Factors affecting ultimate tensile strength and impact toughness of 3D printed parts using fractional factorial design

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Abstract
This paper aims to investigate the mechanical properties of specimens printed by 3D open-source printers. It discusses the effect of five factors (part orientation, layer height, extrusion width, nozzle diameter, and filament temperature) on the ultimate tensile strength and the impact toughness of the 3D-printed samples. A 2⁵−¹ resolution V fractional factorial experiment was run with the 16 samples printed on a Prusa I3 MK3S in PLA. Tensile strength and impact toughness were tested using Instron 3367 and Tinius Olsen 66 testers, respectively. In analyzing the data, a normal probability plot of the effects complimented with ANOVA (Analysis Of Variance) revealed that, for both responses, only part orientation was statistically significant at \( p = 0.05 \). Regression equations were used to predict the ultimate tensile strength and the impact toughness as a function of the part orientation. Both the toughness response and the tensile strength response are maximized with horizontal part orientation. Verification experiments have been implemented to validate the adopted regression equations’ predictions under different circumstances, and the results of those experiments appear to confirm the model.

Keywords Polyactic acid (PLA) · Fused filament fabrication (FFF) · Ultimate tensile strength · Impact toughness · Fractional factorial experiment

1 Introduction
Fused filament fabrication (FFF) is an additive manufacturing technique that builds parts layer by layer using the extruded thermoplastic filament at low cost [1]. FFF parts are widely used in many fields such as food Lipton et al. [2], electronics [3], aerospace [4], and automotive [5]. The filament is heated up to a semi-solid state and extruded through a heated nozzle to form a layer that is adhered to the previously deposited layers. One of the most widely used polymers for 3D printers is polyactic acid (PLA) extracted from corn starch, cassava, and sugar. PLA has high hardness, high strength, low toxicity, and good renewability. PLA is an eco-friendly material that reduces the consumption of petroleum resources. It is generally easy to print with, odorless, readily available, and affordable. It requires less energy to print with than other materials because it has a low melting temperature [6, 7].

Despite the enormous advantages of 3D printing technology in the production of complicated parts, its use is limited due to the lack of studies on the mechanical properties of these parts. Tensile strength and Izod impact strength are well-known tests to reveal those properties. Tensile strength testing is a fundamental material science test, where a sample is subjected to a controlled, increasing tension load until failure [8]. The Izod impact strength test is an American Society for Testing and Materials (ASTM) standard method used to measure the impact resistance (toughness) of materials. Impact toughness represents the amount of energy absorbed during the fracture [9].

In recent years, some researchers reported studies regarding the mechanical properties of 3D-printed PLA parts. Tymrak et al. [10] tested different types of RepRap printers and concluded that RepRap printers have similar tensile strength as commercial printers. Bledzki et al. reported that the tensile strength of injection-molded specimens using PLA filament ranges from 30 to 63 MPa [11]. Tymrak et al.
studied the tensile strength of 3D-printed samples using ABS and PLA and reported that the average tensile strength is 28.5 MPa and 56.5 MPa for ABS- and PLA-printed samples, respectively. Tanikella et al. [12] also tested the tensile strength for vertical and diagonal part orientation for eight materials: ABS, Nylon Bridge, T-Glase, HIPS, polycarbonate, NinjaFlex, nylon 618, and SemiFlex. They concluded that the maximum tensile strength of 49.08 MPa is obtained with polycarbonate. The part orientation is reported, in the literature review, as one of the most significant factors of the tensile strength of the 3D-printed samples Liu et al. [13], [14–17]. The authors were not able to find any past studies on a Prius I3 MK3S machine, a fairly common 3D printer amongst hobbyists. Additionally, previous studies using other machines typically measure tensile strength only, not impact toughness, and do not investigate a variety of parameters that conceivably could affect the strength, such as layer height, extrusion width, nozzle diameter, and filament temperature.

1.1 Fractional factorial experiment workflow

In this paper, design of experiment (DOE) methods, specifically a fractional factorial experiment, is used to explore the effects of controllable factors on tensile strength and impact toughness of 3D-printed parts. Fractional factorials enable investigation of the effects of controllable factors on a response efficiently and at a low cost compared to some other classical designs [18]. The fractional factorial experiment is recommended over a full-factorial experiment for experiments where high-order interactions can be neglected. If the high-order interactions are negligible, information on the main effects (effect of individual factors) and low-order interactions (low order joint effect of factors) may be obtained by considering only a fraction of the original design. Thus, it solves the problem of the exponential increase of the number of experimental runs for a full-factorial experiment as the number of factors being studied increases. Based on the number of factors $k$ in the fractional factorial experiment, a half fraction involves $2k - 1$ runs. For each run of our experiment, the 3D part is printed, tested using the Izod impact tester and the Tinius tensile strength tester, and the corresponding tensile strength and impact toughness values are recorded. Data recorded during the experiment is analyzed using MINITAB® software. Normal probability plots (NPPs) and Pareto plots of computed effects are used to identify the larger, potentially significant terms (main effects and two-factor interactions), and analysis of variance (ANOVA) is used to compute the statistical significance of those terms using pooled error to estimate the random error. The mathematical relation between the responses, tensile strength, and impact toughness in our experiment and their significant terms is expressed by regression equations. Finally, plots of residuals are analyzed to verify that the assumption that the random error appears normally and independently distributed is satisfied. After the main experiment is done, a verification experiment is then implemented to confirm the response is as predicted by the model [19].

1.2 Contribution

Since there is no extensive data available about the mechanical properties of parts printed by Prusa I3 MK3S and most home users lack the test equipment necessary to analyze tensile strength or impact toughness, our experiment aims to satisfy the need to study these properties. A half fractional factorial experiment involving five two-level factors is used to study their effect on the ultimate tensile strength and impact toughness of samples printed with Prusa I3 MK3S printer using PLA filament. To the authors’ knowledge, this is the first time that this Design of Experiments strategy has been used in the 3D printing field to determine the choices of the significant parameters and optimize the tensile strength and impact toughness of 3D-printed parts. The five factors considered in this experiment are part orientation, layer height, extrusion width, nozzle diameter, and filament temperature. This paper proposes a regression model to describe tensile strength and impact toughness mathematically as a function of their significant terms. Verification experiments are also implemented to validate the regression model resulting from this experiment. The remainder of this paper is organized as follows: Sect. 2 describes the test sample design, the required physical instruments, the setup of the tensile strength and the impact toughness testers, and the fractional factorial experimental design. Sect. 3 shows and analyzes the results of this experiment and presents the implementation of verification experiments to validate the prediction of the proposed regression models. Finally, Sect. 4 provides a conclusion and discusses potential future work.

2 Data and methods

2.1 Sample design

The test specimen is designed to allow the implementation of impact toughness and tensile strength testing using the same specimen. Figure 1 shows the engineering drawing of the test specimen with all dimensions in millimeters. As shown in Fig. 1, the left part of the specimen has a standard 45° notch with 1.6 mm depth including a 0.25-mm radius for Izod impact testing. This geometry results in a nominal cross-sectional area of 84 mm² for the impact section. The right part of the specimen shows a narrow section that has...
a nominal 70 mm$^2$ cross-sectional area used for the tensile testing. Solidworks is the software used to model the specimen as shown in Fig. 2 and saved as a ”.STL” file. PrusaSlicer software takes the generated STL files as an input and produces the G-code that instructed the printer to make the 3D parts. This software has been used to adjust the printer settings, such as part orientation, layer height, scan speed, extrusion width, and filament temperature.

2.2 Experimental fractional factorial design

In this investigation, a fractional factorial design was applied to evaluate the effect of the variation in part orientation (A), layer height (B), extrusion width (C), nozzle diameter (D), and filament temperature (E) on the tensile strength and impact toughness of the 3D-printed samples. Those factors are chosen based on our knowledge and experience in 3D printing in addition to literature studies. This experiment comprises five factors with the two levels represented by “−1” and “+1” for each factor. Table 1 describes the experiment’s factors and their levels in detail. This experiment tests the tensile strength and the impact toughness of each of the 16 printed samples.

The fractional factorial experimental design is a ½ fraction a full-factorial design encompassing 16 runs. Since only half of the total full-factorial runs are used in a half-fractional factorial experiment, a design generator is used to choose this fraction with some desirable properties. The desirable properties are the balance and independence between the factors. Balance in a factor refers to an equivalent number of the two levels (each factor has 8 of the two levels −1 and +1 in our experiment), whereas the independence (or orthogonality) between factors refers to having a zero dot product between any two factors as shown in Table 2. The best design generator in a half fractional factorial is that it minimizes the seriousness of the aliasing of the terms. In this experiment, the levels of the first four factors (A, B, C, and D) are constructed as a full-factorial design of those four factors (all possible combinations of them), and the last factor (E)’s levels are generated using the design generator $E = ABCD$ as shown in Table 2 to guarantee the desirable properties. This construction refers to resolution V which provides estimates of all main effects.

Fig. 1 Engineering drawing of test specimen

Fig. 2 Solidworks 3D model of test specimen
which are not aliased with any terms containing less than four factors. The resolution of an experiment identifies the degree of terms to which the main effects are aliased and is expressed with Roman letters (I, II, III, IV, V, VI,…). In resolution V designs, two-factor interactions are not aliased with main effects or other two-factor interactions but may be aliased with three-factor interactions. Based on the sparsity of effects principle, we will assume three factors and higher-order interactions are negligible.

### 2.3 Test setup

The required physical elements to run this experiment are a FFF 3D printer, PLA material, an Izod impact tester, an Instron tensile tester, and calipers for gauging the actual dimensions for the tested samples. Additionally, MINITAB® software was used in the analysis of the data. All machines used in this paper are provided by the University of Detroit Mercy (UDM), MI, USA. Original Prusa i3 MK3S (Fig. 3) is the FFF 3D printer model used to print all the test samples in this experiment. The precision (tolerance) of an original Prusa printer is 0.1 mm on the Z-axis and 0.3 mm on X and Y. The Instron 3367 tensile testing machine, shown in Fig. 4, has been used to perform tensile tests in this experiment. This machine was equipped with a 20 KN load cell to measure the tensile strength of the 3D-printed parts. The measurement data was controlled, monitored, and recorded using “Series IX/s” Instron software. The Tinius Olsen 66, shown in Fig. 5, has been used to implement the impact toughness test in this experiment. It has a pivoting arm that is raised to a specific height to maintain constant potential energy and then released to hit and break a notched sample. The angle to which the arm swings is indicative of energy lost in breaking the specimen which represents the impact resistance. All of the weights that can be attached to the pendulum of the impact toughness testing machine were removed, thereby maximizing the sensitivity of the device; the maximum readings obtained were below the full-scale capacity at this sensitivity.

### Table 1 Factors and its experimental levels

| Factors          | Description                                                                 | Levels               |
|------------------|------------------------------------------------------------------------------|----------------------|
| Part orientation | Direction of stacked layers across the part relative to the part geometry   | Horizontal, Vertical |
| Layer height     | Height of the layer (step) that is stacked to form the part                  | 0.15 mm, 0.25 mm     |
| Extrusion width  | Width of the line extruded by the printer that forms the layers of the part. | 100%, 150%           |
| Nozzle diameter  | Diameter of orifice of the printer nozzle                                   | 0.4 mm, 0.6 mm       |
| Filament temperature | Temperature of the filament while passing through the extruder nozzle | 208 °C, 217 °C       |

### Table 2 Experimental fractional factorial design matrix

| Std order | Run order | A  | B  | C  | D  | E  | Tensile strength (MPa) | Toughness (J/m²) |
|-----------|-----------|----|----|----|----|----|------------------------|------------------|
| 1         | 12        | 1  | 1  | 1  | 1  | 1  | 25.61                  | 1954.56          |
| 2         | 15        | 1  | 1  | 1  | −1 | −1 | 24.33                  | 3132.20          |
| 3         | 14        | 1  | 1  | −1 | 1  | −1 | 22.94                  | 2006.74          |
| 4         | 10        | 1  | 1  | −1 | −1 |−1 | 13.57                  | 1625.03          |
| 5         | 7         | 1  | −1 | 1  | 1  | −1 | 27.66                  | 2948.46          |
| 6         | 16        | 1  | −1 | 1  | −1 |−1 | 23.10                  | 2146.78          |
| 7         | 5         | 1  | −1 |−1  | 1  | 1  | 21.70                  | 2336.96          |
| 8         | 6         | 1  | −1 |−1  |−1 | 1  | 29.34                  | 1448.65          |
| 9         | 13        | −1 | 1  | 1  |−1 | 1  | 56.89                  | 9997.24          |
| 10        | 8         | −1 | 1  | −1 |−1 | 1  | 55.04                  | 6338.50          |
| 11        | 3         | −1 |−1  | 1  | 1  | −1 | 51.78                  | 6278.17          |
| 12        | 9         | −1 |−1  | 1  |−1 |−1 | 59.83                  | 5481.66          |
| 13        | 11        |−1  |−1  | 1  | 1  | 1  | 65.49                  | 7302.59          |
| 14        | 1         |−1  |−1  |−1 |−1 | 1  | 47.67                  | 10,286.20        |
| 15        | 2         |−1  |−1  |−1 | 1  |−1 | 57.49                  | 9731.62          |
| 16        | 4         |−1  |−1  |−1 | 1  |−1 | 56.96                  | 5197.47          |
The Prusa i3 MK3S used the same "STL" file with different slicing settings to print all 16 samples in the randomized "Run Order" order shown in Table 2. Some printing settings which were not factors in this experiment were kept constant for all samples. These included 60 °C bed temperature, 100% infill percentage, and grey PLA filament material. In this experiment, the 3D parts are printed either horizontally or vertically. Figure 6 shows the difference between the horizontal and vertical printed samples. In the vertical printing of the left sample, the square base is printed first, and other layers are then accumulated vertically, whereas the sophisticated base is printed first for the horizontal right sample. The mass of every sample is measured using a scale to make sure that there is no interior under-extrusion. All samples weighed approximately 14 g which suggests that each extrusion is good.

The whole Instron machine with a close-up of a sample in the test setup clamped between the jaws of the tensile strength tester is shown in Fig. 4. The tensile strength tester, used in this experiment, applied a 20 KN tensile load on each specimen at 5 mm/min cross-head speed. The Instron tester is used to measure the maximum force that the specimen can withstand before failure in Newtons as shown in Table 3. This force is then divided by the narrow cross-sectional area to calculate the ultimate tensile strength (UTS) of each specimen. The Tinus Olsen 66 Izod impact resistance tester (Fig. 5) is used for this experiment with a pivoting arm raised to a specific height (to maintain constant potential energy) and swings down to hit and break a notched sample. The energy absorbed by the sample is measured from the height the arm swings after hitting the sample. The impactor can be configured with different weights (or no weights) to adjust the sensitivity of the device; this experiment was performed with no weights to maximize sensitivity. The impact resistance tester measures inch-pounds (energy) absorbed by breaking the specimen at the notched
cross-sectional area. Toughness ($J/m^2$) is then calculated by multiplying the absorbed energy (in-lbs) by 0.112984825 to be converted into joules and then divided by the notched cross-sectional area. The recorded tensile force (N), impact resistance (in-lbs), and the printing time for each specimen are shown in Table 3. It also includes the measured length and width in millimeters of the cross-sectional area used in the tensile and notched Izod tests for each sample.

### 3 Results and discussions

Each combination of different levels of factors is used to set up the 3D printer to print the 16 samples. Each 3D-printed sample is then exposed to the Izod impact test using the Tinius Olsen tester followed by the tensile strength test using Instron tester in this experiment. The 3D-printed samples’ tensile strength was tested using

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**Fig. 5** Tinius Olsen Izod impact tester

**Fig. 6** Vertical versus horizontal orientation sample. Vertical orientation left, horizontal orientation right
an Instron tensile test machine with a hydraulic linear actuator and a 20 KN load cell. The impact toughness of the parts was measured using an Izod Impact testing machine. Figure 7 shows all the broken samples after the tensile strength and the impact toughness testing. Experimental data, obtained from fractional factorial design runs, were analyzed using the statistical software package MINITAB® 19.

### Table 3 Printed samples recorded measurements

| Run order | Print time (min) | Tensile cross section | Impact cross section | Tensile force (N) | Impact resistance (in-lbs) |
|-----------|------------------|-----------------------|----------------------|-------------------|----------------------------|
|           |                  | Length (mm)           | Width (mm)           | Length (mm)      | Width (mm)                |
| 12        | 71               | 9.83                  | 6.88                 | 9.81              | 8.57                      | 1732                      | 1.4                       |
| 15        | 106              | 9.95                  | 6.97                 | 9.98              | 8.79                      | 1687                      | 2.2                       |
| 14        | 106              | 9.93                  | 6.98                 | 10.07             | 8.61                      | 1590                      | 1.45                      |
| 10        | 163              | 10.03                 | 7.04                 | 10.06             | 8.6                       | 958                       | 1.15                      |
| 7         | 114              | 9.76                  | 6.85                 | 9.87              | 8.58                      | 1849                      | 2.05                      |
| 16        | 171              | 9.86                  | 6.87                 | 10                | 8.8                       | 1565                      | 1.5                       |
| 5         | 171              | 9.92                  | 6.94                 | 9.93              | 8.52                      | 1494                      | 1.6                       |
| 6         | 258              | 9.95                  | 6.98                 | 10.02             | 8.43                      | 2038                      | 1.05                      |
| 13        | 30               | 9.98                  | 7.05                 | 10.11             | 8.7                       | 4003                      | 7.25                      |
| 8         | 47               | 9.95                  | 7.29                 | 9.99              | 8.84                      | 3992                      | 4.8                       |
| 3         | 74               | 9.98                  | 6.92                 | 9.97              | 8.59                      | 3940                      | 4.5                       |
| 9         | 68               | 9.97                  | 7.12                 | 10.05             | 8.81                      | 4247                      | 3.9                       |
| 11        | 50               | 10.06                 | 6.95                 | 10.23             | 8.66                      | 4579                      | 5.25                      |
| 1         | 45               | 9.88                  | 6.91                 | 9.89              | 8.79                      | 4144                      | 7.75                      |
| 2         | 71               | 9.96                  | 6.9                  | 9.99              | 8.69                      | 3951                      | 7                         |
| 4         | 107              | 10.04                 | 7.01                 | 10.03             | 8.71                      | 4009                      | 3.72                      |

**Fig. 7** All test samples after the tensile strength and toughness testing
The ultimate tensile strength (UTS) is defined as the maximum tensile load a part can withstand before failure divided by its cross-sectional area. During the tensile test, 16 specimens have been stretched until failure and their corresponding data are recorded in Table 3. The tensile strength (MPa) of each part was calculated with Microsoft Excel based on the recorded tensile values and measured dimensions included in Table 3, and the results are shown in Table 2. Because a single replicate (one experiment with 16 runs) of a fractional factorial provides no direct measure of the error to perform ANOVA directly, normal probability plot (NPP) and Pareto plots of the effects are used to reveal the larger, likely significant effects. Significant terms are the terms that deviate from the straight line near the center of the normal effects plot or exceed the threshold in the Pareto chart. The theory is that the insignificant terms will be normally distributed based on the central limit theorem, and hence, only terms deviating from that normal trend are likely significant. Part orientation is the only term that appears likely significant based on the NPP of effects shown in Fig. 8a, and it is also the only term that exceeds the threshold in the Pareto chart as shown in Fig. 9a. Based on the NPP of effects and Pareto chart, part orientation (A) is the only significant factor at 5% significance level for the ultimate tensile strength.

Analysis of variance (ANOVA) indicates how likely it is that the obtained results happened by random chance. If the $p$-value of a term is less than the significance level, the term will be significant (the probability that effect would have occurred by random chance would be the $p$-value). The $p$-value of a term is calculated based on

![Fig. 8 Normal Probability Plot for a UTS’s effect and b impact toughness’s effect](image)

![Fig. 9 Pareto chart of a ultimate tensile strength and b impact toughness](image)
the F-distribution value computed by the division of the adjusted mean square of the term over the adjusted mean square of error. Adjusted mean squares (Adj MS) are computed by the division of “Adj SS” over the degrees of freedom. The degree of freedom is “1” for all terms in a half fractional experiment with two levels. Since this experiment involved only one replicate, there is no direct measure of error, but the apparently insignificant terms based on the aforementioned plots can be lumped together to provide an estimate of error. This estimate of error is referred to as pooled error. ANOVA of the UTS, included in Table 4, shows that part orientation factor (A) is significant and with the confidence of virtually 100% affects tensile strength since its p-value is virtually zero, assuming all apparently insignificant effects represent the error. The regression equation of the UTS (Y1) is shown in Eq. (1) where the constant term is the average of values in column “Tensile Strength (MPa)” and the effect of factor A is the average of the product of values in column “A” by values in column Tensile Strength (MPa) in Table 2. Based on this equation, the maximum value of ultimate tensile strength (UTS) is 56.39 MPa, obtained for horizontal part orientation (A = −1). This result confirms those reported for PLA [10].

\[ Y1 = 39.96 - 16.43 \times A \]  

(1)

ANOVA assumes the random error of the experiment is normally and independently distributed with constant variance. Analysis of the residuals (random error terms) is used to check the assumptions. A normal probability plot of the residuals, a plot of residuals versus the fitted values, and a plot of residuals versus observation order were made and checked to make sure that the model’s assumptions are satisfied. The normal probability plot of the residuals (Fig. 10) shows that the error distribution is approximately normal as residuals are adjusted to an approximately straight line. The plot of residuals versus the fitted values of the UTS (Fig. 11a) shows no pattern, thereby indicating that independence of the residuals seems reasonable. The plot of residuals versus observation order (Fig. 11b) reveals nothing unexpected affected residuals over time (run order).

### 3.2 Impact toughness data analysis

Material’s toughness measures a material’s ability to absorb energy and plastically deform without fracturing. Part orientation (A) is the only significant factor for impact toughness depending on the normal probability plot (NPP) of effects in Fig. 8b and Pareto chart in Fig. 9b with a 5% significance level. The regression equation of impact toughness Y2 is Eq. (2) with constant term and effect of factor A computed in the same way as tensile strength analysis. The maximum

![Fig. 10 Normal Probability Plot for UTS’s residuals](image)
toughness of the 3D-printed part (7576 J/m²) occurs at \(A = -1\) (horizontal part orientation).

\[ Y^2 = 4888 - 2688 \ast A \]  

(2)

From the analysis of variance of the impact toughness of the 3D-printed samples, pooling insignificant terms to error, shown in Table 5, part orientation is statistically significant at 95% confidence as the \(p\)-value is less than 1.5. Residual analysis is done to ensure that the error is normally and independently distributed with constant variance. NPP of residuals in Fig. 12 shows a roughly linear trend, indicating that the residuals can be considered to be normally distributed. The plot of residuals of the toughness versus the fitted values (Fig. 13a) shows no relationship between the size of the residuals and the fitted values indicating that we can assume independence and constant variance. The plot of the impact toughness’s residuals versus observation order (Fig. 13b) does not show any concern about unexpected issues that may affect the validity of the results.

### 3.3 Verification experiments

Two nominally identical specimens for the two verification experimental runs are built resulting in four test specimens, two for the vertical part orientation and the other two for the horizontal part orientation. Those four samples were used to validate the model’s prediction for the ultimate tensile strength and material toughness for an unseen 3D-printed specimen. Repetition was used to decrease error variance and to avoid possibly missing data due to periodic unexpected problems in the tensile tester. Sometimes, the tensile strength tester suffers from a sudden increase in tensile load resulting in breaking the sample without recording the associated load. This problem prevented one of the two vertical verification samples from being included as its associated value was not recorded. The response (recorded value) is the average of the two recorded measurements for each experimental run.

The standard order of each experiment and the measurements of length and width in millimeters for the tensile and impact cross-sectional area are recorded in Table 6. Each sample is subjected to the Izod impact test to measure the impact resistance followed by the tensile test to measure the tensile force with “run” order, and experimental data is shown in Table 6. Similar to the main experiment, the tensile force and the impact resistance are used to calculate the ultimate tensile strength and the material impact toughness, respectively. The average of values is obtained by practical tensile strength and toughness testing of the two specimens as shown in Tables 7 and 8, respectively. The regression Eqs. (1 and 2) are then used to predict the tensile strength and the impact toughness associated with the specific orientation as shown in the “Model predicted value” column in Tables 7 and 8, respectively. The standard deviation obtained from MINITAB® analysis is used to calculate the low and high limits of the model-predicted values. The low and high limits are calculated by the subtraction and addition of the standard deviation value from the model-predicted value, respectively.

### Table 5 Analysis of variance (ANOVA) for impact toughness

| Source  | DF | Adj SS     | Adj MS     | F-value | P-value |
|---------|----|------------|------------|---------|---------|
| Model   | 1  | 115,638,228| 115,638,228| 48.14   | 0.000   |
| Linear  | 1  | 115,638,228| 115,638,228| 48.14   | 0.000   |
| A       | 1  | 115,638,228| 115,638,228| 48.14   | 0.000   |
| Error   | 14 | 33,631,941 | 2,402,281  |         |         |
| Total   | 15 | 149,270,169|            |         |         |
Table 6  Verification experiment recorded measurements

| Std order | Run order | Tensile cross section | Impact cross section | Tensile force (N) | Impact Resistance (in-lbs) |
|-----------|-----------|-----------------------|----------------------|-------------------|--------------------------|
|           |           | Length (mm) Width (mm)| Length (mm) Width (mm)|                   |                          |
| 1         | 1         | 9.83 6.91             | 9.88 8.71            | 1739              | 1                        |
| 2         | 3         | 10.13 6.86            | 10.13 8.66           | 3943              | 5                        |
| 3         | 4         | 9.80 6.93             | 9.88 8.69            | Fail              | 1                        |
| 4         | 2         | 10.03 6.90            | 10.11 8.79           | 3909              | 6                        |

Table 7  Tensile strength verification experimental data

| Part orientation | Recorded value (MPa) | Model predicted value (MPa) | Standard deviation (MPa) | Low limit (MPa) | High limit (MPa) |
|------------------|----------------------|----------------------------|--------------------------|-----------------|-----------------|
| Vertical         | 25.61                | 23.53                      | 5.03                     | 18.5            | 28.56           |
| Horizontal       | 56.61                | 56.39                      | 51.36                    | 61.42           |                 |
The summarized verification results for the tensile strength and the impact toughness models are shown in Tables 7 and 8, respectively.

The lab measurements lie between the low and high limits of the predicted values by the models for the tensile strength and the material toughness. For example, the average UTS obtained by the verification experiment for horizontal part orientation (56.61 MPa) is only 0.39% greater than the predicted value (56.39 MPa) in Table 7 and well within ±2 error standard deviations. These results confirm the effectiveness of regression equations to predict experimental results accurately and enhance its validation to predict the ultimate tensile strength and the impact toughness for untested 3D-printed parts.

### 4 Conclusion

This experiment investigates the mechanical properties of the 3D-printed samples by implementing the tensile strength test and the Izod impact test. A fractional factorial experiment with five process factors was implemented. Based on the experimental results, the only significant factor identified in this experiment is part orientation. Those results emphasize the fact that to get a significant change in the tensile strength or toughness of a 3D-printed sample, there is no need to change nozzle diameter, layer size, extrusion width, or filament temperature, just change part orientation. The other parameters may be chosen to minimize the print time with no effect on the tensile strength or impact toughness. Higher tensile strength and impact toughness have been obtained at horizontal part orientation irrespective of the level of the other four process factors. 3D parts printed with horizontal part orientation also take less time than vertical ones. Verification experiments are implemented in the same procedure as the main experiment with an untested combination of factors’ levels. The recorded values of verification experiments for the tensile strength and impact toughness model lie within the standard deviation of the predicted values. The reliability of the obtained regression equations was validated by comparing the established experimentally UTS and impact toughness with the corresponding predicted values. This proves the effectiveness of the model regression equations and confirms that the model can predict correctly the response for future 3D-printed parts under similar conditions.

This preliminary study has some limitations. There was a minimal error introduced by the oversized (20 KN) load cell used in the tensile strength tester. The 20 KN load cell used in the tensile tester has not had a verified calibration, and the average maximum tensile force measured with this cell for the 16 samples was 2861 N. This average value is within the generally accepted 10 to 90% of the nominal rating minimum accurate range of the 20 KN load cell (greater than 2000 N), but 7 of the 16 responses were measured to be below the 2000 N threshold. Thus, a 5 KN load cell would be recommended for follow-on work.

In a future study, calibration across the expected range of the load cell should be done to verify its accuracy in the range of the test measurements, or another reliable measurement method should be employed in a future test. Finally, a proper gauge R&R ought to be done before such an experiment to determine how much variance is due to the measurement process rather than the simple variation in response and other noise factors.

### Availability of data and material
The data that support the findings of this study are available in Table 2.

### Code availability
Not applicable.

### Declarations

#### Ethics approval
Not applicable.

#### Consent to participate
Not applicable.

#### Consent for publication
Not applicable.

#### Conflict of interest
The authors declare no competing interests.

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