Determination and Comparison of the Anisotropic Strengths of Fused Deposition Modeling P400 ABS

Kshitiz Upadhyay, Ravi Dwivedi and Ankur Kumar Singh

Abstract Fused deposition modeling (FDM) is an additive layered manufacturing technique used to build prototypes and functional products out of thermoplastic materials. The properties of the FDM parts are affected by many factors like geometry of the material bead, process conditions, and orientation of the part and layers etc. The present study focuses on the effect of build direction on the mechanical properties of acrylonitrile butadiene styrene (ABS) P400 part specimens. Tensile, compressive, Izod impact, and hardness tests were performed on specimens built in the horizontal and vertical orientations with an intention to find the build direction that gives maximum strength in a particular working condition. Fractured specimens were then analyzed under the Jeol JSM 5600 Scanning Electron Microscope to study the impact failure pattern. The findings of this research can further be used to formulate product design rules for optimizing mechanical strength in layered manufacturing.

Keywords Rapid prototyping · Anisotropy · Fused deposition modeling · ABS · Build orientation · Mechanical strength

1 Introduction

Conventional manufacturing consisted mostly of subtractive and forming processes like milling, turning, coining, grinding etc., in which a part is shaped by either material removal or plastic deformation. Rapid prototyping, however, belongs to the generative or additive production processes. First emerged with the introduction of steriolithography technology in 1987, many RP technologies have been developed since then, for example fused deposition modeling, selective laser melting, selective laser sintering, laminated object manufacturing, solid ground curing etc.

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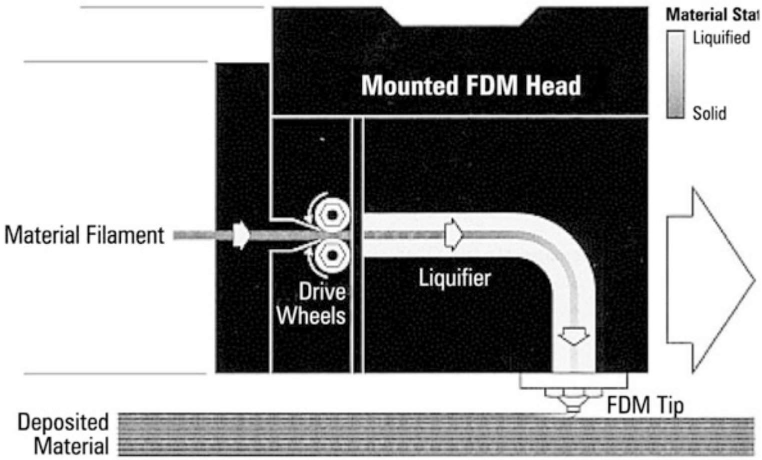

Fig. 1 Fused deposition modeling process [5]

It is a technology of huge significance in today's world because of its ability to decrease the manufacturing lead time by 30–50 %, yet maintaining part complexity [1, 2].

Fused deposition modeling (FDM) is one such RP process in which a part is fabricated by stacking layers of a molten thermoplastic material one above the other [3]. In the FDM process, first a 3D CAD model is created. This model is then exported to a slicing software like the FDM Quick Slice software using steri-olithography (STL) format that tessellates the part into numerous basic triangular components. Although the part loses some resolution while exporting, STL format is advantageous because it simplifies the geometry [4]. The Quick Slice software slices the model into numerous horizontal sections. These are the two-dimensional contours that the FDM process will later generate and stack above each other. The software then uses this data to formulate a process plan for the FDM machine's hardware (Fig. 1).

During fabrication, a thermoplastic filament passes through a heating element that partially melts the filament. This semi-molten filament is then dropped through a nozzle which can move in the *XY* plane, onto a platform. The deposition takes place according to a path which is generated by the software. After completing one layer of deposition, the platform holding the part moves vertically in the *Z* plane and the process repeats. The newly fed heated filament fuses with the material in the adjacent layers of the partially constructed part. In a period of time, usually several hours, a complete part forms on the platform. An overhang or an intricate part geometry, may sometimes necessitate a support material. This material is fed through a second nozzle that is present beside the first one. The support material can be easily removed after the process by either breaking it off, or dissolving it in warm water bath. To maintain a constant heated environment, the entire process is done in a closed chamber which is also known as the envelope. This heated environment

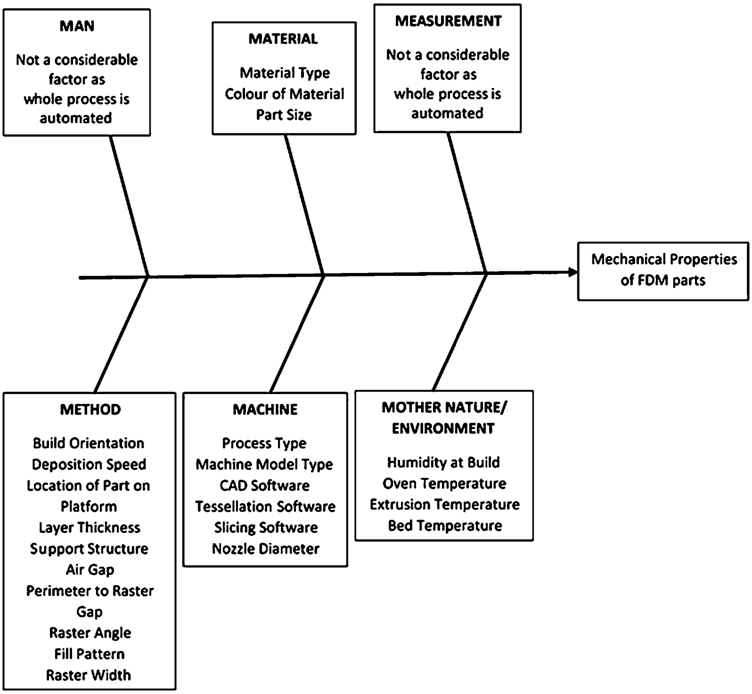

Fig. 2 Fishbone diagram (6M) showing factors that can affect the mechanical properties of the FDM prototypes/parts

helps to improve the interlayer bonding [6] and reduces shrinking, warping, and internal stresses [7].

Although the objects produced by FDM are mainly used as models and prototypes, there is a potential that these can be used as functional products. However, this would require improvements in these procedures and a sound knowledge about the material properties like mechanical, electrical, thermal properties etc. [8]. The properties of an FDM part also depend on the process parameters listed in Fig. 2. Determination of the FDM process parameters such as air gap, layer thickness, raster width and angle, and build orientation have remarkable effects on the mechanical properties and performance of the component [9, 10].

Variation in the properties of the parts produced by the FDM due to process parameters' change has also been studied in the past. Hossain et al. [11] focused on improving the tensile properties of FDM-manufactured polycarbonate parts by adjusting the parameters and analyzing the stress concentration features between the adjacent roads of material. The parameters that were changed are raster angle, contour width, raster width, and raster to raster air gap. Fatimatuzahraa et al. [12] measured and compared the tensile, bending, impact, and deflection strengths of the FDM ABS specimens manufactured in two different raster angles/orientations, which were cross (0°/90°) and criss-cross (45°/−45°). The results of their experiments showed that the criss-cross raster orientation gave higher strengths in all the tests except the tensile strength test, in which cross raster gave a higher strength value. Anitha et al. [13] studied the effect of layer thickness, road width, and deposition speed on the surface roughness of parts produced by FDM. The experimental results concluded that the surface roughness is mostly affected by layer thickness, followed by road width and then deposition speed. Reddy et al. [14] determined that road gap, extrusion temperature, and oven temperature all had a significant impact on part strength for parts fabricated from ABS, a finding that holds for most materials. Es-Said et al. [15] studied the tensile strength, modulus of rupture, and impact resistance of ABS models produced using various raster orientations. The results suggested that the 0° raster orientation demonstrated superior strength and impact resistance among the five raster orientations examined.

In addition to the factors discussed in the previous paragraph, one important process parameter that has shown huge significance in the optimisation of FDM process is the build orientation. Build orientation (also called part orientation) is the direction along which the part is actually built on the platform. Thrimurthulu et al. [16] attempted to improve surface finish and reduce building time by optimizing part deposition orientation. They developed models to evaluate average part surface roughness and build time. Moreover, a real coded genetic algorithm was used to obtain the optimum solution. Waghchore [17] aimed at the determination of optimum-built orientation angle for minimum build time for fused deposition modeling (FDM). To achieve this, simple machine parts were manufactured at different angles from 0° to 90° in step interval of 15° and time for each orientation was taken by using the Catalyst software. Tagore et al. [3] focussed on optimizing the build orientation to get the best surface quality, part accuracy, build time, and cost. Masood et al. [18] tried to determine the optimum build orientation in FDM using volumetric error for tessellated CAD models. They formulated a generic algorithm for this purpose. Volumetric error was calculated for various build orientations and the best orientation had the least error. Byun and Lee [19] aimed at determining the optimal buildup direction of a part for different RP systems using simple additive weighting method. Factors under their consideration were average weighted surface roughness, build time, and part cost appraised by build cost, labor cost, and material cost etc.

Ahn et al. [5] compared the tensile and compressive strengths of the FDM prototypes made of ABS P400, with the injection-molded parts of the same material. The factors considered in tensile strength measurements were raster orientation, air gap, bead width, color, and model temperature. On the other hand, build orientation was the factor that was considered in compressive strength measurement. It was shown that the build orientation significantly affects the compressive strength of the FDM specimens. Lee et al. [20] compared the FDM, 3D printer, and Nanocomposite deposition (NCDS) processes by performing experiments on directionally fabricated cylindrical parts. The effect of build direction on the compressive strength of parts was examined. Anoop et al. [9] concluded that raster angle and orientation, layer thickness, raster width, and air gap are the four significant factors that should be taken into account in an FDM process. It was stated that these parameters strongly influence the tensile, deflection, impact, and flexural strength. Bagsik et al. [21] studied the variation in the tensile properties of Ultem*9085 material FDM specimens by changing the build orientation, raster angle, filament thickness, raster to raster air gap, and perimeter to raster air gap. A total of 54 experiments were conducted each for tensile strength and strain measurement that showed that the tensile properties vary substantially by changing process parameters. Bellini et al. [22] claimed that building strategies in an FDM process affect the mechanical properties of produced parts. The authors predicted that the bond between layers is an important factor. They envisaged that when an FDM part is pulled along the build direction, the bond between layers is too weak and defects are usually present. Similar conclusion was drawn by Chakraborty et al. [23], who concluded that the mechanical strength of FDM parts suffers from anisotropy. Furthermore, they stated that as compared with the interlayer adhesive strength, the strength of continuous filaments is much greater.

Literature suggests that build orientation is an important FDM process parameter. Although extensive research has been done on the anisotropic nature of tensile and compressive properties of FDM prototypes, there is a lack of research done on other important mechanical properties like hardness and impact strength. These mechanical properties are especially more important for polymer and composite materials, where there is no general relationship between indentation hardness and tensile strength. The usage of ABS in FDM process provides the ability to conduct functional tests on fabricated part samples, by offering impact resistance, heat stability, chemical resistance, and toughness [12]. However, there is a need to quantify these properties so that build rules may be formulated. Also it can serve as a data sheet for manufacturers so that better properties may be imparted to the part even before its manufacturing begins. This paper attempts to analyze a broader spectrum of mechanical strengths of FDM ABS P400 parts. Experiments were conducted in which the effect of build orientation on the mechanical properties, namely tensile strength, compressive strength, impact strength, and the Rockwell hardness of FDM parts were examined. Fractured specimens were also analyzed under the Jeol JSM 5600 Scanning Electron Microscope to study the Impact failure pattern.

2 Build Parameter Consideration

The FDM process basically requires fixing of several build/process parameters which can affect the mechanical properties of the manufactured prototypes. These parameters were fixed for both the build orientations on which experiments were intended to perform to determine and compare their mechanical properties. The two build orientations tested in the experiments are depicted in Figs. 3 and 4. Both the

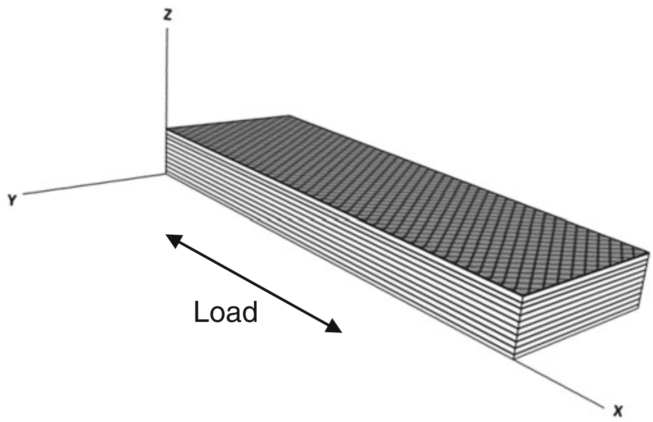

Fig. 3 Horizontal (*X*) build orientation of an FDM specimen

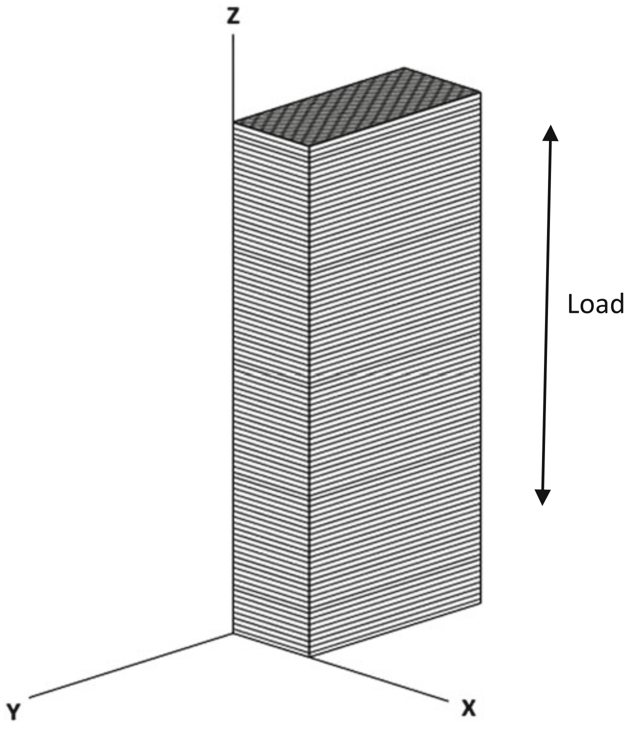

Fig. 4 Vertical (*Z*) build orientation of an FDM specimen

parts depicted in the figures have identical dimensions and are built from bottom to top (positive *Z*) in the FDM, but the orientation of fibers under stress will be different (example of a tensile load shown in the Figs. 3 and 4). In general, *X* orientation has the greatest projected footprint on the FDM bed while *Z* orientation has the least.

The research used CatalystEX slicing software for this purpose. The selected parameters are listed below.

2.1 Layer Resolution

Layer resolution is the thickness of each layer that the FDM nozzle deposits. In the FDM SST-768 machine, it can either be the standard 0.2540 mm layer or a 0.3302 mm layer. In the present research, the layer resolution selected was 0.2540 mm.

2.2 Model Interior

Model interior refers to the way in which the solid interior areas of a part get filled with material. The "Solid-normal" option in FDM is used when a strong and durable part is desired. This fill type uses more amount of material and is costlier and time-taking. The "Sparse" option creates a part that is honeycombed or hatched from inside. Sparse option creates part with lesser material and reduced time/cost. The present paper uses "Solid-normal" as its model interior.

2.3 Support Fill

An additional support material is used to provide a build substrate if the component part shows an overhang, offset, or cavity [21]. This additional material prevents the component part from collapsing during the building process. The support fill parameter can be modified to basic, sparse, minimal, and surround. The present paper used "basic" support fill for *X* orientation specimens, and "surround" fill for the *Z* orientation specimens.

2.4 Color

ABS P400 is available in white, blue, black, yellow, green, and red colors among others. Color is a qualitative parameter which has a little effect over the tensile strengths of the FDM parts [5]. The present paper used white ABS P400 polymer as a raw material.

Table 1 Build time of the FDM specimens

Specimen	Orientation	Build time (min)
Tensile	*X*	32
Tensile	*Z*	270
Compressive and hardness	*X*	17
Compressive and hardness	*Z*	48
Izod impact	*X*	20
Izod impact	*Z*	104

The build time for the specimens is given in Table 1. This data is obtained from the Catalyst EX software. It can be observed that the building time for horizontal specimens is generally lesser than that of vertical specimens. The reduction in build time can be attributed to fewer number of slices in an orientation with minimum vertical z height [17].

3 Experimental Setup

The experiment was conducted in which a number of standardized samples were built in the Dimension SST-768 FDM machine by modifying the orientation of build in CatalystEX software. Manufactured prototypes were then tested for their mechanical strengths.

3.1 Tensile Strength Test

The tensile tests were carried out according to the ASTM D638 procedure. Instron 3382 machine with 100 kN capacity was chosen for the experiments that has a measurement accuracy of ±0.5 % of the reading value. The loading rate was set to 5 mm/min. A total of five samples were made for each build orientation. The test samples were built according to the ASTM D638, type I tensile standard. Figure 5 shows the dimensions of the tensile test specimen.

3.2 Compressive Strength Test

The compression tests were carried out according to the ASTM D695 procedure. Instron 3382 machine with 100 kN capacity was chosen for the experiments that has a measurement accuracy of ±0.5 % of the reading value. The loading rate was set to 1.3 mm/min. Maximum load was noted during the test when the rupture took

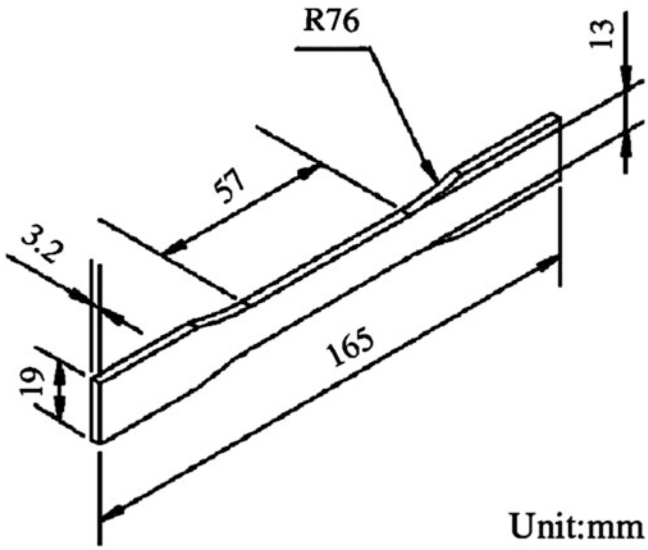

Fig. 5 ASTM D638 type I tensile bar

place. A total of five samples were made for each build orientation. The test samples were built strictly according to the ASTM D695 standard. The specimens were rectangular prisms and had a size of 12.7 mm × 12.7 mm × 25.4 mm.

3.3 Izod Impact Strength Test

The ASTM D4812 testing procedure was adopted in the experiment on a Cantilever Beam Impact machine, according to which the standard specimen size was 64 mm × 12.7 mm × 3.2 mm. The samples were un-notched and the impact blow was edgewise impact (hitting the smallest dimension). As this standard size is prone to bend or crush easily, the specimen thickness was increased from 3.2 to 6.4 mm. A total of five samples were made for each build orientation.

3.4 Rockwell Hardness Test

The ASTM D785 testing procedure was adopted for the test in which the specimens had a minimum constant thickness of 6.4 mm. Procedure A under D785 was used to find the hardness values. The scale adopted for testing was *M* scale, which is typically used for soft bearing metals and plastics. A minor load of 10 kgf and a temporary major load of 100 kgf was applied by a 1/4″ diameter steel ball indenter.

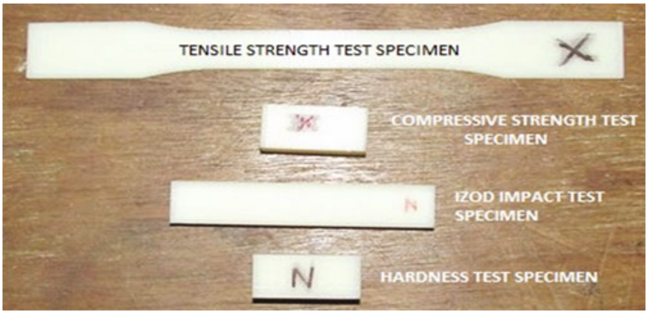

Fig. 6 Test samples used in the experiment

The 12.7 mm × 25.4 mm face was indented for both build orientations. For *Z* orientation, all such faces are identical. For *X* orientation, the indentation was made on the hatched face (parallel to the part building direction). The minor load was applied for 10 s and the major load application time was set to 15 s. Although the specimens were built identical to the compressive test specimens which had a thickness of 12.7 mm (greater than the standard of 6.4 mm), tests were performed separately. A total of five samples were made for each build orientation (Fig. 6).

4 Results

4.1 Tensile Test

Five samples of each orientation were tested for their tensile strength . Tables 2 and 3 show the results of the experiments conducted on *X* and *Z* orientation, respectively.

From the results, it can be examined that the *X* orientation demonstrates a greater value of ultimate tensile strength as compared to the *Z* orientation. The tensile strength obtained for injection-molded ABS P400 by Sung-hoon Ahn et al. was

Table 2 Tensile test results for the horizontal orientation samples

Sample No.	Width (mm)	Thickness (mm)	Failing load (kN)	Ultimate tensile strength (MPa)
X1	12.73	3.12	0.73	18
X2	13.12	3.17	0.83	20
X3	12.82	3.31	0.72	17
X4	12.85	3.22	0.78	19
X5	13.07	3.22	0.80	19

Avg. Ult. tensile strength (S_{ut}) = 19 MPa
Standard Deviation (s) = 1.1

Table 3 Tensile test results for the vertical orientation samples

Sample No.	Width (mm)	Thickness (mm)	Failing load (kN)	Ultimate tensile strength (MPa)
Z1	12.67	2.93	0.56	15
Z2	12.98	3.32	0.56	13
Z3	13.21	3.36	0.58	13
Z4	12.84	2.91	0.56	15
Z5	13.28	3.05	0.59	15

Avg. Ult. Tensile strength (S'_{ut}) = 14 MPa
Standard Deviation (s) = 1.1

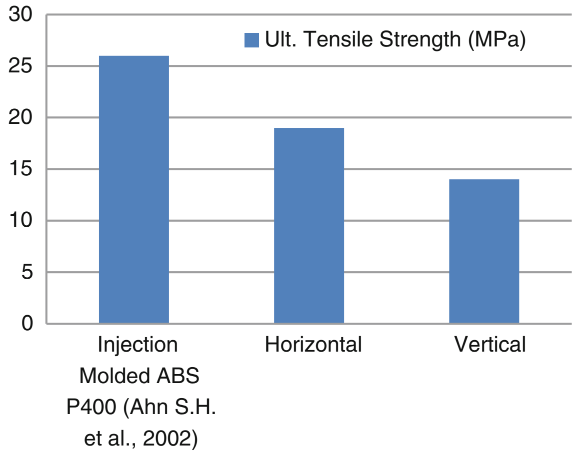

Fig. 7 Comparison of the Ult. tensile strength values

26 MPa [5]. We can note that the tensile strength of the oriented parts made by FDM is lesser than that of injection-molded P400 part. The difference can be observed from the chart in Fig. 7.

This difference in the values between the two orientations can be explained by the arrangement of layers in the prototypes. From Fig. 3, it can be seen that the layers in the horizontal orientation are arranged parallel to the applied load during the tensile test. On the contrary, the layers in the vertical orientation are stacked one above the other, i.e. perpendicular to the applied load. This makes the vertical orientation more vulnerable to fracture during the test. The horizontal specimens showed tensile failure of individual fibers resulting in higher tensile strength. The vertical specimens, however, resulted in lower tensile strength because the tensile load was taken by the bond between the fibers, and not the fibers themselves. The macroscopic view of six fractured specimens is presented in Fig. 8.

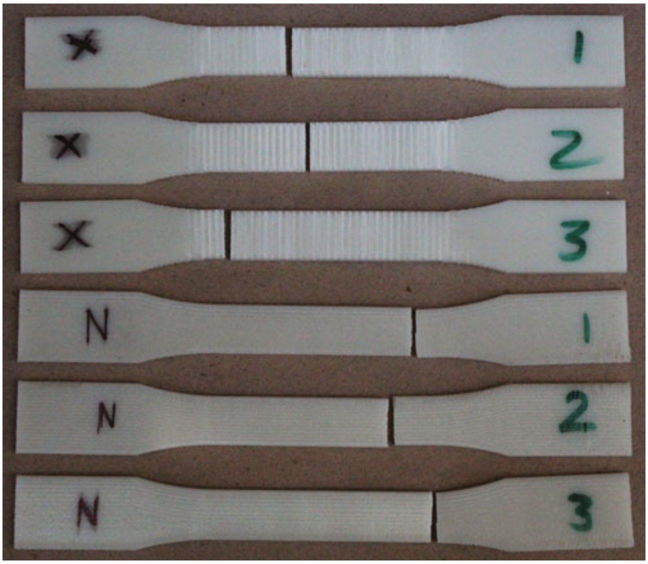

Fig. 8 Failure pattern of the fractured test samples

Table 4 Compressive test results for the horizontal orientation Samples

Sample No.	Length (mm)	Width (mm)	Failing load (kN)	Compressive strength (MPa)
X1	12.82	12.71	5.40	33.1
X2	12.80	12.67	5.24	32.3
X3	12.75	12.87	5.40	32.9
X4	12.68	12.65	5.32	33.2
X5	12.75	12.81	5.41	33.1

Avg. compressive strength = 32.9 MPa
Standard Deviation (s) = 0.36

4.2 Compressive Test

Five samples of each orientation were tested for their compressive strength. Tables 4 and 5 show the results of the experiments conducted on *X* and *Z* orientation respectively.

From the results, it can be seen that the vertical orientation demonstrates a higher value of compressive strength as compared to the horizontal orientation. This difference can be observed from the chart in Fig. 9.

It can be seen from the test results that the average compressive strength of the vertical specimens is higher than that of the horizontal specimens. Also, the compressive strength of typical bulk ABS ranges from 65 to 90 MPa [24]. So we can

Table 5 Compressive test results for the vertical orientation samples

Sample No.	Length (mm)	Width (mm)	Failing load (kN)	Compressive strength (MPa)
Z1	12.85	12.77	8.28	50.5
Z2	12.68	12.82	7.78	47.8
Z3	12.62	12.74	8.54	53.1
Z4	12.83	12.70	8.13	49.9
Z5	12.74	12.71	7.99	49.4

Avg. compressive strength = 50.1 MPa
Standard Deviation (s) = 1.9

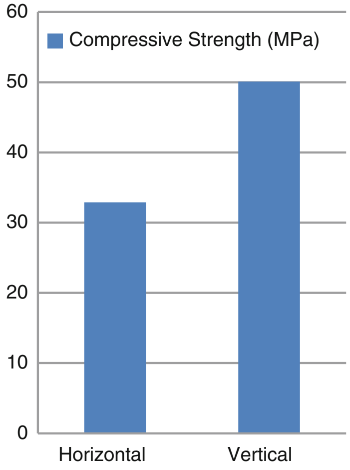

Fig. 9 Comparison of the compressive strength values

infer that the oriented parts made by FDM have lower compressive strengths as compared to bulk ABS. The difference in strengths of the two orientations can be attributed to the slender and long geometries involved in the horizontal samples, which resulted in a higher probability of buckling of individual layers. On the contrary, the layers in the vertical specimens are arranged perpendicular to the applied compressive load, resulting in a higher compressive strength.

Figure 9 shows higher compressive strengths compared to the tensile strengths shown in Fig. 7. Bulk ABS materials and polymers often show a greater compressive strength [24].

The macroscopic view of some of the tested specimens is presented in Fig. 10. It can be noticed that although the *X* orientation parts have shown near homogenous compression during the test, the *Z* orientation parts showed barreling and shear compression pattern to a greater extent.

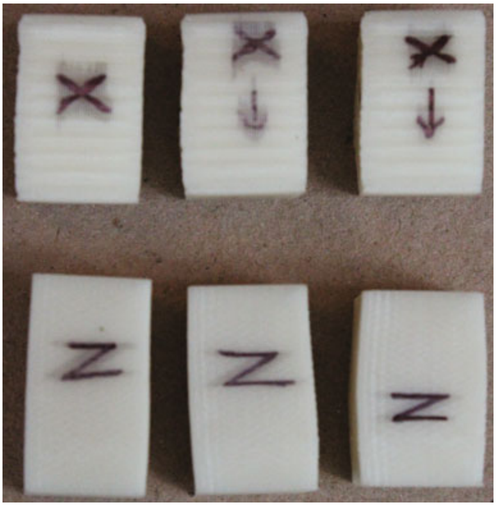

Fig. 10 Failure pattern of the tested samples

4.3 Izod Impact Test

Unnotched Izod Impact Test is a standard test for determining a material's resistance to impact. A pendulum held at a height is released to hit a sample. On impact, the specimen either breaks or the pendulum rests on the sample. Izod impact is the energy that is required to initiate fracture, and continue the fracture until the sample breaks. A material's impact resistance indicates its ability to absorb applied energy. It can also be inferred that more is a material's impact resistance; more will be its overall toughness. Theoretically, the value of impact energy can be calculated by the Eq. (1) below:

$$E = mg\,(h_{\mathrm{i}} - h_{\mathrm{f}}) \tag{1}$$

where E = Absorbed energy, m is the mass of the hitting pendulum bob, g is the acceleration due to gravity, h_0 is the initial height of the pendulum, and h_{f} is the final height of the pendulum.

The impact resistance in turn is calculated from the Eq. (2) given.

$$S = \frac{E}{t} \tag{2}$$

where S is the Impact resistance in J/m, and t is the thickness of the specimen in meters.

Five specimens were tested for their impact resistance in a Cantilever Beam Impact machine. Failure pattern C (Complete Break) was observed in each experimental run. Tables 6 and 7 show the results of the impact test conducted on X and Z orientation, respectively.

Table 6 Impact test results for the horizontal orientation specimens

Sample No.	Thickness (mm)	Absorbed energy (J)	Impact resistance (J/m)
X1	6.31	1.19	189
X2	6.38	1.27	199
X3	6.46	1.37	212
X4	6.42	1.32	206
X5	6.37	1.25	196

Avg. impact resistance = 200 J/m
Standard Deviation (s) = 8.9

Table 7 Impact test results for the vertical orientation specimens

Sample No.	Thickness (mm)	Absorbed energy (J)	Impact resistance (J/m)
Z1	6.52	0.69	106
Z2	6.47	0.78	121
Z3	6.32	0.59	93
Z4	6.30	0.63	100
Z5	6.39	0.69	108

Avg. impact resistance = 106 J/m
Standard Deviation (s) = 10

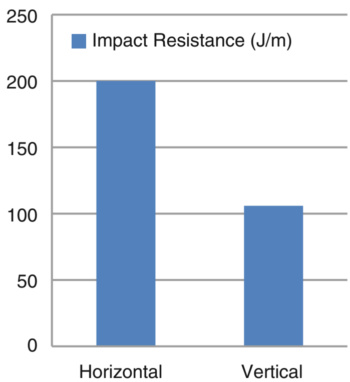

Fig. 11 Comparison of the impact resistance values

From the results, it can be inferred that the horizontal orientation indicates a higher value of impact resistance and thus absorbs more energy until fracture as compared to the vertical orientation. As impact resistance is a measure of the toughness of the material, we can say that the *X* orientation produces tougher parts than the *Z* orientation. The difference can be observed from the chart in Fig. 11.

The macroscopic view of some of the tested specimens is presented in Fig. 12.

Fractured specimens of both the orientation were studied under the JEOL JSM-5600 SEM. Figure 13 shows the magnified views of the fractured surfaces of the specimens tested for their impact resistance.

Fig. 12 Failure pattern of the fractured test samples

By analyzing the SEM pictures, it can be inferred that the horizontal specimens showed failure of individual fibers resulting in higher impact resistance among the two orientations. The vertical specimens resulted in lower impact resistance because of the weaker bond between individual layers.

4.4 Rockwell Hardness Test

Hardness is basically the resistance of a material to plastic deformation. Rockwell hardness number is a value that is based on the permanent increase in the depth of penetration on a material, when a major load on an indenter is applied and then removed alongside a constant minor load. Hardness numbers have no units and are given in various scales depending upon the material to be tested. This is basically a macroindentation test in which higher numbers in same scale indicate harder materials.

Five samples were tested in the Rockwell hardness testing machine using the *M* scale of hardness. All readings were taken 15 s after the removal of major load. Tables 8 and 9 show the results of the hardness test conducted on *X* and *Z* orientation, respectively.

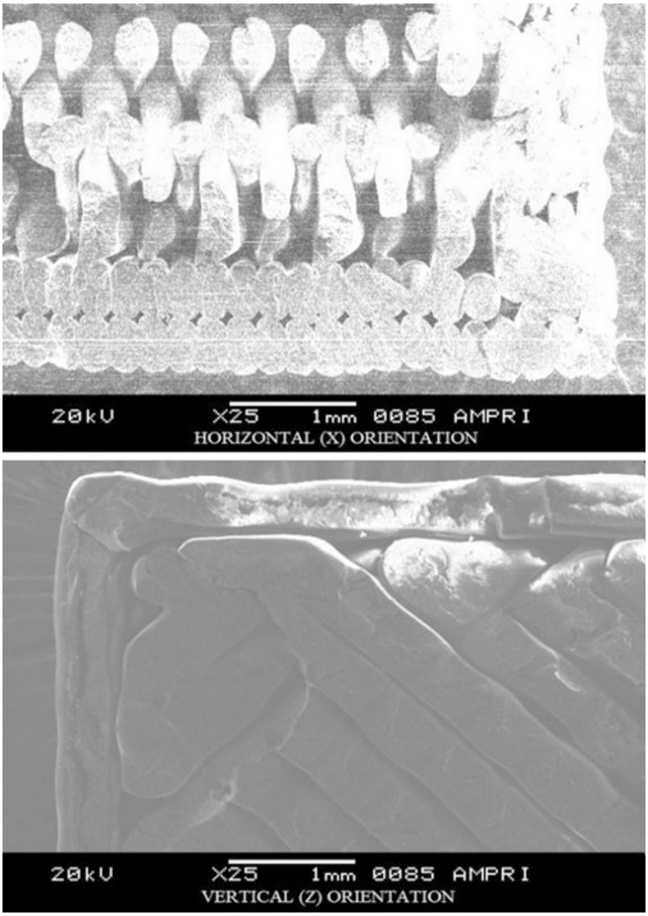

Fig. 13 Scanning electron microscope (SEM) pictures of the fractured horizontal and vertical specimens

Table 8 Hardness test results for the horizontal orientation samples

Sample no.	Hardness no. (M scale)
X1	30
X2	26
X3	32
X4	30
X5	27

Avg. hardness number = 29 HRM
Standard Deviation (s) = 2.4

Table 9 Hardness test results for the vertical orientation samples

Sample no.	Hardness no. (M scale)
Z1	52
Z2	42
Z3	48
Z4	50
Z5	45

Avg. hardness number = 47 HRM
Standard Deviation (s) = 4.0

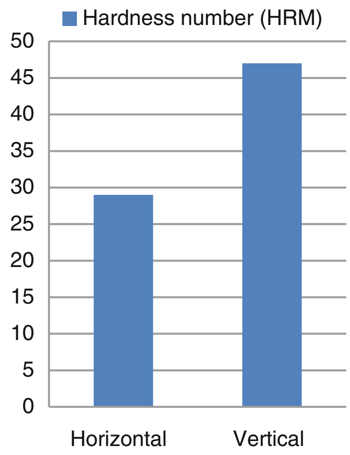

Fig. 14 Comparison of the hardness values

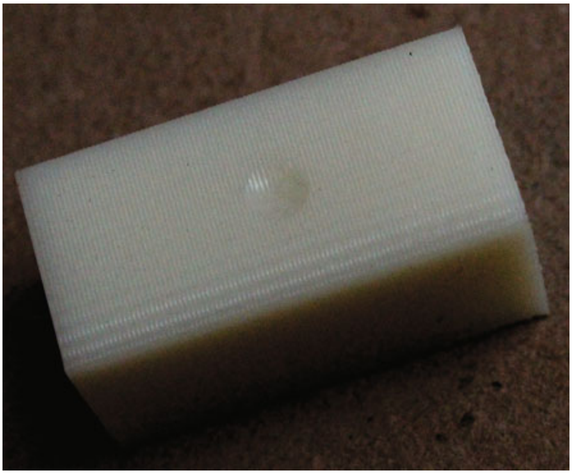

Fig. 15 Failure pattern of an indented *Z* orientation test sample

From the results, it can be examined that the vertical orientation indicates a higher value of hardness number as compared to the horizontal orientation. The difference can be observed from the chart in Fig. 14.

The macroscopic view of a tested specimen is presented in Fig. 15.

5 Conclusion and Future Work

The present paper studies in detail the effect of build orientation on the mechanical properties of ABS P400 FDM parts. The following conclusions may be drawn on the basis of this research:

(a) Horizontal (*X*) build orientation produces parts with a greater tensile strength as compared to vertical (*Z*) orientation. However, these strengths are lesser than the tensile strength of injection-molded P400 ABS.
(b) Vertical (*Z*) build orientation produces parts with a greater compressive strength than horizontal orientation. These strengths are lesser than that of bulk ABS material.
(c) Horizontal orientation produces tougher parts with more impact resistance than vertical orientation.
(d) Vertical orientation produces harder parts with more resistance to plastic deformation than vertical orientation.
(e) The manufacturing of an FDM part should be done keeping the working conditions in mind. If the part would be subjected to greater tensile or impact loads, horizontal orientation should be set before giving run command to the machine. On the other hand, if the part is expected to bear more compressive loads or plastic deformation, vertical orientation should be set.
(f) Compressive strength of ABS P400 parts in any build orientation is greater than the tensile strength.

As can be seen in the Fishbone diagram in Fig. 2, there are many other process parameters that affect the properties of an FDM part, for example raster width, fill pattern, deposition speed etc. Opportunities exist to study the variation in mechanical properties with these process parameters. Also there are some mechanical properties like flexural and torsional properties which also play an important role in many operational environments. Experiments quantifying the relation of various process parameters with these properties can also be an area that can be researched.

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