A
DISSERTATION REPORT
ON

"Strength analysis of 3D printed Polymer materials"

Submitted for partial fulfilment of the requirement for award of the degree of
MASTER OF TECHNOLOGY
IN
Discipline (Polymer Science and Technology)

Submitted by
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CERTIFICATE

This is to certify that the thesis entitled "**STRENGTH ANALYSIS OF 3D PRINTED POLYMER MATERIAL**" submitted by **S. GOWRI SHANKHAR** in partial fulfilment of requirement for the award of the degree of **MASTER OF TECHNOLOGY** in Polymer Science and Technology, Indian Institute of Technology, Roorkee. This is a bonafide work carried out by him under our supervision.

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CANDIDATE'S DECLARATION

I hereby declared that the work which is being presented in this Dissertation Report entitled " Strength analysis of 3D Printed Polymer materials" in partial fulfilment of the requirement for the award of the degree of Master of Technology in Polymer and Process Engineering, IIT Roorkee is a record of my own work carried out, under the supervision of Dr. M. Kamaraj, Department of Metallurgical and Materials Enginnering, IIT Madras and Dr.Gaurav Manik, Department of Polymer and Process Engineering , IIT Roorkee. The experiments were done in Department of Engineering Design, IIT Madras with the permission of Dr. Nilesh Jayantilal Vasa, Head of the Department and under the guidance of Dr. G. Saravana Kumar, Associate Professor. This work was done in Department of Metallurgical and Material Science & Department of Engineering Design, IIT Madras.

The matter embodied in this project report has not been submitted by me for the award of any other degree.

Date: 6th June 2014

Place: Saharanpur

S. Gowri Shankhar

ABSTRACT

3D Printing or Rapid Prototyping has been next big thing in manufacturing industry so far. But materials that are 3D printed are observed to have less strength. Systematic study on the strength of printed materials is still needed. In this work, the strength of a 3D printed material is analysed with different orientations and base area systematically. Using the software Minitab a design of experiment has been done to study how the strength varies when other parameters like base area, angle are changed both individually and simultaneously. Finally an equation has been formed relating Strength, Base area and angle.

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1. Certificate

5. Introduction

7. Rapid Prototyping Machine

8. FDM

9. Conclusion and Future scope

5. INTRODUCTION

5.1 INTRODUCTION TO MANUFACTURING METHODS

In manufacturing, and machining in particular, subtractive methods refer to more traditional methods. The term subtractive manufacturing is developed in recent years to distinguish it from newer additive manufacturing techniques. Although fabrication has included methods that are essentially "additive" for centuries (such as joining plates, sheets, forgings, and rolled work via riveting, screwing, forge welding, or newer kinds of welding), it did not include the information technology component of model-based definition. Machining (generating exact shapes with high precision) has typically been subtractive, from filing and turning to milling, drilling and grinding.

5.2 ADDITIVE MANUFACTURING

5.2.1 3D PRINTING/RAPID PROTOTYPING

Rapid Prototyping technology is based on micro-jetting of materials, whose work principle is like the inkjet printer. According to the difference of jetting materials, 3DP has two kinds of processing methods. One is jetting binder to join the powder materials and solidify to get the part, the other is jetting photopolymer materials which are then cured by ultra-violet (UV) light immediately to get the part prototype. The accuracy and the surface quality of parts fabricated by the latter method are better than the former. The work done here is only related to the latter one, namely 3DP based on jetting photopolymer materials.

3D Printing is also termed as additive manufacturing which refers to technologies that create objects through sequential layering. Objects that are made additively can be used anywhere throughout the product life cycle, from pre-production to large-scale production, in addition to tooling applications and post-production processes.

3D printers are machines which make 3D objects from digital models by depositing material, layer by layer on top of each other to form intricate designs. It is different from the traditional machining processes which chips off material from the job. Although 3D printers were first introduced in 1980s, they have not been put to extensive use until the beginning of the 21st century.In 1984, Chuck Hull of 3D Systems Corp created the first working model of a 3D printer.

3D printable models may be created with a computer aided design package. The product designing process of preparing geometric data for 3D computer graphics is similar to plastic arts such as sculpting. 3D scanning is a process of analysing and collecting digital data on the shape and appearance of a real object. Based on this data, three-dimensional models of the designed or captured object can then be printed using a 3D printer.

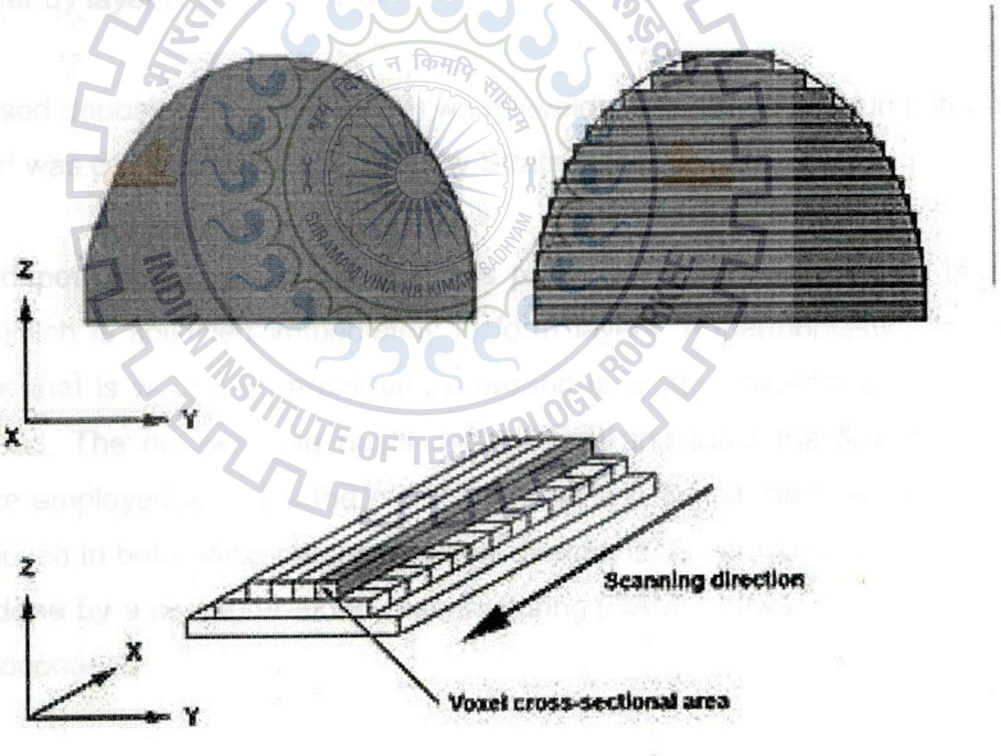


Fig. 1. Shows the comparison of an actual object scanned and the object printed in a 3D printer. The steps that are visible in the printed object is commonly known as staircase effect.

5.2.2 EXTRUSION DEPOSITION

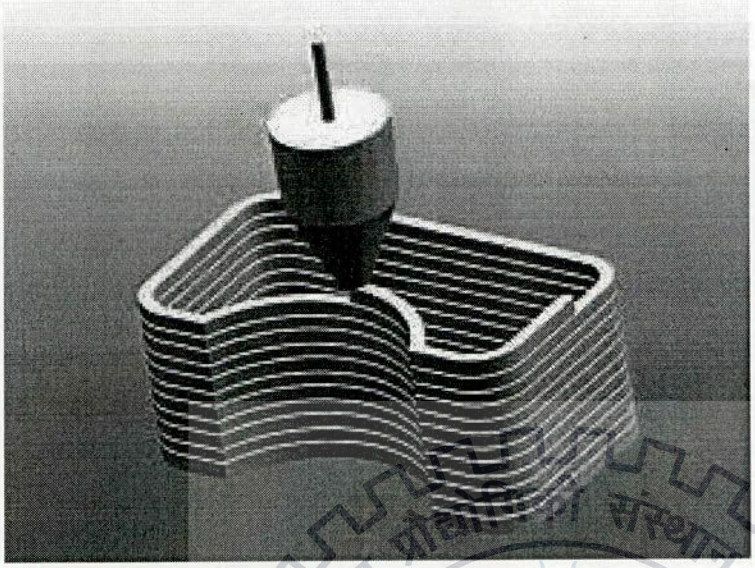


Fig 2. Layer by layer printing of FDM

Fused deposition method (FDM) was developed by S. Scott Crump in the late 1980s and was commercialised in 1990 by Stratasys.

In fused deposition modelling the object is produced by extruding small beads of material which is solidified immediately to form layers. A thermoplastic filament or metal wire that is wound on a coil and unwound to supply material to an extrusion nozzle head. The nozzle head heats the material and turns the flow on and off. Motors are employed to move the extrusion head and adjust the flow and the head can be moved in both horizontal and vertical directions. Control of this mechanism is typically done by a computer-aided manufacturing (CAM) software package running on a microcontroller.

Various polymers are used, including acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polylactic acid (PLA), high density polyethylene (HDPE), PC/ABS, and polyphenylsulfone (PPSU). In general the polymer is in the form of a filament, fabricated from virgin resins. Multiple projects in the open-source community exist that are aimed at processing post-consumer plastic waste into filament. These involve machines to shred and extrude the plastic material into filament.

5.2.3 ELECTRON BEAM FREEFORM FABRICATION

Electron Beam Freeform Fabrication (EBF^3) is an additive manufacturing process that builds complex, near-net-shape parts requiring substantially less raw material and finish machining than traditional manufacturing methods. It uses a focused electron beam in a vacuum environment to create a molten pool on a metallic substrate.

5.2.4 GRANULAR MATERIALS BINDING

Another 3D printing approach is the selective fusing of materials in a granular bed. The technique fuses parts of the layer, and then moves the working area downwards, adding another layer of granules and repeating the process until the piece has built up. This process uses the unfused media to support overhangs and thin walls in the part being produced, which reduces the need for temporary auxiliary supports for the piece. A laser is typically used to sinter the media into a solid. Examples include selective laser sintering (SLS), with both metals and polymers (e.g. PA, PA-GF, Rigid GF, PEEK, PS, Alumide, Carbonmide, elastomers), and direct metal laser sintering (DMLS).

5.3 MOTIVATION

CLOTHING

3D printing has spread into the world of clothing with fashion designers experimenting with 3D-printed shoes and dresses. In commercial production Nike is using 3D printing to prototype and manufacture the 2012 Vapor LaserTalon football shoe for players of American football, and New Balance is 3D manufacturing custom-fit shoes for athletes.

EYEWEAR

3Dprinting has come to the point where companies are printing consumer grade eyewear with on demand custom fit and styling. The on demand customization market for glasses is something that has been deemed possible with rapid prototyping.

3D BIO-PRINTING

3D bio-printing technology has been studied by biotechnology firms and academia for possible use in tissue engineering applications in which organs and body parts are built using inkjet techniques.

5.4 CHALLENGES FACED IN 3D PRINTING

Printing quality:

The quality of printed parts is another major concern for its wide application. Mechanical behaviour of the sintered material is different from that of the material from melts; the printed part may have a slightly distorted shape because of complicated processing conditions.

Properties of printed materials:

Our knowledge about printed material in general is very limited; the interface between layers might be weak. Systematic investigation of properties of printed materials is still needed.

5.5 SCOPE

Due to lack of available data on 3D printed materials, their strength behaviour it becomes tough to predict what is the best way to print a material. So the proposed idea is to study the strength of a material with different orientation systematically by doing a design of experiment with different parameters that are involved (Base area and angle between the direction of object and printing direction). An astm sample is taken and printed in different orientations in Objet Rapid prototyping machine and FDM machine and the sample is tested for tensile properties. Finally the results are analysed to get a relation between strength and orientation.

6. DESIGNING OF PROTOTYPE

3D Modelling:

First step is to design the model that needs to be printed. 3D Models can be drawn using 3D software such as Google SketchUp, SolidWorksTM, Pro ETM, Autodesk InventorTM, CreoTM etc. These models are saved in the .STL format for further processing. Below is the screenshot of a model being designed in SolidWorksTM.

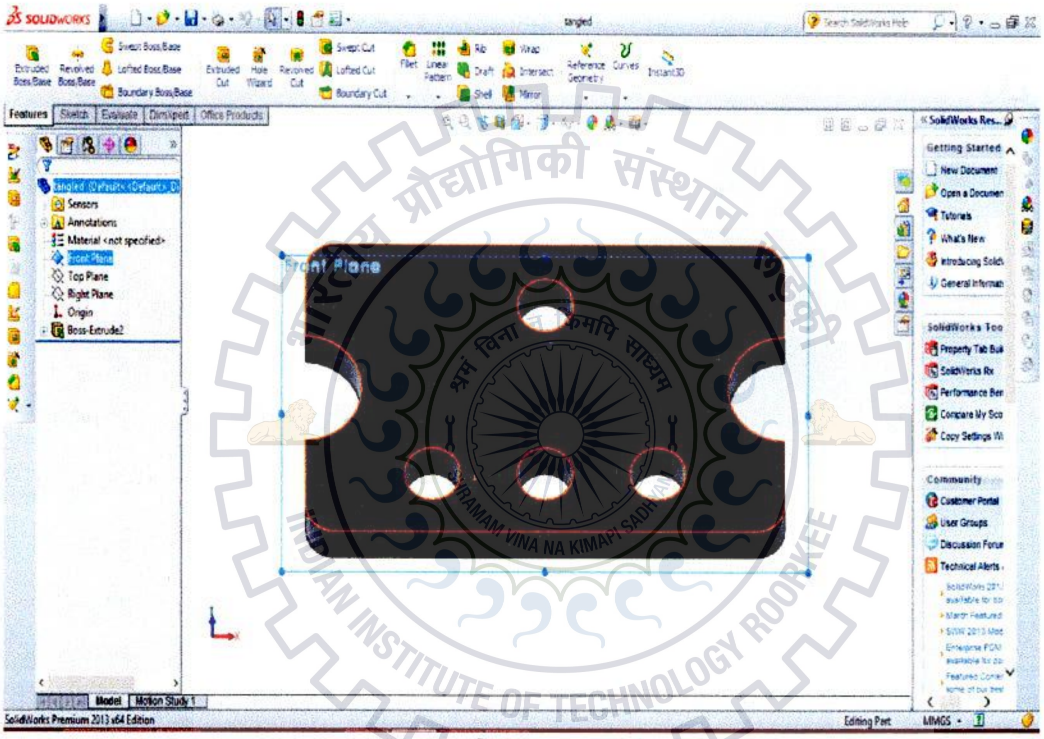


Fig 3. Screenshot of a model being designed in SolidWorksTM

In case of Objet N350 the .stl file need not be converted to .gcode as the software is in built to recognize. But in case of FDM the .stl file needs to be converted to .gcode using Skeinforge software. Which is then input to a Pronterface software which controls the motor and thermal settings of the machine.

Slicing and GCODE generation:

Now the 3D models need to be converted to a format that can be understood by the 3D printer. For this, first, a process called slicing is done. The 3D models are sliced into thin layers along the Z-axis. The 3D Models can be converted to the corresponding GCODE format using the software Skeinforge which slices the model into thin layers in the Z-axis and gives a .GCODE file as output. It also decides the nozzle path as it deposits the material later by layer. Below is a sliced 3D model as seen in Skeinforge.

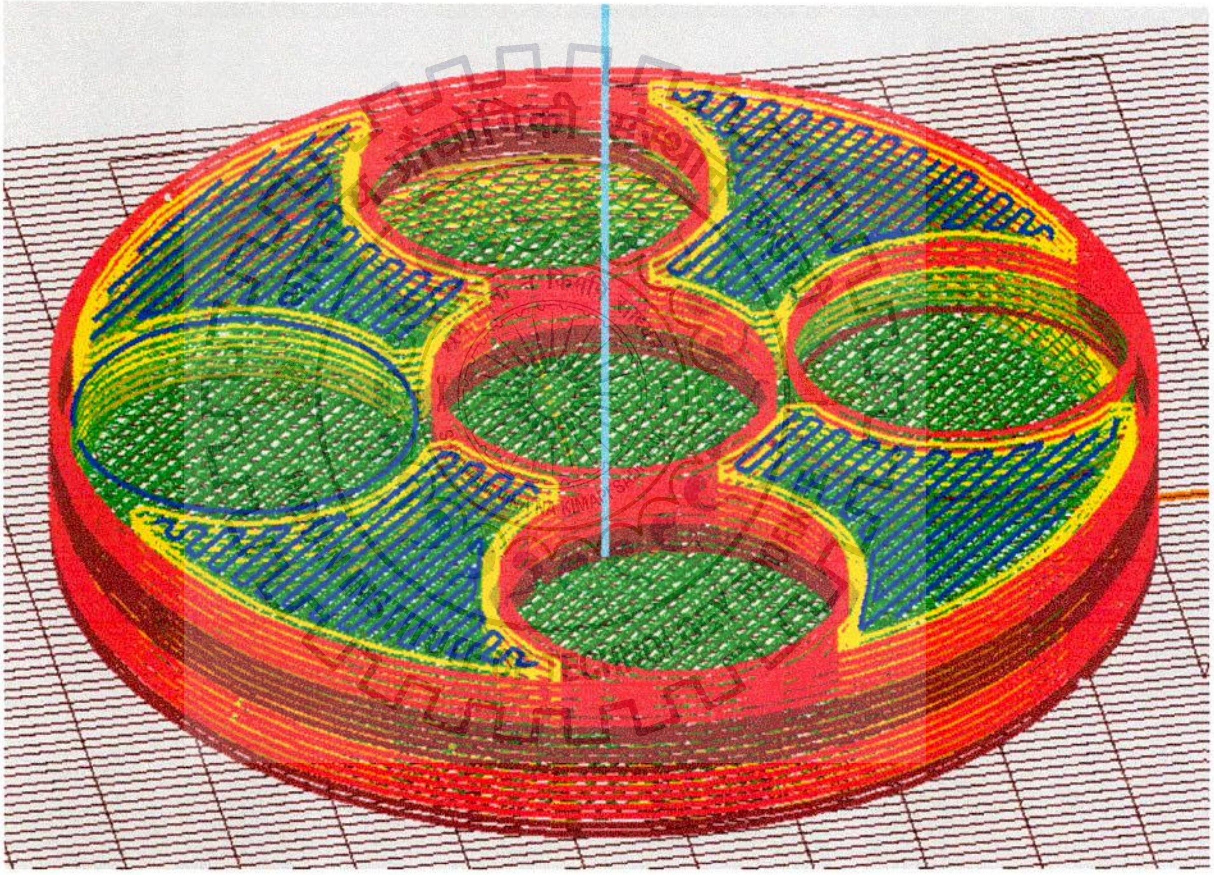


Fig. 4. stl file converted to gcode file

Printing:

Finally, the GCODE file is sent to the printer which rotates the motors of each axis and with corresponding rotation of the extruder motor, the material is fed on to the print surface layer by layer, forming the 3D model. The printer can be controlled manually using the software Pronterface, which is also used for the purpose of connecting to the printer while printing actual 3D models. This software accepts a GCODE file as an input.

IN OUR CASE tensile strength specimen of the following dimensions was designed in Autodesk.

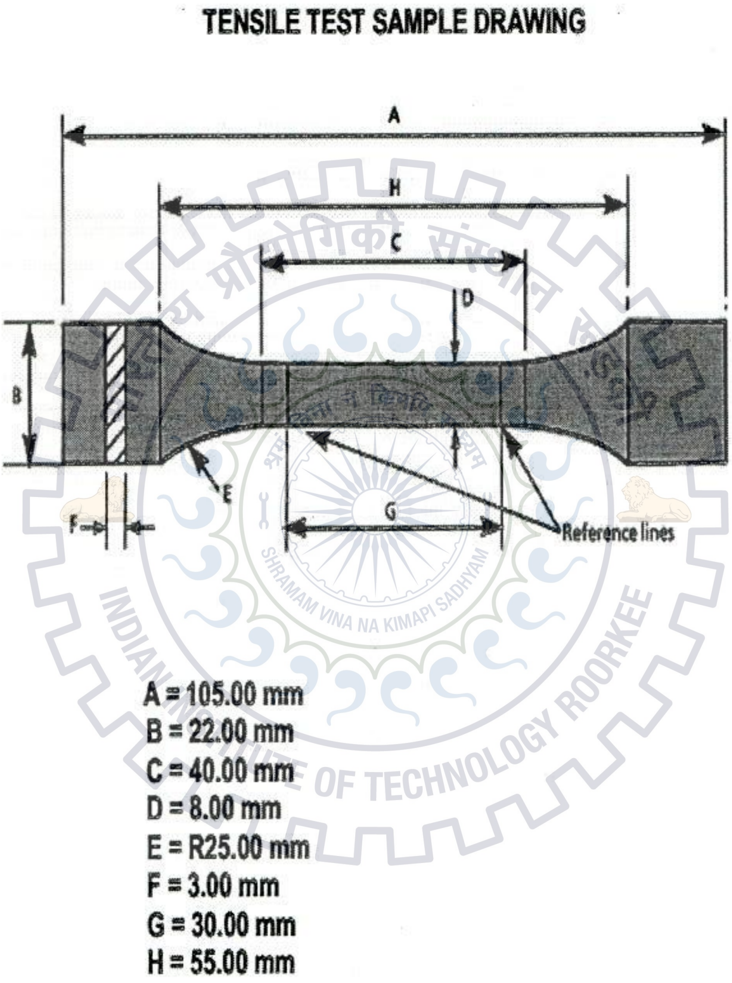


Fig. 5. Standard dimensions of a 'dogbone' sample

CHAPTER SUMMARY-

To print an object it has to first be designed in CAD software where a stl file is obtained. The stl file is converted to gcode file which has layer by layer information about the object. Then gcode file is fed to the machine which prints the object

7. RAPID PROTOTYPING MACHINE

7.1 PRINTING THE 'DOGBONE' SAMPLE

The 3D printer used to run the experiment was Objet N350 in Department of Engineering Design, IIT Madras. The material is Polypropylene.

The converted .stl file was then fed into the software that converts the file to the language the printer understands .gcode format. Then the sample was printed in the following orientations.

1) X-Y plane , the line A is along x-axis
2) X-Y plane , the line A is along y-axis
3) Y-Z plane , the line A is along y-axis
4) Y-Z plane , the line A is along z-axis
5) X-Z plane , the line A is along x-axis
6) X-Z plane , the line A is along z-axis

The direction of printing is along x-axis and the plane of printing is X-Y plane in all the above cases.

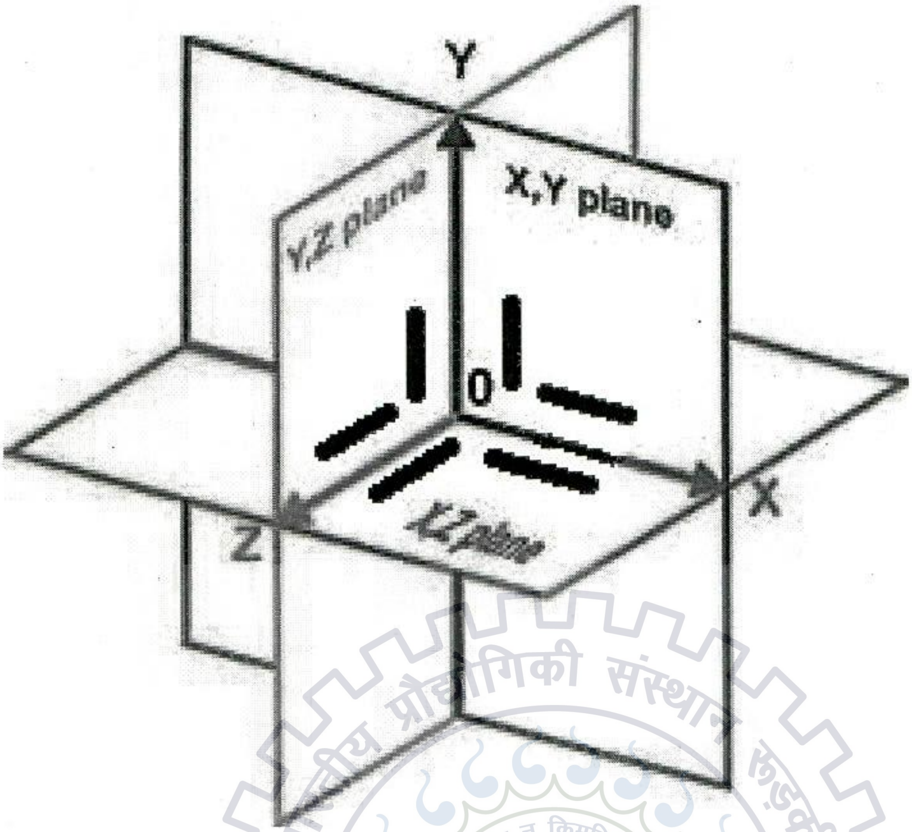
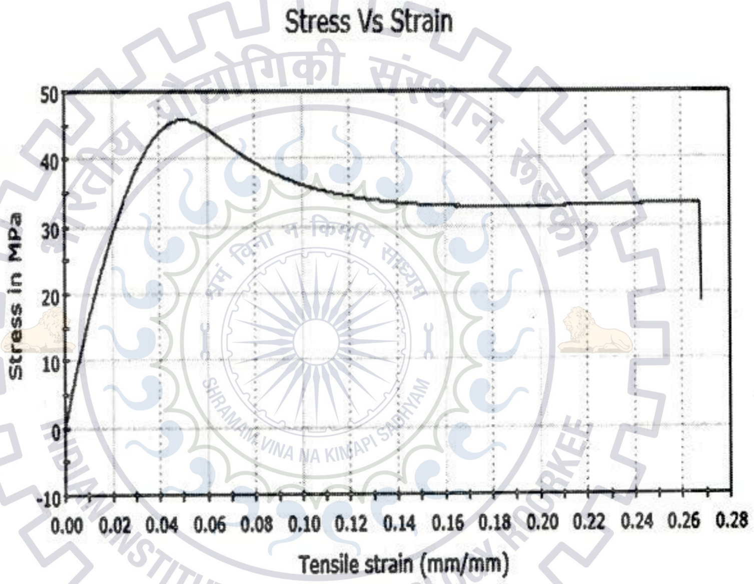


Fig 6. Line A of the sample shown in 3D plane for all orientations (Refer Fig 5 for line A)

Fig.7 Samples printed in different orientations

7.2 TENSILE STRENGTH TEST

Dimension: Geometry	Rectangular
Dimension: Diameter	10.00000 mm



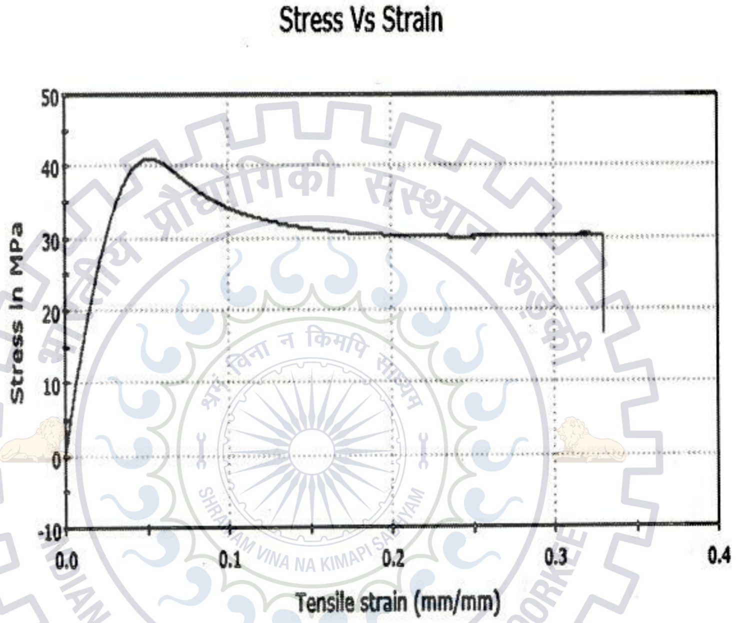
	Area (mm^2)	Tensile strain at Tensile Strength (mm/mm)	Extension at Tensile Strength (mm)
1	21.45000	0.05508	2.20339

	Tensile stress at Tensile Strength (MPa)	True strain at Tensile Strength (mm/mm)	True stress at Tensile Strength (Pa)
1	45.33415	0.05362	47831373.88541

	Rate 1 (mm/min)
1	2.00000

Fig 8. X-Y plane, the line A is along x-axis

Dimension: Geometry	Rectangular
Dimension: Diameter	10.00000 mm



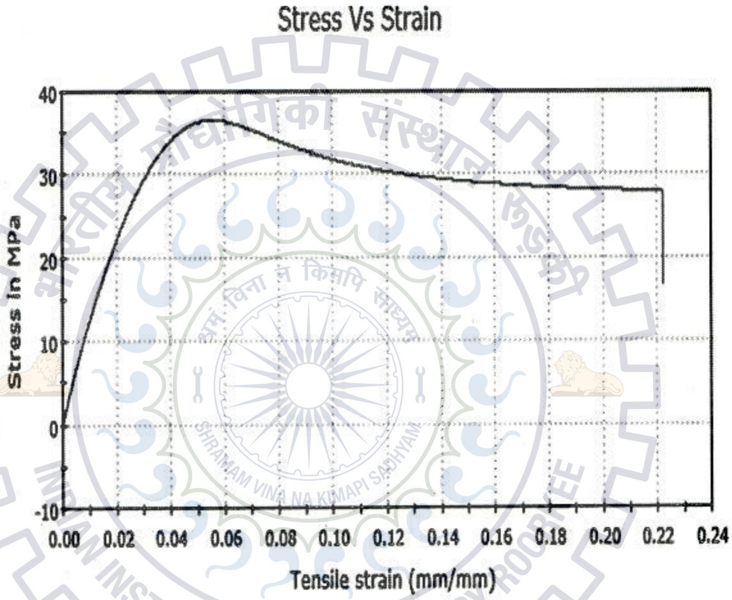
	Area (mm^2)	Tensile strain at Tensile Strength (mm/mm)	Extension at Tensile Strength (mm)
1	23.20000	0.05792	2.31664

	Tensile stress at Tensile Strength (MPa)	True strain at Tensile Strength (mm/mm)	True stress at Tensile Strength (Pa)
1	40.63966	0.05630	42993345.43193

	Rate 1 (mm/min)
1	2.00000

Fig 9. X-Y plane, the line A is along y-axis

Dimension: Geometry	Rectangular
Dimension: Diameter	10.00000 mm



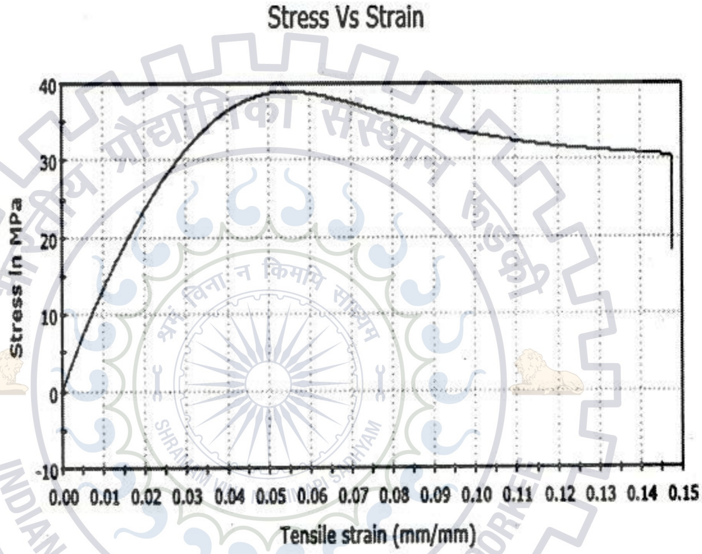
	Area (mm^2)	Tensile strain at Tensile Strength (mm/mm)	Extension at Tensile Strength (mm)
1	24.00000	0.06158	2.46327

	Tensile stress at Tensile Strength (MPa)	True strain at Tensile Strength (mm/mm)	True stress at Tensile Strength (Pa)
1	36.27243	0.05976	38506146.06577

	Rate 1 (mm/min)
1	2.00000

Fig 10. Y-Z plane, the line A is along y-axis

Dimension: Geometry	Rectangular
Dimension: Diameter	10.00000 mm



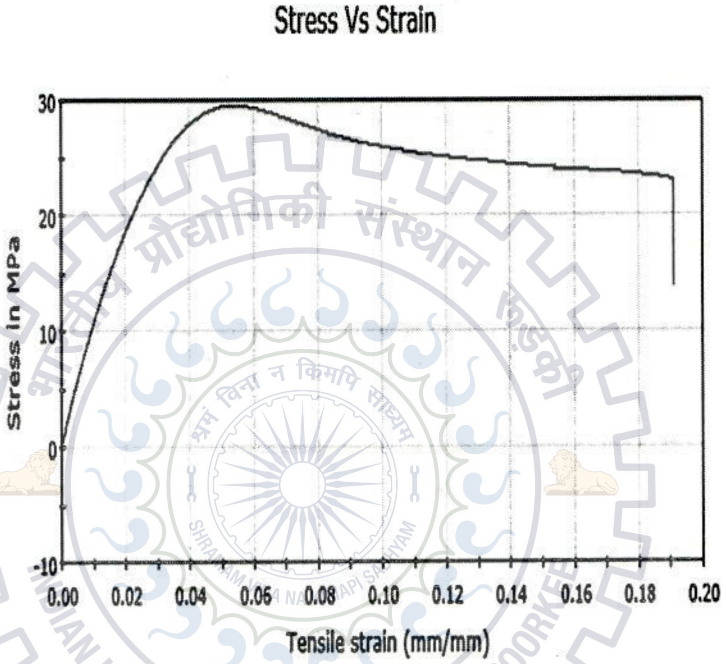
	Area (mm^2)	Tensile strain at Tensile Strength (mm/mm)	Extension at Tensile Strength (mm)
1	24.00000	0.06050	2.42003

	Tensile stress at Tensile Strength (MPa)	True strain at Tensile Strength (mm/mm)	True stress at Tensile Strength (Pa)
1	38.59566	0.05874	40930736.07849

	Rate 1 (mm/min)
1	2.00000

Fig 11. Y-Z plan, the line A is along z-axis

Dimension: Geometry	Rectangular
Dimension: Diameter	10.00000 mm



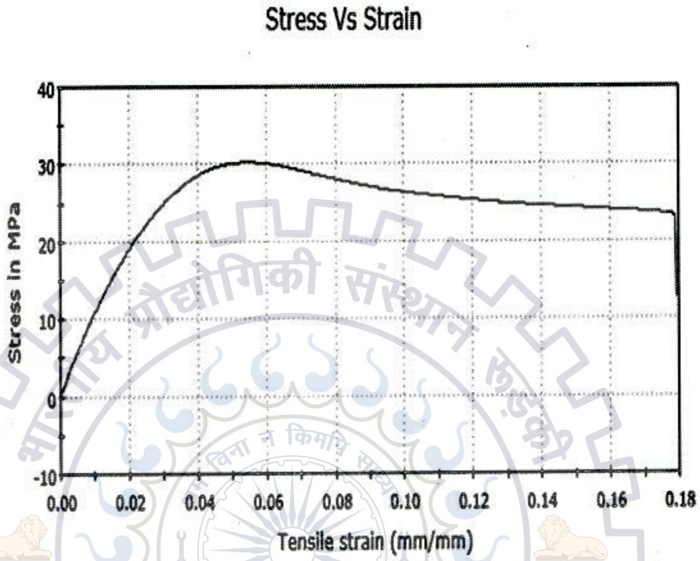
	Area (mm^2)	Tensile strain at Tensile Strength (mm/mm)	Extension at Tensile Strength (mm)
1	24.00000	0.06050	2.42009

	Tensile stress at Tensile Strength (MPa)	True strain at Tensile Strength (mm/mm)	True stress at Tensile Strength (Pa)
1	29.22270	0.05874	30990737.32510

	Rate 1 (mm/min)
1	2.00000

Fig 12. X-Z plane, the line A is along x-axis

Dimension: Geometry	Rectangular
Dimension: Diameter	10.00000 mm



	Area (mm^2)	Tensile strain at Tensile Strength (mm/mm)	Extension at Tensile Strength (mm)
1	24.00000	0.06042	2.41666

	Tensile stress at Tensile Strength (MPa)	True strain at Tensile Strength (mm/mm)	True stress at Tensile Strength (Pa)
1	30.05110	0.05866	31866686.13615

	Rate 1 (mm/min)
1	2.00000

Fig 13. X-Z plane, the line A is along z-axis

7.3 RESULTS AND DISCUSSION

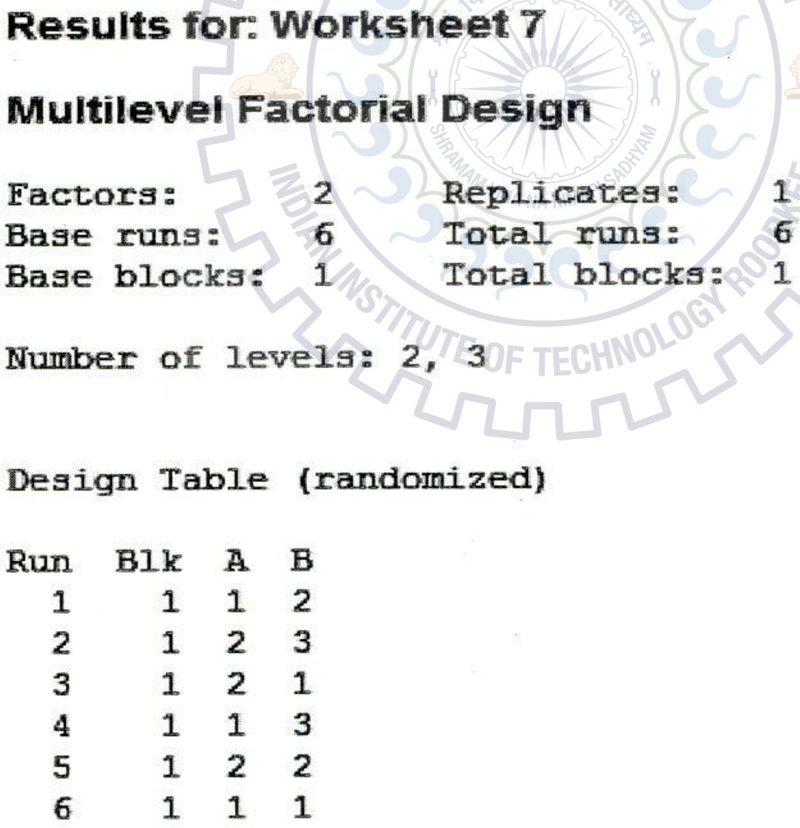
This tensile strength result has to be analyzed to see how strength varies with orientation. So minitab software is used for this.

A design of experiment is setup in minitab. In the DOE orientation as such cannot be quantified. So orientation is taken into 2 factors.

1. Base area
2. Angle between printing direction and line A

So the DOE has 2 factors, the first one with 2 levels and the second one with 3 levels.

The format of such a Design of Experiment is shown below.



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Results for: Worksheet 7

Multilevel Factorial Design

Factors:          2    Replicates:     1
Base runs:        6    Total runs:     6
Base blocks:      1    Total blocks:   1

Number of levels: 2, 3


Design Table (randomized)

Run  Blk  A  B
  1    1  1  2
  2    1  2  3
  3    1  2  1
  4    1  1  3
  5    1  2  2
  6    1  1  1
```

Fig 14. Format of DOE

In this case we have:

Base area has 3 values (66, 315 and 2310), it changes when the plane of the sample is changed. 3 base area value indicates samples were placed in 3 different planes X-Y, Y-Z and X-Z

But the printing angle has only 2 values (0 and 90). It's either along printing direction or perpendicular to it. 2 values show that the samples in 1 plane were placed in 2 different orientation. One along both the axis.

Using the same format and inputting the values we have:

No	Angle (Degrees)	Base Area (sq.mm)	Strength (MPa)
1	0	315	38.59
2	90	66	29.22
3	90	2310	40.63
4	0	66	30.05
5	90	315	36.27
6	0	2310	45.33

Table 1. STRENGTH OF SAMPLE WITH ANGLE AND BASE AREA

This gives us the Main effects plot of strength and interaction plots for strength with base area and angle

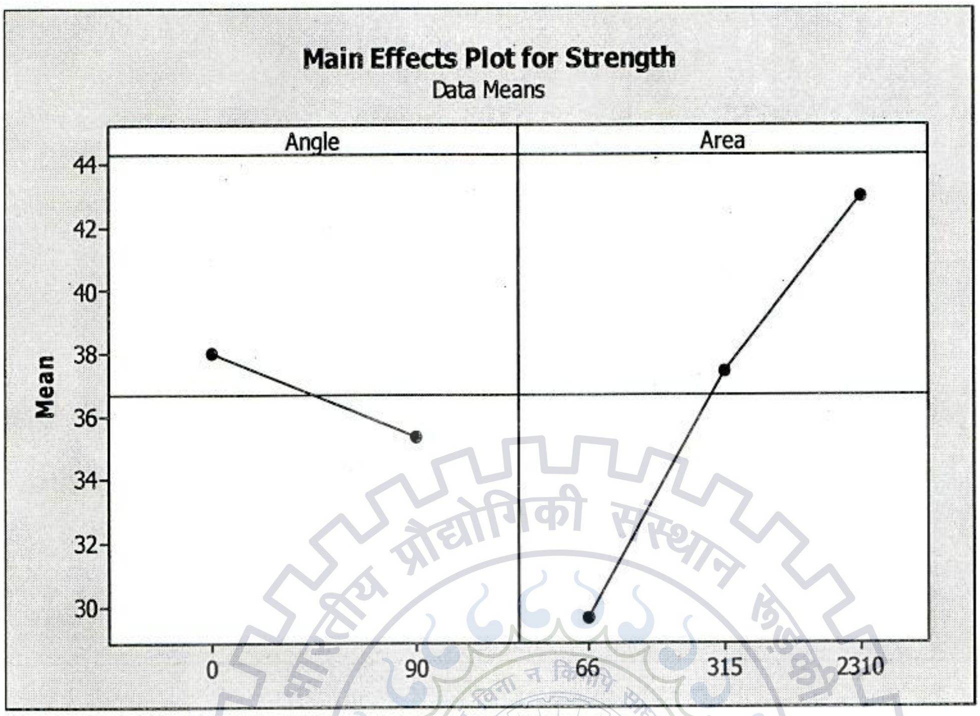


Fig 14. Separate Interaction

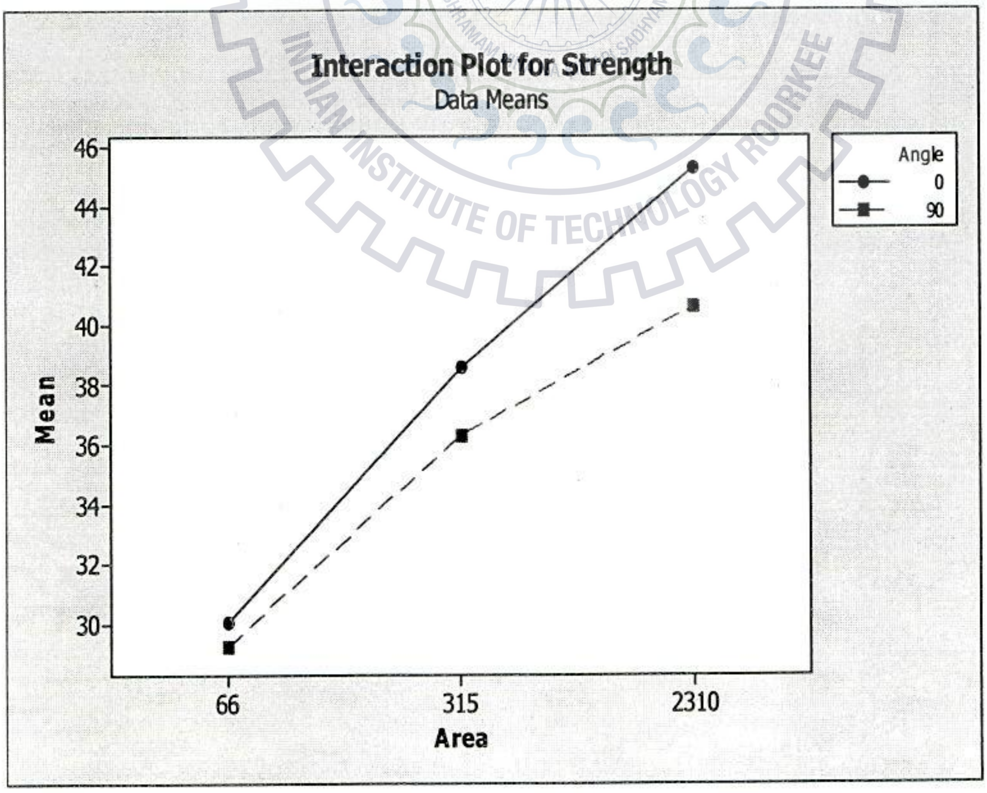


Fig 15. Combined Interaction

After inputting the values in Minitab we get the following equation

Regression Equation:

Strength = 33.745 - 0.0290741 Angle + 0.00473248 Area

Where Strength is in MPa, Angle in degrees and Area in square mm

Analysing the equation-

This equation tells us how strength is related to angle and area. For this sample it is found that Strength increases when the base area is increased and Strength is found to decrease when the object is placed perpendicular to printing direction.

Hence the strength becomes maximum when the orientation of the object is such that the longest edge of the object is along printing direction and the base of object while printing has the maximum possible area.

CHAPTER SUMMARY

This chapter shows the experiment done in Objet rapid prototyping machine. The different orientation of sample, tensile strength in each orientation, and design of experiment using the results. Finally this shows how strength varies with orientation. Strength increases with increase base area and linearly decreases with increase print direction.

8. FDM SAMPLES

8.1 SAMPLE PREPARATION

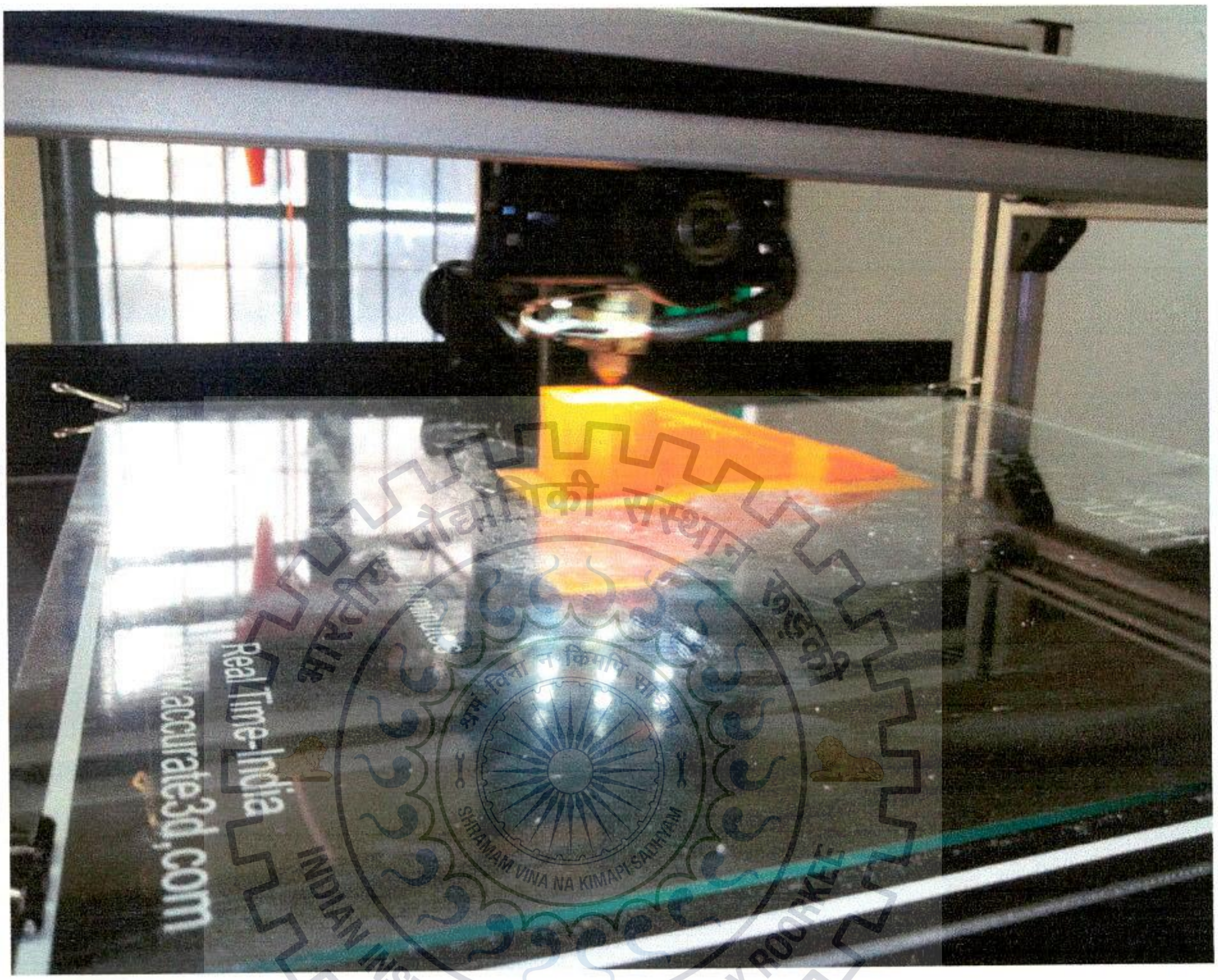


Fig 16. Attempt to print the sample at an inclined plane of 15 degrees

There were also some prints taken in Fuse Deposition Machine.

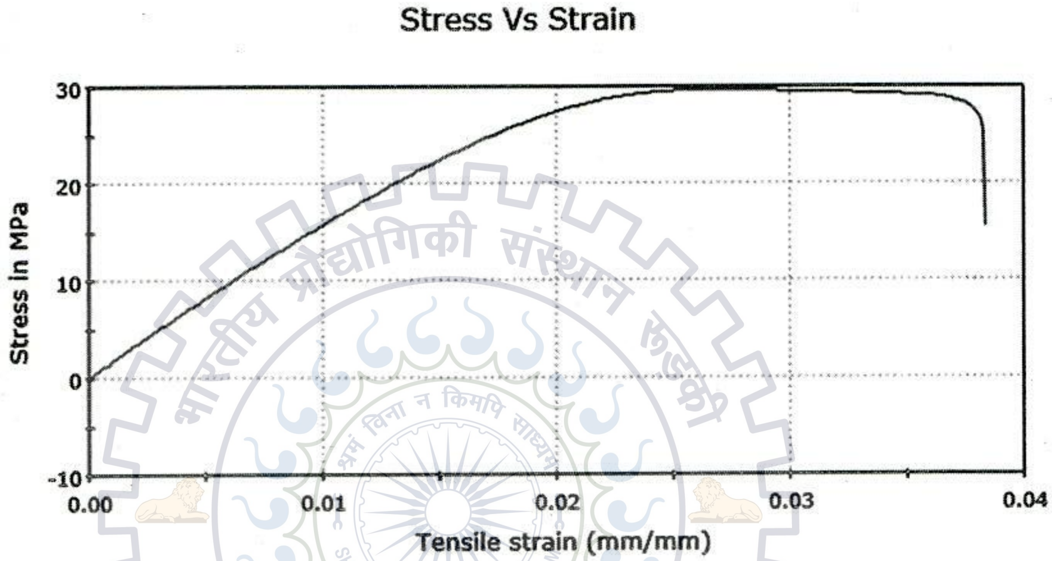
The sample was prepared in 2 Orientation.

1. Horizontal plane
2. Plane inclined to horizontal plane at 15 degrees.

Different orientation in horizontal plane is not required here unlike RPD because there is no single print direction in FDM. The object is printed from outline as shown in Fig 2.

8.2 RESULTS AND DISCUSSION

Dimension: Geometry	Rectangular
Dimension: Diameter	10.00000 mm



	Area (mm^2)	Tensile strain at Tensile Strength (mm/mm)	Extension at Tensile Strength (mm)
1	24.00000	0.02732	1.11327

	Tensile stress at Tensile Strength (MPa)	True strain at Tensile Strength (mm/mm)	True stress at Tensile Strength (MPa)
1	29.62670	0.02695	30.43613

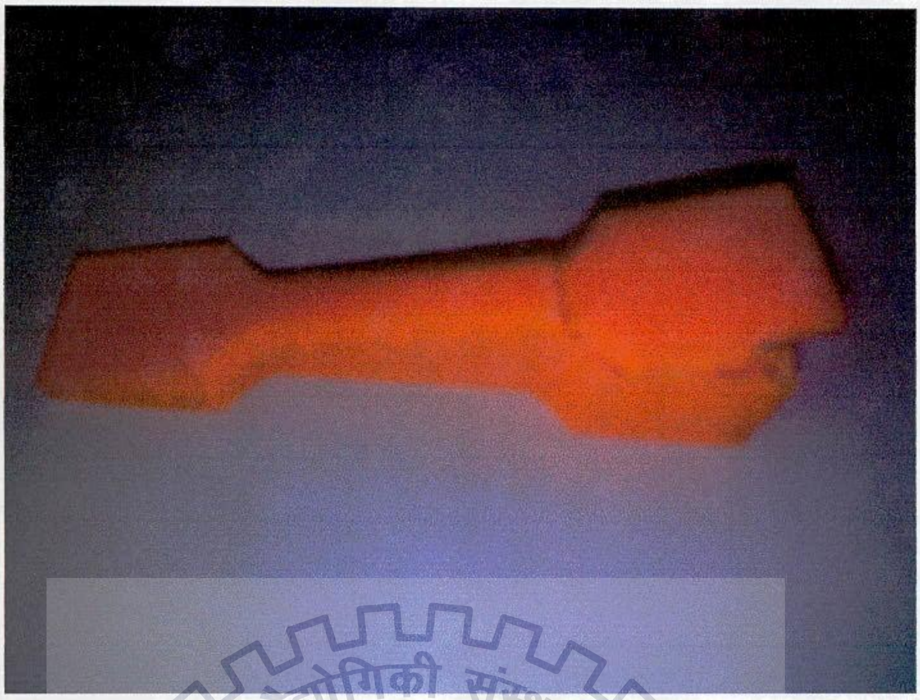
	Rate 1 (mm/min)
1	2.00000

Fig 17. Tensile strength result of sample printed in horizontal plane

When the orientation is horizontal which requires no support material the sample is formed. But when printed at a different orientation other than horizontal direction the actual sample was damaged when tried to separate it from the support Material. Support material is required for stable positioning of the sample while printing at an orientation that is not horizontal. And in FDM the sample material itself is used as support material since there can only be 1 material to the feed.

Fig 18. Sample printed in horizontal orientation

From figure 19, 20 and 21 we can clearly observe the defect when an attempt was made to separate sample from support material. This is because of the formation of homogeneous mixture of sample material and support material.



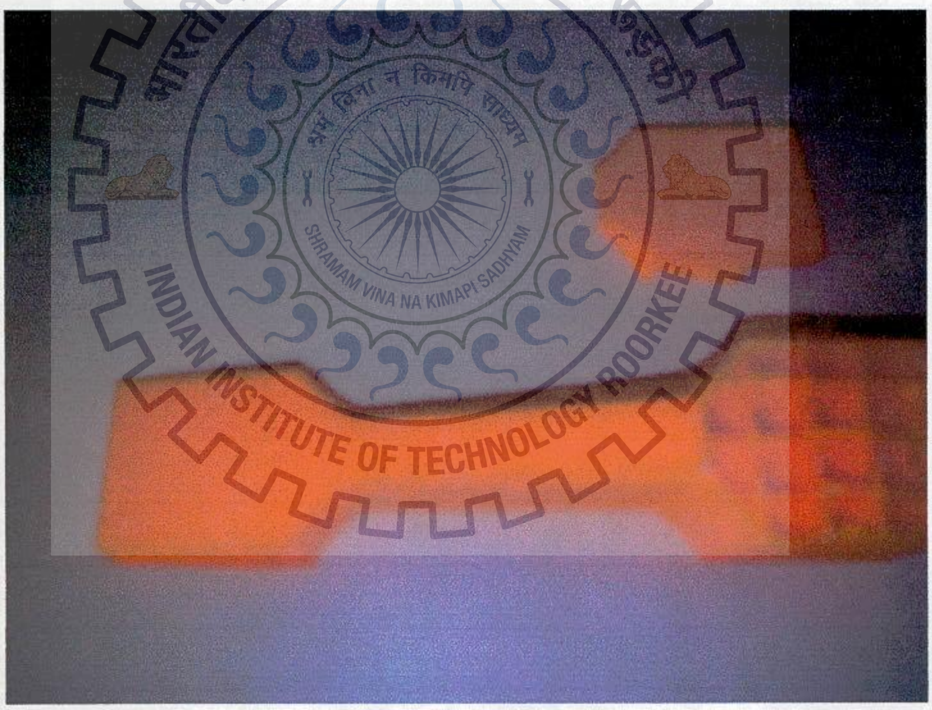


Fig 19 & 20. Defected FDM samples

Fig 21. Defected FDM sample

SUMMARY

This chapters provides the information on what experiments were done on FDM. Samples were taken from 2 types of printer. Objet Printer and FDM. Objet gave good samples whereas FDM had a drawback when it came to printing and separating the material from its support. So study was continued with the samples got from Objet printer.

9. CONCLUSION AND FUTURE SCOPE

9.1 CONCLUSION

STRENGTH VS ANGLE

The regression equation tells us that strength decreases when angle is increased. This can be interpreted that the polymer molecules align along the print direction so when the longest edge of the object is kept along print direction, the molecules align with each other for longer distance which increases the bond strength. As angle is increased the molecular alignment is reduced which reduces the strength.

STRENGTH VS BASE AREA

It is observed that the strength increases as the base area increases. This can be interpreted that strength along the layer is higher than the strength between the layers. So when base area is increased size of each layer increases which increases molecular alignment. When base area is reduced it increases the number of layers and decreases the size of each layer. So the strength as a result reduces.

FDM

This study also shows the limitation of FDM when it comes to printing at multiple orientation due to absence of a separate support material. So this study suggests a modification in FDM where 2 inputs are present, 1 for sample and 1 for support with materials which can be easily separated from each other once the object is printed.

9.2 FUTURE WORK

As shown above this study is limited to relating Strength and Orientation which is the major factor. But there are also other factors that can be considered which include the temperature at which the object is printed, the speed of printing etc. And the angle changed here is along the plane. There can also be a study on the variations if the object is printed across the plane in 3 dimensional orientations. This requires a more rigorous design of experiment with many levels of many factors.

10. REFERENCES

1) R.I. Campbell, M. Martorelli, H.S. Lee, "Surface roughness visualisation for rapid prototyping models", Computer Aided Design Journal, 34 (2002), pp 717-725.

2) K. Thrimurthulu, Pulak M. Pandey, N. Venkata Reddy, IIT Kanpur, "Optimum part deposition orientation in fused deposition modelling", International Journal of Machine Tools & Manufacture, 44 (2004), pp 585-594.

3) LIU Hou-cai, MO Jian-huan, LIU Hai-tao," Part Orientation Optimization in three dimensional printing", CADDM, Vol 18 No.1, June 2008,pp 19-25.

4) Christian Polzin, Sebastian Spath, Hermann Seitz, "Characterization and evaluation of a PMMA- based 3D printing process", Rapid Protoyping Journal, Vol 19 Issue: 1, 2012.