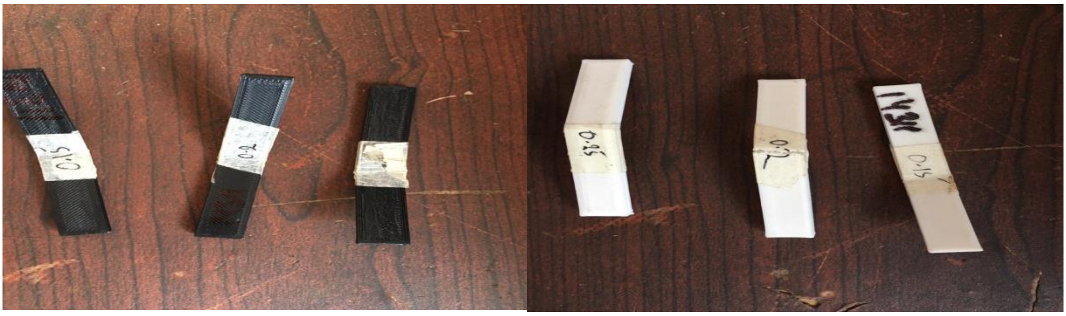
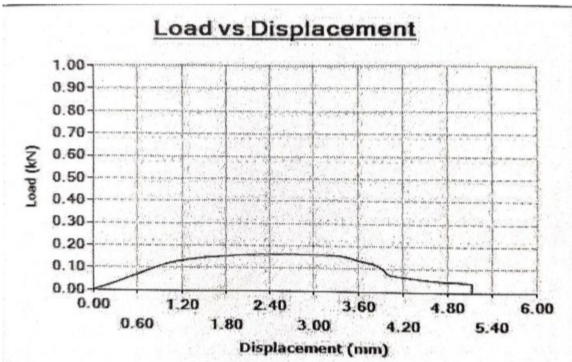


Fig: After Testing the Breaking Areas of Both ABS and PLA Materials

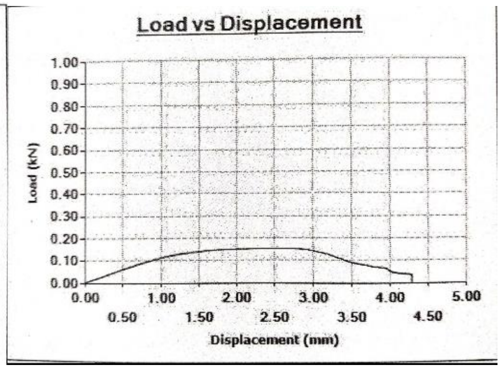
FLEXURAL TEST FOR ABS MATERIAL

Parameters	Units	0.15mm Layer Thickness	0.20mm Layer Thickness	0.25mm Layer Thickness
Ultimate load	KN	0.16	0.15	0.18
Flexural strength	N/mm^2	152.63	149.64	150.55

For 0.15mm layer thickness



For 0.20mm layer thickness



For 0.25mm layer thickness

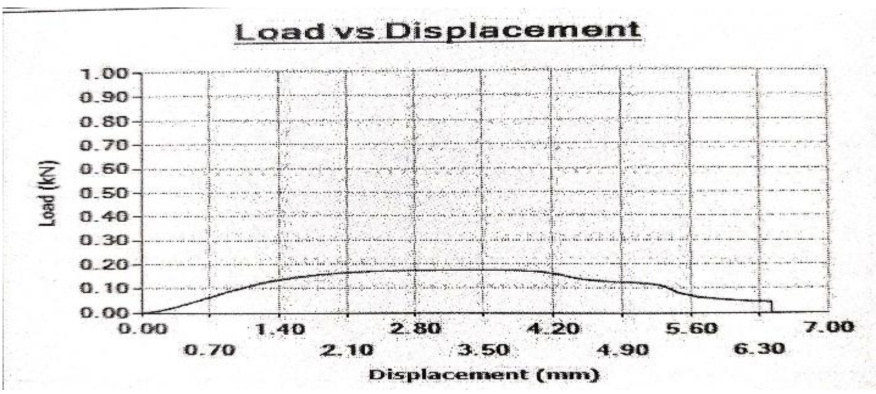


Fig: Load V/S Displacement of ABS Material

FLEXURAL TEST FOR PLA MATERIAL

Parameters	Units	0.15mm Layer Thickness	0.20mm Layer Thickness	0.25mm Layer Thickness
Ultimate load	KN	0.23	0.21	0.33
Flexural strength	N/mm^2	140.08	127.89	203.03

For 0.1mm layer thickness For 0.20mm layer thickness For 0.25mm layer thickness

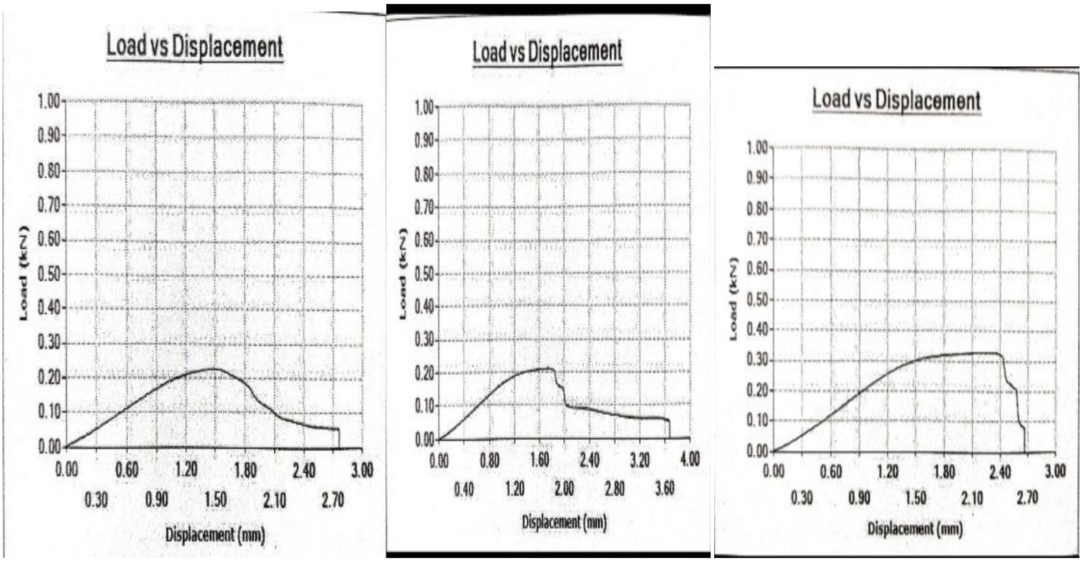


Fig: Load V/S Displacement for PLA Material

7. CONCLUSION

The mechanical properties of ABS and PLA components made with a different layer thickness are 0.15mm, 0.20mm and 0.25mm. where each material taken VI specimens for tensile test and flexural test. In tensile testing for ABS material the tensile strength is increases when layer thickness is increases. But in PLA material the tensile strength is initially decreases and near 0.25mm layer thickness again increases. Comparing both materials PLA have more tensile strength. In a flexural testing both materials the flexural strength is decreases at 0.20mm layer thickness and near 0.25mm layer thickness again the strength is increases comparing both materials PLA have more flexural strength at 0.25mm layer thickness but near 0.15mm and 0.20mm ABS have more flexural strength than PLA material. Thus a detailed comparative study ABS material and PLA material samples by varying of thickness of a samples by using 3D printing.

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