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ANALYZING THE TENSILE, COMPRESSIVE, AND FLEXURAL PROPERTIES OF 3D PRINTED ABS P430 PLASTIC BASED ON PRINTING ORIENTATION USING FUSED DEPOSITION MODELING

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Abstract

To achieve the optimum functionality and mechanical properties in the AM-based parts, it is vital to fully characterize parts under static mechanical loadings (tension, compression, and flexure) that are built in different orientations. This research reports the results of the compression (ASTM standard D695), 4-point flexure (ASTM D790), and tensile (ASTM D 638 Type I) tests on the ABS plastic specimens that are designed according to the ASTM standards and are built in different orientations using the uPrint SE Plus 3D printer. This study examined the effects that printing 3D parts in different orientations (build angles) has on the mechanical properties of ABS P430 plastic. A total of 45 samples (15 tension, 15 compression, and 15 flexure) were printed in 5 orientations; 0 degrees in the XY plane, 45 degrees in the XY plane, 90 degrees in the XY plane, 45 degrees in the Z plane, and 90 degrees in the Z plane. The hypothesis was that the samples printed 0 degrees in the XY plane would be the strongest in compression and flexure, and also have the greatest modulus of elasticity. The samples printed 90 degrees in the XY plane were predicted to be the strongest in tension, having the largest tensile strength and lowest modulus of elasticity. The findings showed that printing 90 degrees in the XY plane resulted in the highest tensile strength compared to the other orientations, but not by a significant margin. Printing 0 degrees in the XY plane significantly increased the compressive and flexure strengths of the material compared to other orientations.

Introduction

As additive manufacturing is becoming an integral part of engineering processes and more parts are being printed for final use rather than prototypes, it is important to understand which build orientations give the part longevity depending on the parts specific use. This paper focuses only on Fused Deposition Modeling (FDM) as there are many more 3D printing techniques. FDM is an additive manufacturing technology commonly used for modeling, prototyping, and production applications [1]. Figure 2 shows the FDM process, laying down material in layers using plastic filament or metal wire that is unwound from a coil and supplies material to produce a part [2]. Many parts can be built in various directions and orientations to achieve the same result. Typically, 3D printed parts are built using an orientation that will use the least amount of time and material. The question is, would this affect the strength of the part being built? In order to test this, samples were designed in CAD software to be printed in 5 different orientations with respect to the X, Y, and Z-axis using ABS P430 produced by Stratasys. The samples were designed based on ASTM standards corresponding to the type of mechanical test (tension, compression, and flexure). Figure 1 displays how each tensile specimen was oriented for printing. Compression and flexure samples were also oriented in this fashion.

Build speed of the uPrint is closely related to material use. In general terms, a lesser amount of support will allow for greater build speed. Another factor affecting speed is the axis orientation. The printer can build faster across the XY plane, than it can along the Z-axis. Therefore, orienting a part so that it is 'shorter' within the modeling envelope will produce a quicker build. A model is stronger within a layer than it is across layers. Depending upon what features a part must demonstrate, it may need to be oriented in a way to have its greatest strength across a specific area [3].

Loyola Marymount University's Mechanical Engineering Department has performed research studying the effects of varying layer orientations of ABS plastic using Fused Deposition Modeling. This study focused on ABS P400, also produced by Stratasys. In the area of tensile strength, samples printed in the 0 degrees orientation were significantly stronger (ultimate/yield) than those printed in any other orientation with an average ultimate strength of 20.6 MPa. The weakest orientation observed was printed 45 degrees with an average ultimate strength of 7 MPa [4]. ABS P400 is similar to P430, so we expect to see results like those seen in Table 1.

Table 1: Tensile Properties of ABS P400 Based on Printing Orientation [4].

Sample Orientation	Ultimate MPa (ksi)	Yield MPa (ksi)
45/-45°	12.6 (1.83)	9.0 (1.31)
45/-45°	15.0 (2.17)	11.6 (1.68)
45/-45°	13.7 (1.98)	10.5 (1.52)
Average	13.7 (1.99)	10.4 (1.50)
0°	21.0 (3.04)	
0°	20.1 (2.91)	
0°	20.6 (2.98)	16.3 (2.36)
Average	20.6 (2.98)	16.3 (2.36)
45°	6.8 (0.98)	5.9 (0.85)
45°	6.4 (0.92)	6.1 (0.88)
45°	9.4 (1.36)	9.0 (1.31)
45°	5.7 (0.82)	5.5 (0.80)
Average	7.0 (1.02)	6.6 (0.96)
90°	7.0 (1.02)	4.1 (0.60)
90°	9.9 (1.43)	9.2 (1.33)
90°	8.6 (1.24)	7.7 (1.11)
90°	10.1 (1.47)	
90°	11.0 (1.59)	10.5 (1.52)
Average	9.3 (1.35)	7.9 (1.14)
45 / 0°	13.9 (2.01)	13.7 (1.99)
45 / 0°	13.9 (2.01)	12.9 (1.87)
45 / 0°	14.2 (2.06)	14.2 (2.05)
Average	14.0 (2.03)	13.6 (1.97)

In another study of the anisotropic material properties of fused deposition modeling ABS, there was not much of a difference in the compressive strengths of the samples based on build orientation. Although the compressive strength of FDM samples was higher than the tensile strength, the ultimate and yield strength was not affected much by build direction. Because of the anisotropic behavior of the parts made by the FDM process, the strength of a local area in the part depends on the direction of the beads of material (roads) relative to the loading of the part rather than the angle at which the parts were printed. Raster orientation and air gaps were most important in determining strength in the samples [5].

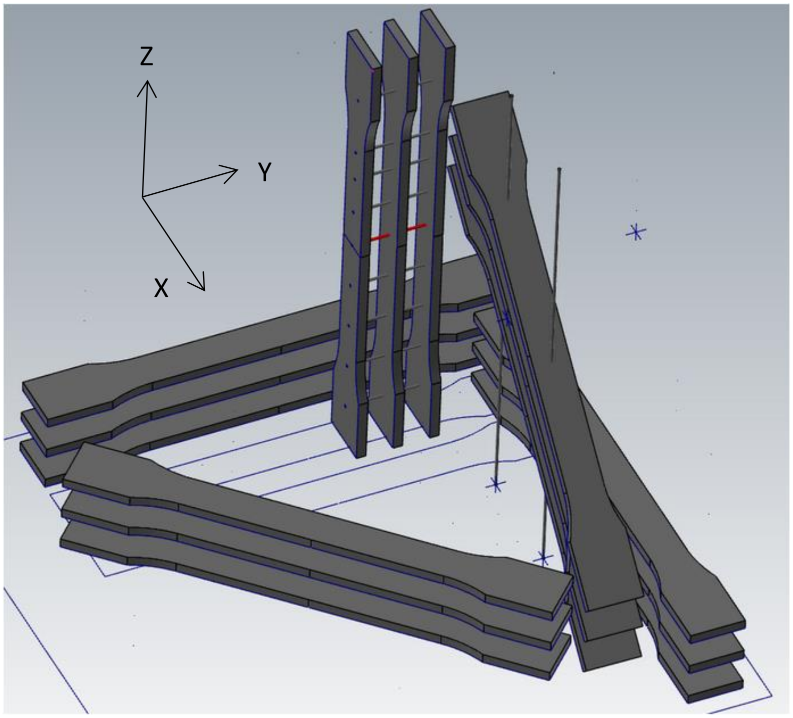


Figure 1: Specimens in various degree orientations

Methods and Materials

Printing

- 3D Printer: uPrint SE Plus
  - Model Material: ABS P430
  - Support Material: SR-30 soluble
  - Layer resolution: 0.254mm

uPrint SE Plus 3D printer has fixed parameters. Machine doesn't allow changing any parameters.

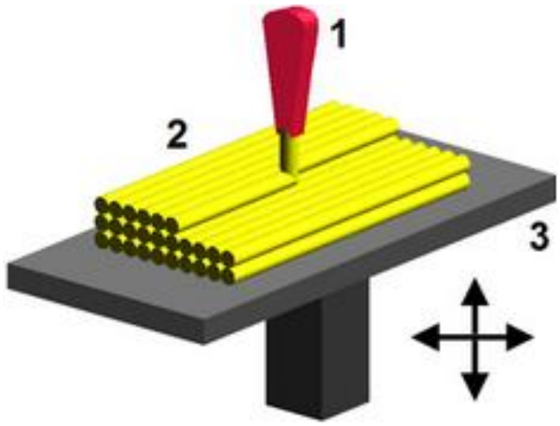


Figure 2: FDM Process [2]

Testing

Apparatus:

The apparatuses used for these experiments are as follows:

- Testing Machine: *MTS* 810 Material Test System Load Unit
- Drive Mechanism: *MTS* Hydraulic Power Unit
- Load Indicator: *MTS* FlexTest System Electronics
- Micrometers: Whitworth Digital Caliper
    - Range: 0.01-150mm
    - Resolution: 0.01mm

Figure 3: MTS Servohydraulic Test System

Test Specimens:

For tension, test specimens were manufactured according to ASTM D638. Dimensions used corresponded to Type I dogbone specimens, having an overall length of 165 mm, an overall width of 19 mm, a depth of 7 mm, a narrow width of 13 mm, a narrow length of 57 mm, a radius fillet of 76 mm, and a gage length of 50 mm [6]. According to ASTM standard D695, the specimen dimensions for unreinforced plastics in compression are a cylinder of size 12.7 mm in diameter by 25.4 mm in length [7]. As for flexure, ASTM standard D790 states the dimensions for thermoplastic materials are to be 127 mm in length, 12.7 mm in width, and 3.2 mm in depth [8].

Conditioning:

All specimens were conditioned at room temperature, approximately 24°C, at least 40 hours prior to testing. Each mechanical test was performed under similar temperature conditions to conditioning [6] [7] [8].

Number of Test Specimens:

Normally, the standard number of isotropic test specimens per sample required by all three ASTM standards is at least five. However, due to time constraints, only three specimens per sample were tested [6] [7] [8].

Speed of Testing:

The speed of each tension test was held at a constant rate of 5 mm/min [6], while the speed of each compression and flexure tests was held at a constant rate of 1.3 mm/min [7] [8], each relative to the motion of the test fixtures.

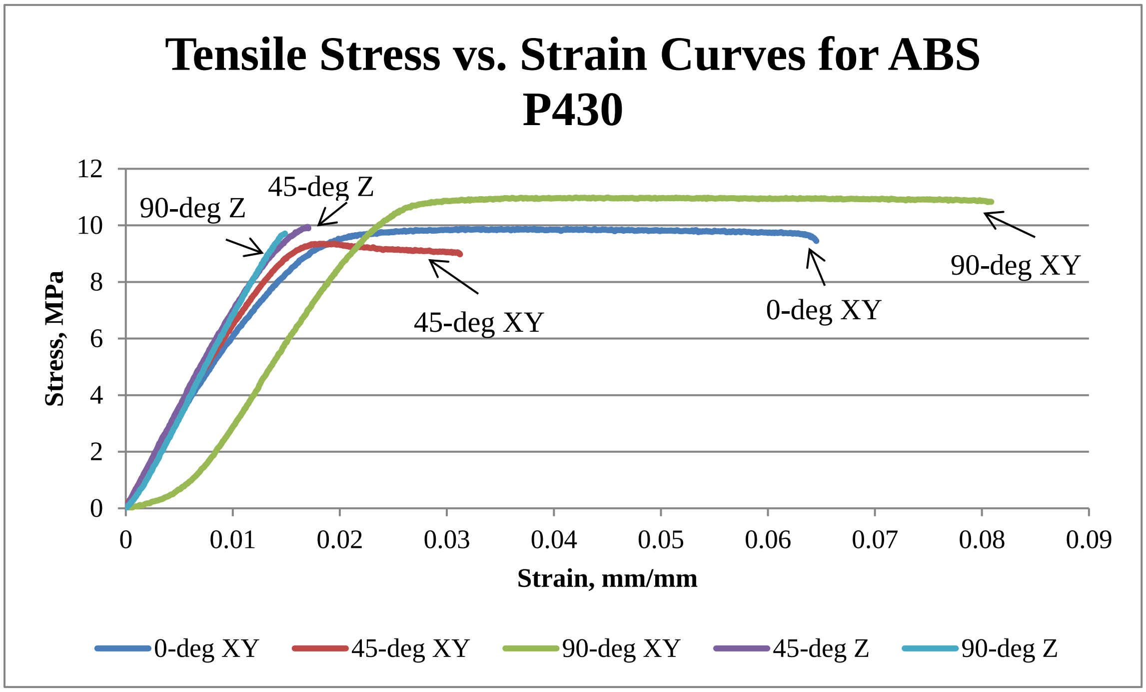
Procedure

Test specimens were modeled in MasterCAM according to their respective ASTM standards. They were then exported and printed on the u-Print SE Plus 3D printer in ABS P430. For each mechanical test, three specimens were printed for each orientation on various axes: 0 degrees in the XY plane, 45 degrees in the XY plane, 90 degrees in the XY plane, 45 degrees in the Z plane, and 90 degrees in the Z plane.

Results

Tension

Figure 4: ABS P430 FDM Tension Sample



Compression

Figure 6: ABS P430 FDM Compression Sample

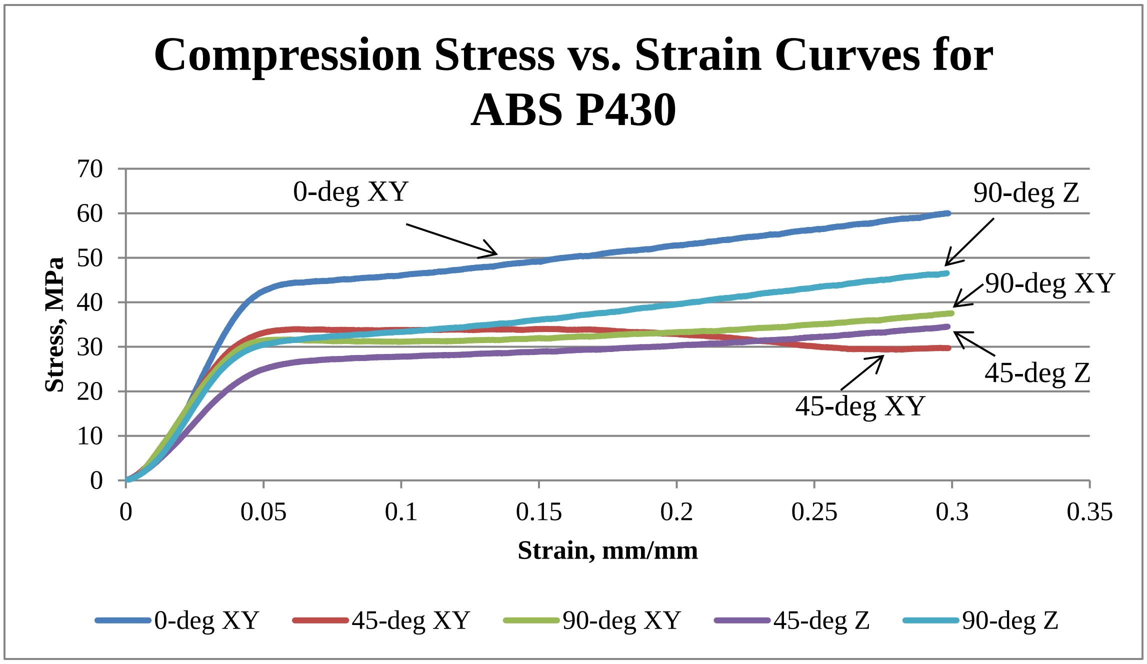


Figure 7: Compression Stress vs. Strain Curves of ABS P430 in Various Orientations

Data for the stress-strain curves are capped at a strain of approximately 30 mm/mm, roughly equivalent to an axial displacement of 7.62 mm, or 30% of the original length. This distance was decided based on the nature of ABS plastic. A preliminary test was conducted on a cylindrical sample. The sample was compressed until it was almost entirely flattened by the test fixtures. The data collected showed that there was no definite point of failure, so a cutoff point needed to be established, as seen in Figure 7 [7]. It should be noted that strain is computed as moving head displacement of moving head divided by gage length. Since no strain gages were used, strain and modulus data is only for relative comparison between various orientations.

Flexure

Flexure tests were conducted as per ASTM D790 and sample is exhibited in Figure 8. Figures 9 display load vs moving head displacement curves for various orientations. It should be noted that displacement of moving head is assumed as deflction while computing flexural modulus. Since no LVDT was used, flexural modulus data is only for relative comparison between various orientations.

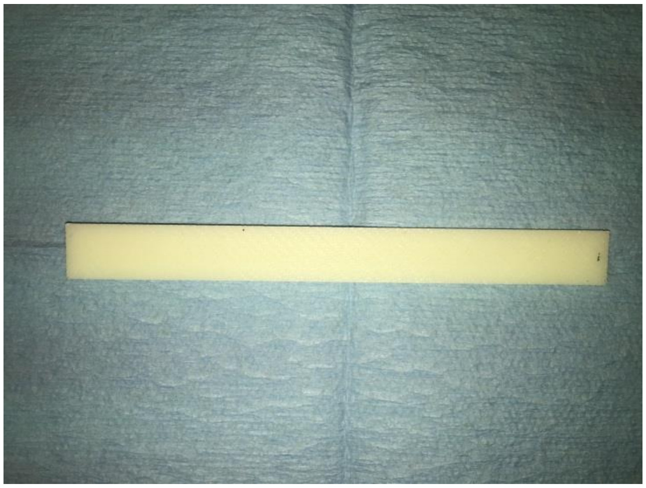


Figure 8: ABS P430 FDM Flexure Sample

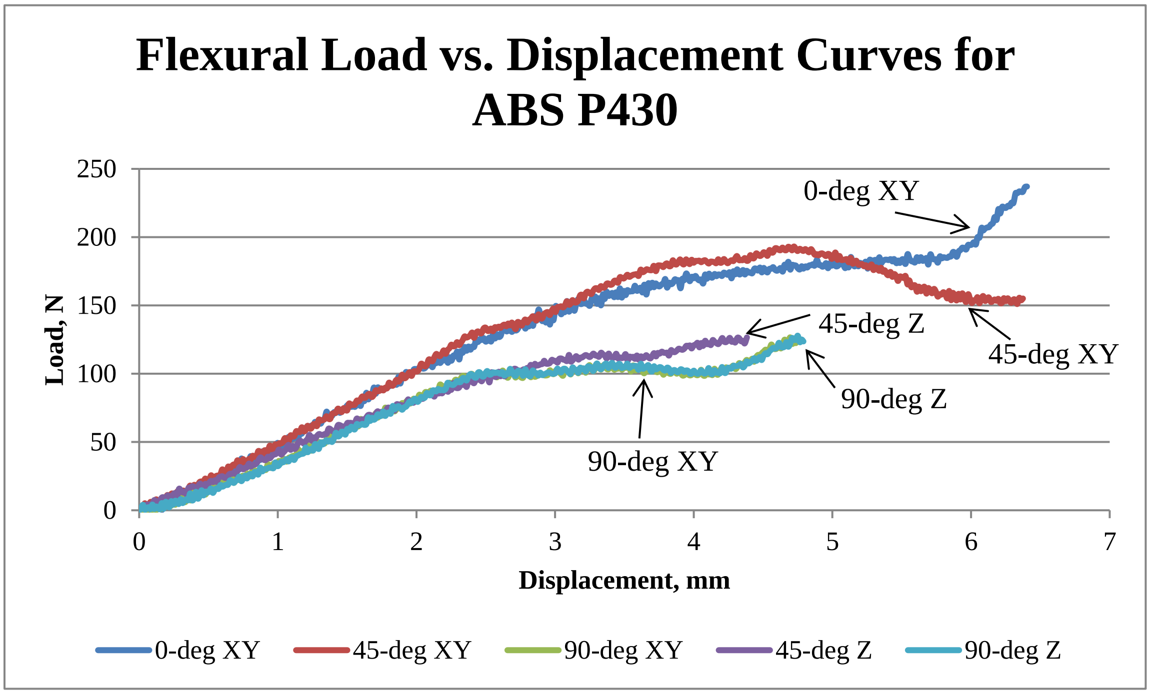


Figure 9: Flexure Load vs. Displacement Curves of ABS P430 in Various Orientations

Discussion

Table 2 indicates the tensile, compressive, and flexural test data for all categories. Values in parenthesis indicate standard deviations. Figures 10 and 11 show the strength and moduli of all five orientations, respectively. ABS P430 printed in 90 degrees in the Z plane shows the highest tensile strength of the five orientations, equaling 10.8 MPa. This orientation also has the largest percent elongation and the lowest modulus of elasticity, 6.92% and 586 MPa, respectively. However, the tensile strengths of the other four orientations fall very close to the highest tensile strength recorded. The percent difference between the largest and smallest tensile strengths was calculated to be 14.3%, a relatively small margin. According to the manufacturer, ABS P430 has a tensile strength of 37 MPa, a percent elongation of 3%, and a tensile modulus of 2320 MPa [9]. The drastic difference in values between the collected data and the manufacturer's data could be a result of a difference in printing methods or printing accuracy. Regardless, this data can still be used to compare strengths amongst the different build angles. For compression, ABS P430 printed 0-degrees in the XY plane resulted in the largest compressive strength, compressive yield strength, and modulus values, 59.3 MPa, 44.1 MPa, and 854 MPa, respectively, compared to the other orientations. There was a 67.4% difference between the highest compressive strength of 0-degrees in the XY plane (59.3 MPa) and the lowest of 45-degress in the XY plane (29.4 MPa). There is no data currently available from the manufacturer on the compressive properties of ABS P430, but from comparing the data collected from these samples to one another, 0-degrees in the XY plane appears to be the strongest overall. In flexure, ABS P430 printed 0-degrees in the XY plane resulted in a strain value of 5 mm/mm, and a flexural strength of 122 MPa, the highest of any of the orientations. ABS P430 printed 45-degrees in the XY plane resulted in a strain value of 5 mm/mm, and also a flexure modulus of 3630 MPa. The percent difference between the highest and lowest flexural strengths (122 MPa and 59.5 MPa) equaled to 69.2%, while the percent difference between the highest and lowest flexural modulus (3630 MPa and 2200 MPa) was 49.1%. According to the manufacturer's website, ABS-P430 has a flexural strength of 53 MPa, and a flexural modulus of 2250 MPa [9].

Table 2: Mechanical Properties of 3D Printed ABS P430 in Various Build Angle

Mechanical Properties of 3D Printed ABS P430 in Various Build Angles					
Build Angles	**0-deg in XY**	**45-deg in XY**	**90-deg in XY**	**45-deg in Z**	**90-deg in Z**
Tensile Strength, MPa	10.0 (0.16)	9.46 (0.84)	10.8 (0.19)	9.47 (0.44)	9.36 (0.50)
% Elongation	5.50 (0.90)	2.99 (0.26)	6.92 (1.0)	1.69 (0.04)	1.47 (0.02)
Tensile Modulus, MPa	602 (0.25)	631 (26)	586 (52)	707 (43)	737 (2.6)
Compressive Strength, MPa	59.3 (1.3)	29.4 (0.44)	37.2 (0.29)	34.2 (0.40)	45.5 (0.90)
***Compressive Modulus, MPa**	854 (0.15)	748 (0.11)	832 (0.07)	527 (0.05)	760 (0.02)
Flexural Strength, MPa	122 (1.6)	99.6 (3.1)	60.9 (10.)	59.5 (2.1)	59.8 (7.4)
***Flexural Modulus, MPa**	3410 (110)	3630 (150)	2950 (150)	2200 (45)	3100 (100)

**Note: Compressive and flexural mouli are computed to compare the performance between various orientations. These are not absolute values. Values in the parentheses indicate standard deviation.*

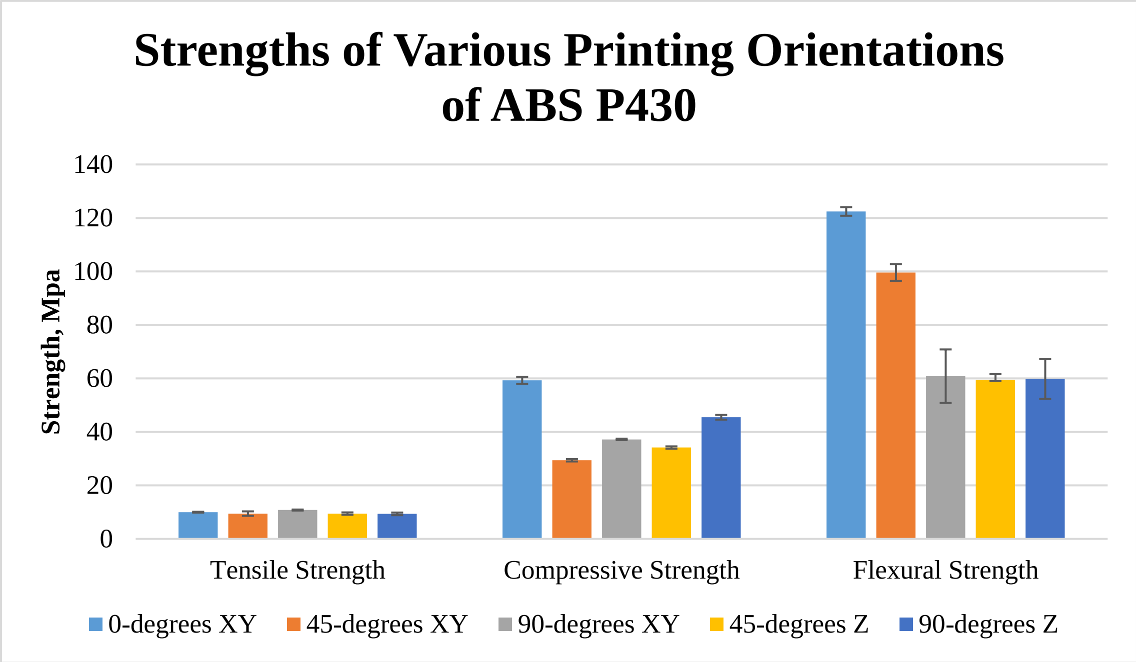


Figure 10: Strengths of Various Printing Orientations of ABS P430

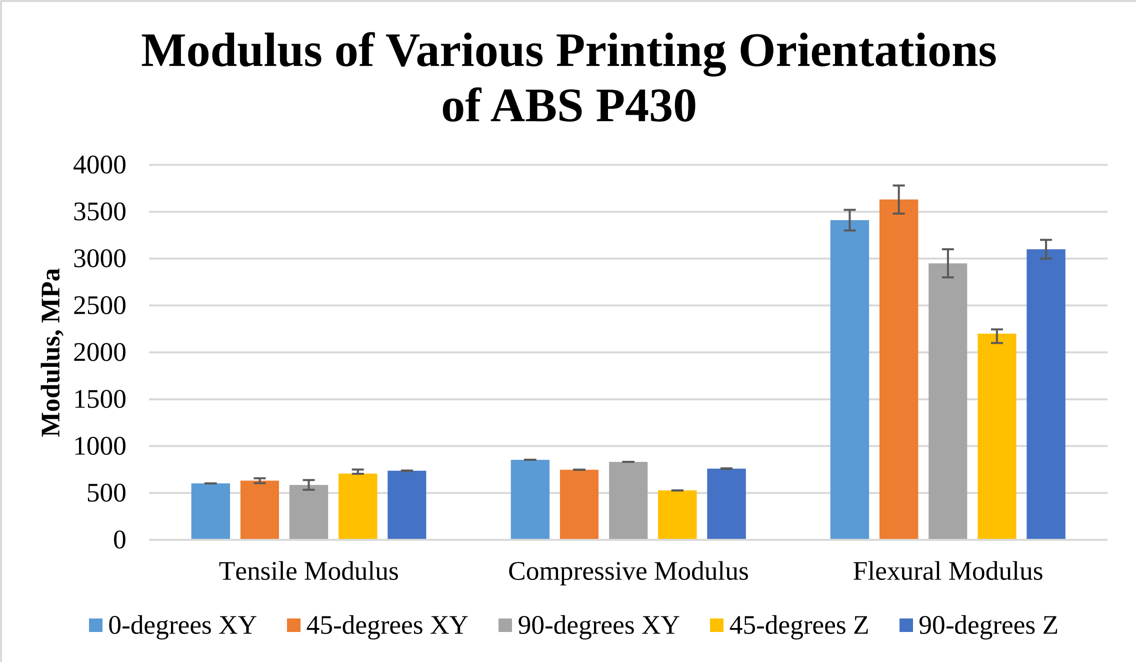


Figure 11: Modulus of Elasticity of Various Printing Orientations of ABS P430

Conclusions

It can be concludedthat there is no significant difference in tensile strength of ABS P430 when altering the orientation, with the highest and lowest values ranging from 9.36 MPa to 10.8 MPa. Although, ABS P430 90-degrees in the XY plane proved to have highest percent elongation of 6.92% but lowest tensile modulus. 90-degrees in the XY plane orientation shall provide better toughness. ABS P430 90-degrees in the Z plane had the highest tensile modulus of 737 MPa but lowest percent elongation. 90-degrees in the Z plane orientation shall provide makes material stiff but at the expense of toughness. Build angles seem to play a larger factor in the compressive and flexural properties of this material. A compressive strength of 59.3 MPa and a flexural strength of 122MPa, both orientated 0-degrees in the XY plane, were calculated to be the highest values in their respective categories.The highest compressive modulus was 854 MPa for 0-degrees in the XY plane whereas highest flexural modulus was 3630 MPafor 45-degrees in the XY plane. Depending on the application, build orientation can and does make a difference in the strength, stiffness, and toughness of the part.

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