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To cite this article: Sridharan Kannan and Manoharan Ramamoorthy 2020 *Mater. Res. Express* **7** 015341

Materials Research Express

PAPER

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OPEN ACCESS

RECEIVED
30 October 2019

REVISED
31 December 2019

ACCEPTED FOR PUBLICATION
10 January 2020

PUBLISHED
27 January 2020

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Keywords: 3D printing, modal analysis, PC-ABS, polymers

Abstract

Additive manufacturing (AM) process builds the parts, layer by layer precisely from Computer-Aided Design (CAD) models, whereas traditional subtractive manufacturing process removes layers from materials to attain the desired shape. Of late Rapid prototyped (RP) parts are used for the direct production of components for manufacturing and testing in the industries. Understanding material, machine used along with the process variables that affect the strength of the final part gains importance as the parts can be printed directly from CAD data and effectively integrated into structures. The main aim of this investigation is to present the mechanical characterization and free vibration analysis of various 3D printed Engineering Plastic Materials. Acrylonitrile Butadiene Styrene (ABS), Polycarbonate (PC), and Polycarbonate–Acrylonitrile Butadiene Styrene (PC-ABS) materials are used in this study. Spools are prepared from plastic pellets using wire extruder. Tensile tests have been performed on dog bone specimens to evaluate strength, fractured specimen's surfaces which are further evaluated using Field Emission Scanning Electron Microscope (FESEM) to explore fracture of the raster and bonding between layers. From the experimental results it's noticed that the PC-ABS material exhibits improved elastic limit and load-carrying capacity compared with ABS and PC. Three types of beams are fabricated using different materials and modal analysis has been conducted to predict the stiffness of beams in terms of natural frequencies under clamped free (CF) and clamped clamped (CC) end conditions. Higher natural frequencies observed with PC-ABS is compared with the rest of the materials.

1. Introduction

Fused Deposition Modelling (FDM), Fused Layer Manufacturing (FLM) or 3D printing is an Additive Manufacturing (AM) process that produces parts layer by layer by deposition of molten material through nozzle [1]. Digital file is used to manufacture parts directly in a 3D printing machine so the time for product development cycle is very less compared to traditional product development techniques. AM process is suitable for producing parts with complex geometries and finds applications in automobile, energy, aerospace and biomedical applications. Mechanical properties of FDM parts are lower in comparison to traditionally manufactured parts. In order to overcome this issue, adjustment of FDM process parameters to get better properties is a way, while the other way is to develop new material with improved material properties. The blending of polymers is an efficient way of developing novel materials with enhanced material properties [2]. ABS is a rubber toughened thermoplastic characterized by notch insensitivity with limitation of low thermal stability while PC has high thermal stability and good impact strength and difficult to process due to high melt viscosity. On the other hand, PC-ABS thermoplastic blends provide good mechanical behaviour when subjected to dynamic loading conditions as it combines the heat and impact resistance of PC and good processability of ABS [3]. PC-ABS was developed by Borg-warner in 1963 with the brand name, cycoloy800, further in 1995, General Electric developed a material with good heat resistance and impact resistance, without the need for paint and suited for dashboard and steering wheel cover of automobiles [4]. NASA used 70 3D printed parts in rover

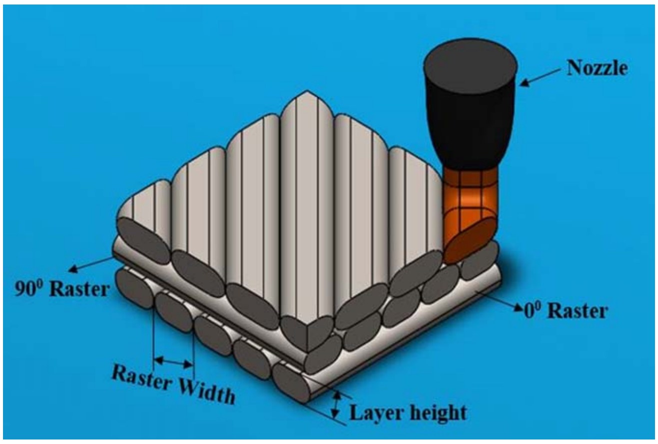


Figure 1. Process parameters in FDM.

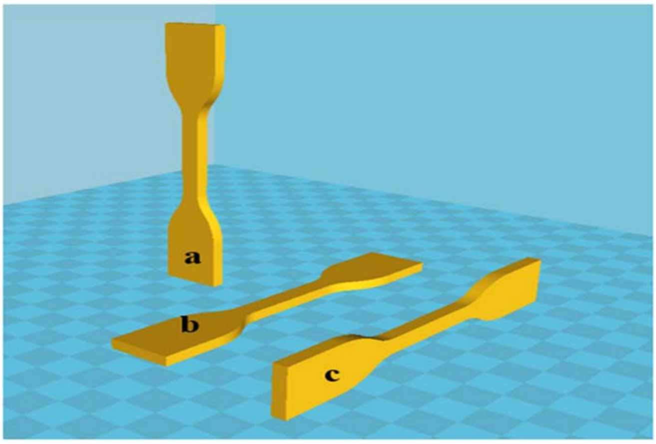


Figure 2. Orientation of the specimen (a) upright (b) flat (c) on –edge.

using ABS, PC, PC-ABS material which was lightweight and durable [5]. The present study is to characterize three different materials printed with similar process settings and test their strength. ABS, PC and Blend of both materials i.e. PC-ABS material was chosen. Except for bed temperature and nozzle temperature all other process parameters were kept constant while printing the specimens. A brief summary of process parameters, tests performed, the material used, the influence of the variation in process parameters on test results are presented below. Process parameters and orientation of the specimen is shown in figures 1 and 2, respectively.

Raster width, layer height, orientation of the specimen, raster angle and air gap were the parameters chosen with three levels by Anoop Kumar Sood *et al* [6] to evaluate the mechanical properties and it was concluded that the distortion between the raster was the reason for less strength. Onwubolu *et al* [7] considered the same parameters with two-levels to study the effects on tensile strength and suggested that minimum layer height & width and negative air gap could increase the strength. The effect of varying raster angle on mechanical properties investigated by Ziemian *et al* [8] keeping other parameters constant concluded that the Specimen built with 0° rasters gave higher tensile, flexural and impact strength. The number of contours/shells and the orientation of the specimen considered by Dario *et al* [9] concluded that the number of shells increases the strength and stiffness without modifying other parameters. Tymrak *et al* [10] made an effort to fabricate functionally strong parts with an open-source 3D printer RepRap. They suggested that quality, age of the polymer filament used, with proper settings for an individual printer could be considered in the open-source 3D printer to fabricate parts similar to commercial printing. Raster angle, orientations were considered as input parameters and surface finish, tensile and flexural strength were measured by Ismail *et al* [11] and suggested that the Orientation had more significance than raster angle on mechanical behaviour and surface roughness of the final FDM parts. The raster angle and orientation on tensile and fatigue behaviour was investigated by Sophia Ziemina *et al* [12] for ABS material and concluded that the orientation of the specimen, air gap between the raster, porosity influenced the tensile strength. The Raster angle and the number of layers was considered by

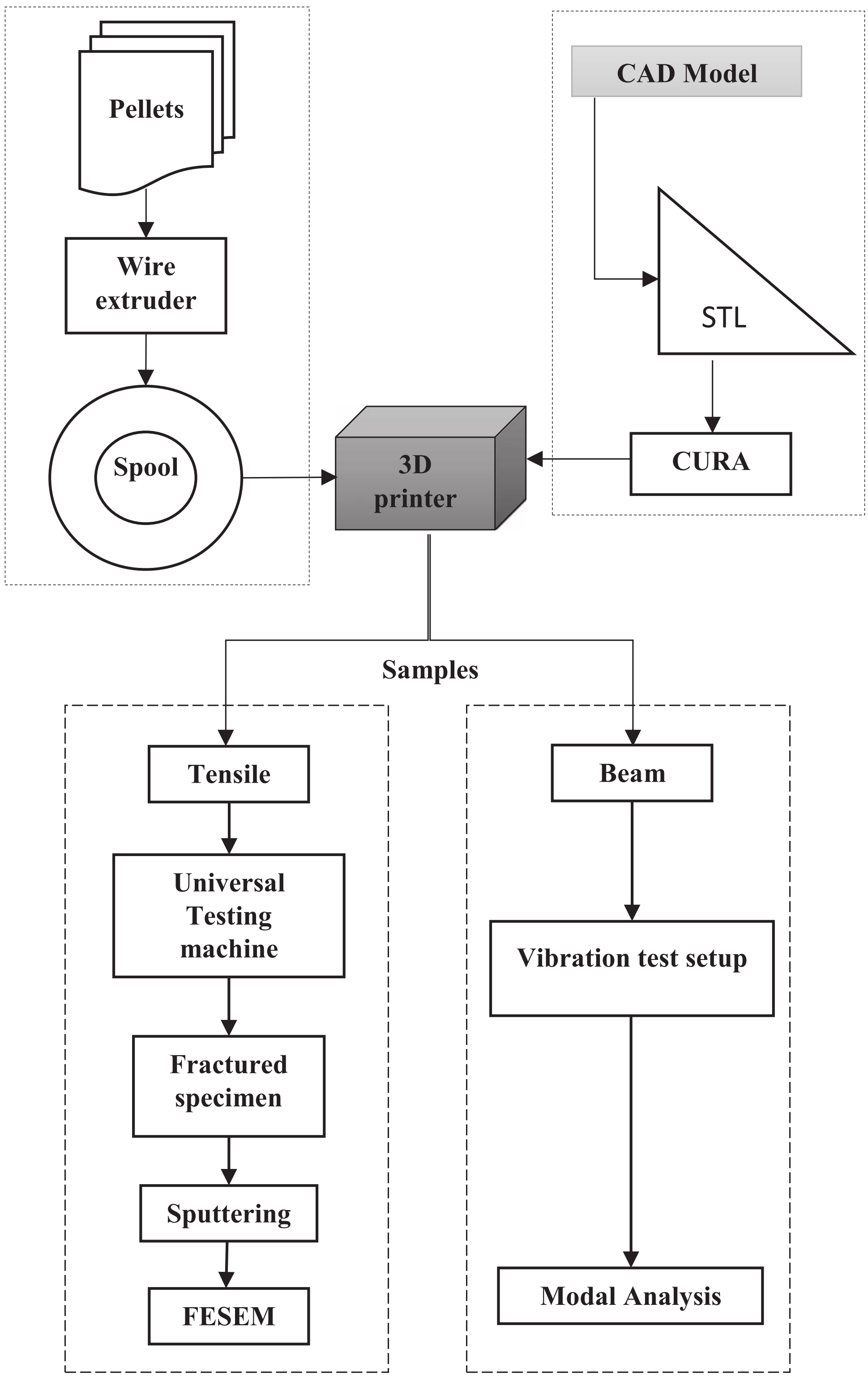


Figure 3. Sample fabrication and testing process.

Todd Letcher *et al* [13]. High variations were observed under maximum stress for the specimens build with less than 12 layers, whereas lower variations were observed above 12 layers. Effect of infill pattern and density were considered by Miguel Fernandez-Vicente *et al* [14] to reduce the material consumption, printing time and they concluded that pattern with 100% infill gives highest tensile strength. While most research is focused on varying machine parameters and measuring the strength, Angel R Torrado *et al* [15] varied the geometry of the tensile specimen, raster angle, the orientation of the specimen build and reported the strength and failure analysis. Layer thickness and raster angle effect on mechanical properties experimentally studied by Behzad *et al* [16] from test results along with statistical analyses suggested lower the layer thickness stronger the specimen strength.

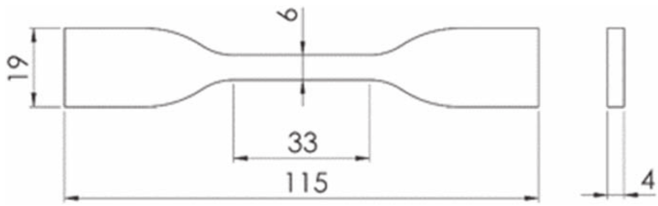


Figure 4. Tensile specimen (dimensions in mm).

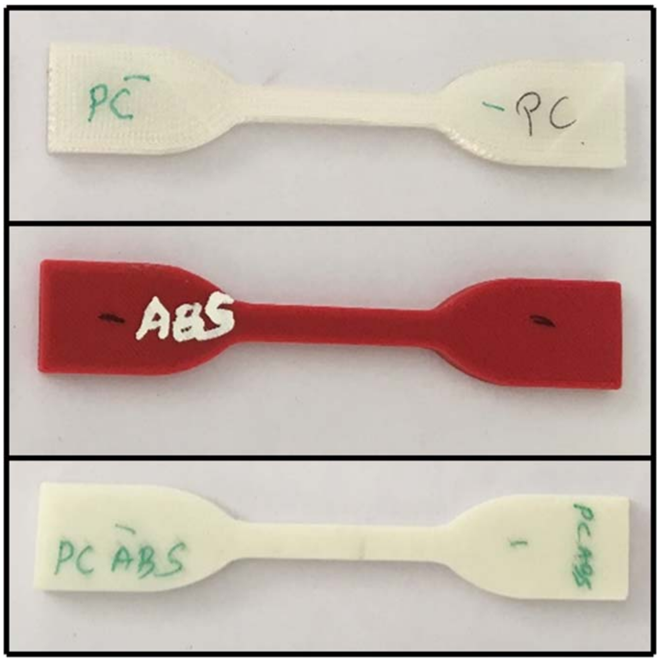


Figure 5. Printed samples of three materials.

Shahrain Mahmood *et al* [17] considered number of shells, infill density, width and thickness of the specimen and measured the strength. They recommended instead of calculating the gross cross-sectional area of the FDM parts, effective area of printed excluding the voids would be more accurate. Layer thickness, the orientation of the specimen, and raster angle were considered by Uddin *et al* [18] and evaluated tensile and compression properties with 3d printed ABS specimens. Conclusions were drawn that the raster angle had a negligible influence on compressive properties. Rohde *et al* [19] fabricated Iosipescu shear specimens and evaluated shear properties and concluded that Flat oriented specimen gave higher shear modulus compared to on–edge orientation for PC material and also discovered that changing the raster angle did not make any difference in shear modulus for ABS specimens but orientation made a significant difference. Samykano *et al* [20] considered layer height, raster angle and infill density to study the effects on mechanical properties of ABS and a mathematical equation was developed to predict optimum parameter for the ultimate tensile property.

Few works listed below summarise the process parameter variations and their effects on dynamic properties. Viscoelastic deformation of PC, ABS and PC-ABS alloys as reported by Yin *et al* [21], performed Dynamic Mechanical Analysis (DMA) for various blends of PC, ABS, and reported storage and loss moduli. Mohammed *et al* [22] performed an impact hammer test on rectangular specimen printed using PET—G and ABS material, where Infill density, layer thickness and printing speed were considered while designing experimental design. Yap *et al* [23] characterized the PC-ABS by ultrasonic testing and results were validated with the tensile test. The finite element simulation was carried out and results were compared with four-point bending and impact hammer test. Mohamed *et al* [24] performed DMA for PC-ABS material and considered parameters similar to reference [6] along with the number of shells and a total of six variables with six levels were used while designing experiments and suggested air gap, extrusion thickness and contours were the influencing parameters.

From the literature survey, it was found that most of the work was carried out to measure the mechanical properties by varying process parameters settings. Optimization of process parameters for better strength,

Figure 6. Tensile testing procedure.

dynamic properties changes for variation of process parameters were carried out by few researchers. Experimental modal analysis together with characterization of 3D printed ABS, PC, and PC-ABS was rarely published. The present study is aimed to characterize three different polymers printed under similar process parameter settings. Strength of materials is evaluated using tensile specimen as per ASTM standards. FESEM analysis on fractured surfaces were carried out to observe the bonding of raster, fracture patterns of the raster. Finally, an impact hammer test was performed on the beam samples to evaluate the structural performances of different 3d printed polymer materials.

2. Mechanical characterization and experimental modal analysis

The proposed work is explained (figure 3) through the flow chart. CAD data and slicing are represented on top the right side, while material processing is shown on the top left side. Samples prepared using 3D printer machine, the testing sequences carried represented in two blocks will clearly show the sequences followed throughout the work.

2.1. Materials and preparation of the test specimen

Three materials were used in this experimental analysis namely ABS, PC and PC–ABS. Pellets purchased from SRF Chennai was extruded into 1.75 mm wire. The tensile specimen was fabricated as per ASTM D638—Type IV [25] to evaluate the strength. Prior to the printing process, the specimen shown in figure 4 was modelled using solid works and converted into Stereolithography (STL) file format. Slicing was performed in Ultimaker Cura an open-source software and G –Code was generated for 3D printing process. The samples were printed using core XY Machine in flatbed orientation and the process parameter settings are tabulated below in table 1. Printed samples of the three different materials is shown in figure 5.

2.2. Tensile test

Tensile tests were performed using Instron 8801 universal testing machine (figure 6) with a displacement rate of 1 mm min^{-1}. Five samples were fabricated for each material and tested in a universal testing machine until the specimen failed. Broken samples are shown in figure 7(a) and it's observed that specimen is broken at the gauge

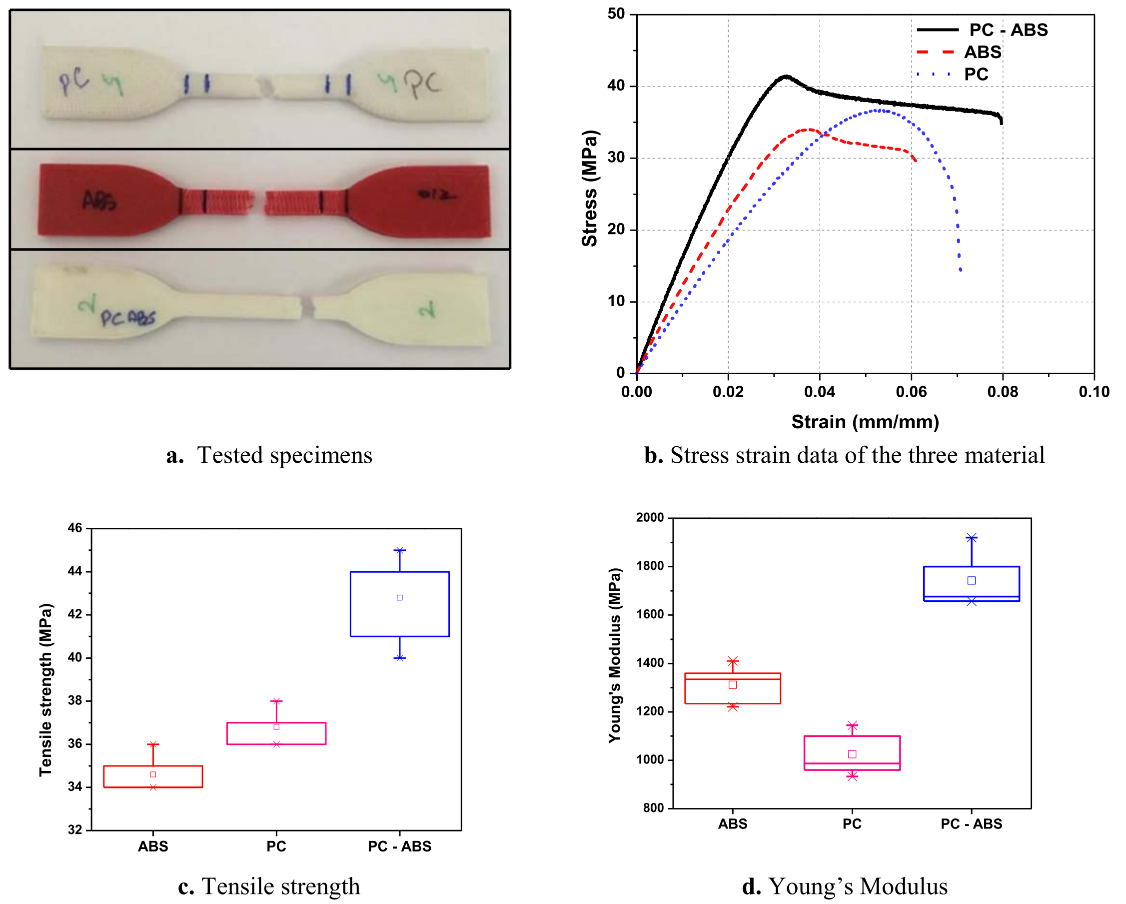


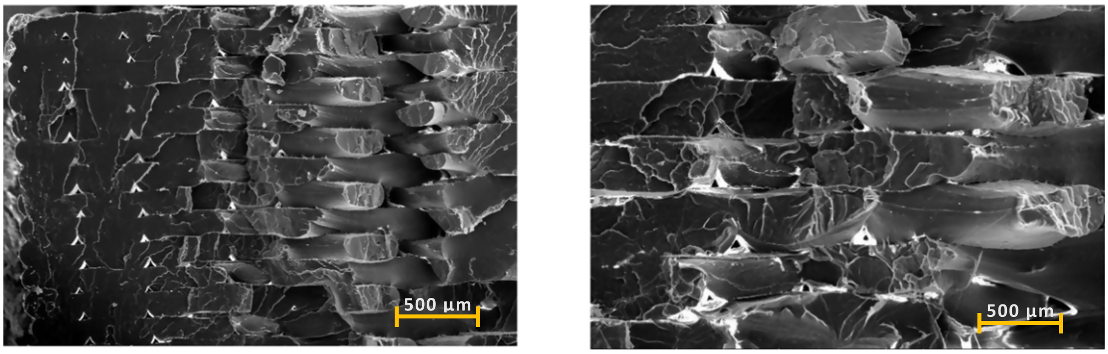
Figure 7. Tensile test data of three materials.

Table 1. FDM process settings used in this work.

Parameter	Value
Infill density	100%
Raster orientation	[+45, −45]
Infill speed	55 mm s^{-1}
outer shell speed	35 mm s^{-1}
Nozzle extrusion temperature	250 °C for ABS, PC-ABS 270° for PC
Bed temperature	80 °C for ABS, PC-ABS 110° for PC
Layer height	0.1 mm

length. Young's modulus of the specimen is determined from the first linear segment of the stress-strain graph and is found from the slope by the linear fitting procedure [9].

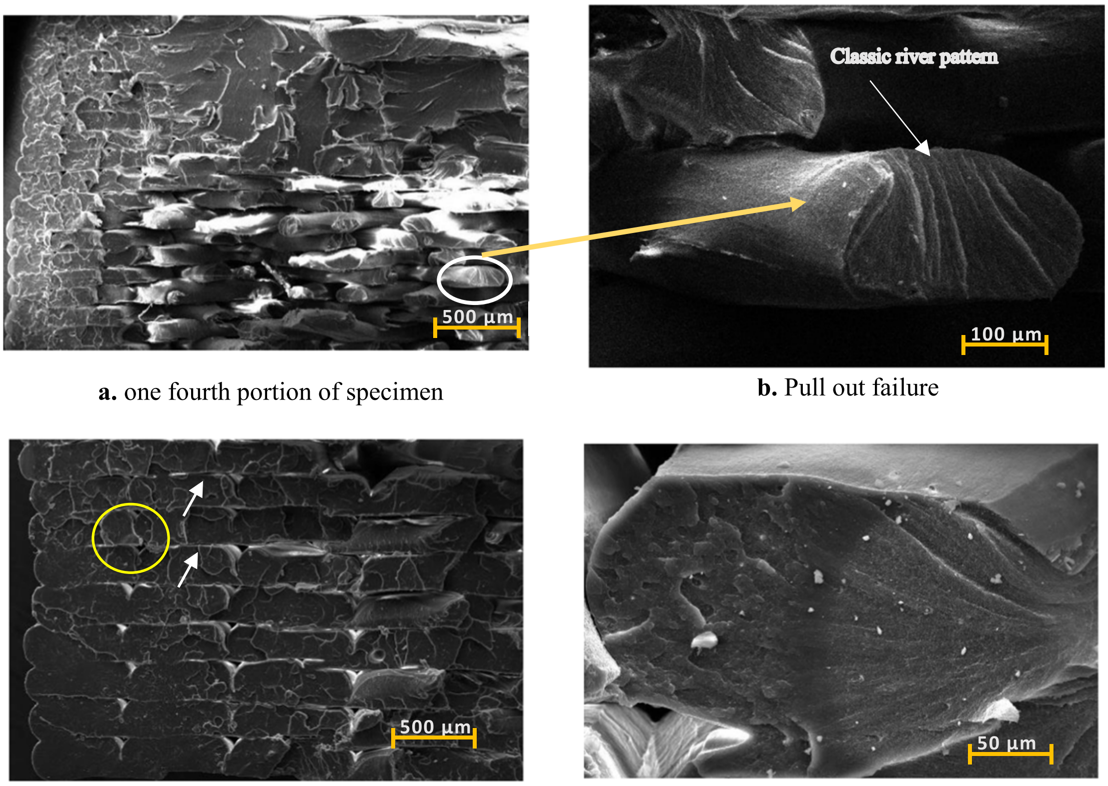
The data close to mean values of tensile properties were chosen and stress-strain curves for the sample plotted is shown in figure 7(b). Tensile Properties of materials is reported using Box—Plots as shown in figure 7(c) comparison of the values and representation of the three groups in less space was done using a Box plot. The Minimum and maximum values are represented by a dash (—) at the two extremes, Mean value is represented with a symbol '☐', Median value is represented by a line inside the box. It could be observed that the median line for Young's modulus plot is clearly visible inside the box. For the UTS box plot the median values (37 MPa for ABS, 36 MPa for PC, 44 MPa for PC–ABS) falls exactly on boundary of the box i.e. it's coinciding with the box boundary lines. From the experimental results, it could be observed that the PC-ABS gives higher values of UTS and Elastic modulus compared to the rest. It is observed that the UTS of the PC-ABS is higher than ABS by 24% and 16% higher than PC. Since the 3d Printed material properties are anisotropic in nature and it is dependent on printing parameters, orientation, and the machine used to print will decide the final strength of the specimen. In order to compare the properties, authors made efforts to print all the samples in the same machine with the same printing parameters listed in table 1. The results predicted that (figure 7(d)), the Young's



a. one portion of the specimen

b. More number of fracture lines observed

Figure 8. FESEM images of PC-ABS specimen.



a. one fourth portion of specimen

b. Pull out failure

c. Bonding with adjacent raster

d. Rupture interface

Figure 9. FESEM images of ABS specimen.

modulus value of the PC-ABS blend is higher than the corresponding value of pure ABS and PC. This improvement in the property is due to the anti-plasticization effect which was formed due to the chain mobility property of PC. Due to such effect, the PC chains were packed more tightly with the secondary cross-linking molecules of the PC chain. As a result, easy movement of the main molecular chain of PC gets arrested which may be the cause for getting higher modulus value of the blended material [2]. The elastic modulus of the blended material is higher by 24% compared to ABS, and 41% compared to PC.

2.3. FESEM analysis of broken samples

One sample from each material was chosen by cutting it 1 cm away from the failure region and was used for FESEM analysis. Since polymers are non-conducting in nature prior to SEM analysis the fracture surface is Gold coated for 105 s and later mounted for microscopic analysis. Sputtering was done using Qurom SC 7620 'Mini' sputter coater/Glow discharge system with Gold/Palladium on the fractured surfaces. Thermo Fisher scientific

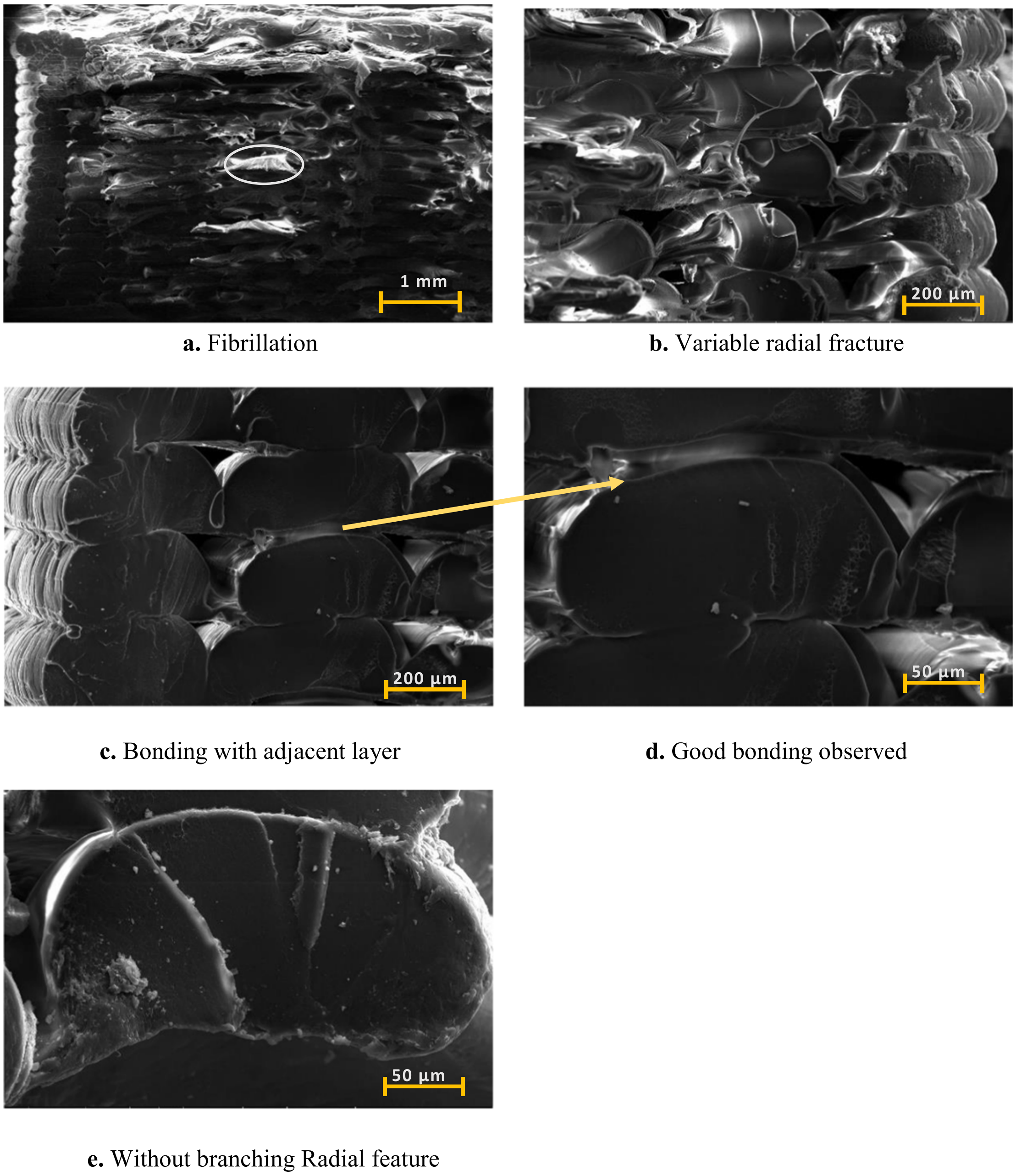


Figure 10. FESEM images of PC specimen.

FEI Quanta 250 FEG was used for FESEM analysis. The bonding between the raster, fracture pattern of the raster was observed in the post-failure analysis.

All the specimen printed with default orientation of $\pm 45^0$ with an outer shell of 0^0 degree raster, when subjected to tensile loading resulted in a whitened crack on gauge lengths on the outer surfaces prior to failure is observed for ABS material as shown in figure 7(a). The same kind of whitened crack was reported with raster oriented with 0^0 in reference [8]. Figure 8 shows the SEM analysis for PC-ABS where more fracture lines are observed compared to other materials i.e. more energy is absorbed before failure.Figure 9(a) shows the quarter portion of fractured surfaces, we can see the two kinds of raster orientations of 0^0 degree raster at the boundary and $\pm 45^0$ raster inside. From figure 9(c), it is observed that failure is mostly brittle with localised micro shearing on raster face. The raster got separated from the adjacent layer after testing (figure 9(c)) and also triangular voids between layers depositions appear. This could be the reason for low tensile strength. For the raster oriented at $\pm 45^0$ relative to the loading axis, the failure occurred by pulling eventually rupturing an individual fibre. Classic river patterns were observed and the starting point of the failure is represented with an arrow in figure 9(b). For polycarbonate, material fracture appears as a radial pattern with a variable radial fracture as represented in figure 10(b). Further it is observed that fibrillation which shows that PC is more ductile compared to ABS. From

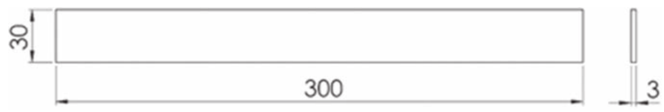


Figure 11. Beam specimen with relevant dimensions in mm.

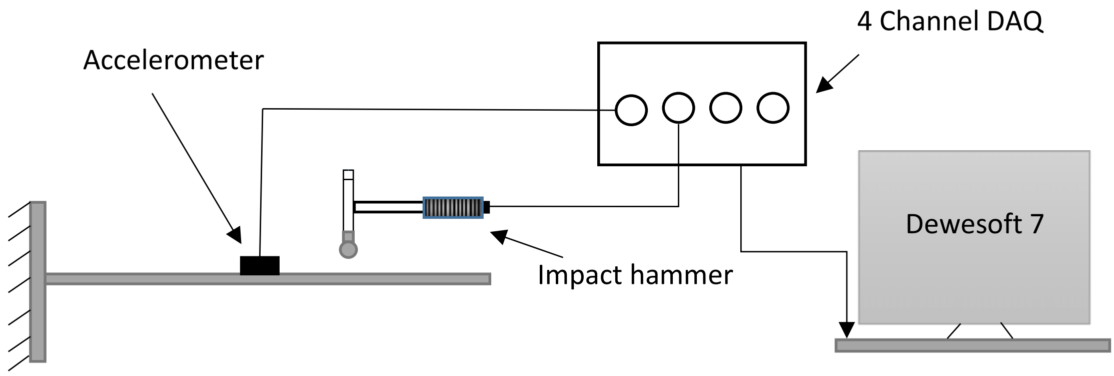


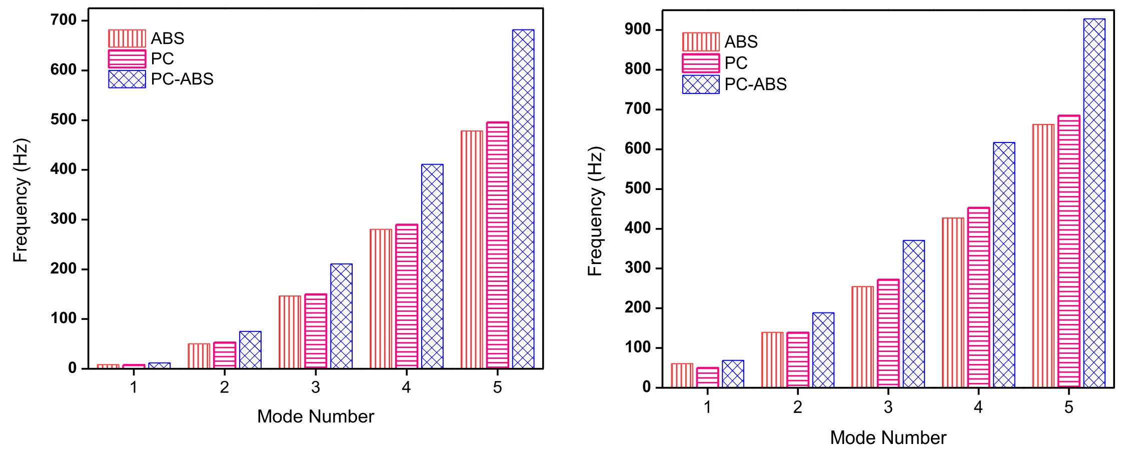
Figure 12. Free vibration testing procedure.

the SEM images it's observed that for 0^0 raster even after failure, bonding with adjacent layer was good. That could be the reason for higher tensile strength compared to ABS. The failure appears as a radial feature without branching (figure 10(e)).

2.4. Experimental modal analysis

Beam specimens were fabricated for modal analysis to measure the natural frequencies, as shown in figure 11, and schematic diagram of experimental set up is shown in figure 12. For fixing the specimen, specially designed fixtures were used. Miniature lightweight (0.5 gm), ceramic shear ICP accelerometer with a sensitivity of 10 mV g^{-1} of PCB electronics, Impulse hammer with a sensitivity of 104.5 mv $lb^{-1}s^{-1}$ of Dytran Instuments Inc., 4 channel Data acquisition (DAQ) by National instrument, Dewesoft 7 software for processing the measured data was used in the experimental modal analysis. The accelerometer was mounted on the specimen using wax at three different points. One Close to the support, second at the middle of the beam and third at the end of the beam. The beam is excited with impulse hammer (roving hammer method) and he response data from accelerometer is acquired with a sampling rate of 5120 Hz/Channel with the help of DAQ.

Modal analysis for a beam sample (300 mm $\times$ 30 mm $\times$ 3 mm) is conducted with two end conditions namely clamped free, clamped-clamped end conditions. A miniature accelerometer (0.5 g) is oriented on the top surface of the specimen using wax. The maximum length of the beam is fixed as 300 mm due to the limitation in the 3D printing machines. In that, 50 mm is utilised for clamping purpose and the remaining 250 mm effective length of the beam is used for modal analysis. The effective length is divided into 25 elements. Using rowing hammer method the beam is excited and responses are measured and the corresponding results are plotted as a bar chart as shown in figure 13. For the ABS material, warping issue was encountered by the authors while printing beam samples, since long models are more susceptible to warping. For ABS material two samples were printed and tested for minimising experimental errors due to warping issues. From figure 13, it can be observed that the blended material shows 30% higher natural frequencies compared to pure PC material under CF end conditions. Due to the increase in Young's modulus of the material the natural frequencies increased. Local yielding and craze create micro plasticity giving damping for ABS material. From the stress-strain plot, it is clear that PC more is ductile and fibrillation in FESEM images confirms the same. Ductility will improve damping, which could be the reason for lesser first natural frequencies for ABS and PC compared to PC-ABS. From FESEM images as seen in figure 8(b), we can infer that energy absorbed is more prior to failure which results in higher natural frequencies for PC-ABS. CC end condition yields higher natural frequencies compared to CF end conditions. Due to the flexibility of the end conditions, CC and CF end condition yield higher and lower stiffness of the structure with identical mass. For CC end condition, the percentage of improvement is similar to CF end conditions which shows the changes in frequency due to the geometrical constraints alone.



a. Natural frequencies with CF end condition

b. Natural frequencies with CC end condition

Figure 13. Free vibration test results of 3D printed Beams.

3. Conclusion

The main aim of the work is to investigate the mechanical properties of ABS, PC, and PC-ABS 3D printed materials and also perform free vibration analysis using beam samples. Our study compared the mechanical properties of the three materials by printing them with same process parameters with the same machine. Through the comparison of the mechanical properties of ABS, PC & PC-ABS samples made by 3D printing, it is observed that PC– ABS material is exhibiting better elastic modulus and load-carrying capacity compared to ABS & PC. The UTS of PC-ABS is 24% higher compared to ABS, 16% higher compared to PC. The elastic modulus of the PC-ABS material is higher by 24% compared to ABS, 41% compared to PC. The results compared here is specific to the machine settings and process parameters used. Free vibration analysis carried out using beam samples for the same materials, PC-ABS exhibits 30% higher natural frequencies in CF end conditions, and 26% higher in CC end conditions. From the experimental analysis, it is concluded that the PC-ABS thermoplastic blend gives improved mechanical properties. However, there is a lot of scope to work in this area. Further research is needed to explore thermoplastic blends with different machine settings and changes in property. Printing the structure as light as possible is important, it is also important that the structure be strong. It is believed that the PC-ABS material may be a promising material with improved mechanical properties for aerospace and automobile industrial application of 3D printed components.

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