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Influence of 3D Printing FDM Process Parameters on Tensile Property of ULTEM 9085

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Abstract

3D printing is a promising digital manufacturing technique that produces parts, layer by layer. Fused deposition modeling (FDM) is a widely employed 3D printing technology that produces components by heating, extruding and depositing filaments of thermoplastic polymers. The properties of FDM-produced parts are significantly influenced by the processing parameters. These processing parameters have conflicting advantages that need to be investigated. This paper investigates the effect of process parameters on the tensile properties of components produced by FDM technique. The study is carried out on high-performance ULTEM 9085 polymeric material, by using full factorial design of experiment to analyze the effects of process parameters on the tensile properties of the material. For the investigation, five parameters – air gap, raster width, raster angle, contour number and contour width – are considered. From the investigation, it is observed that, among the considered parameters, only one parameter (raster angle) significantly influenced the tensile properties of the material.

Keywords: 3D printing; tensile strength, tensile strain;; FDM process parameters; ULTEM 9085

1. Introduction

3D printing (additive manufacturing) is a rapidly advancing digital manufacturing technique that produces parts in a layer fashion. The technology has different advantages over the conventional manufacturing techniques, including

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producing very complex geometries without any tooling, consolidated (integrated) functional parts, lattice structures and multi-material (graded materials) components [1]. Among the different types of additive manufacturing (AM) techniques, fused deposition modeling (FDM) is a process in which thermoplastic filaments are melted, extruded and deposited.

Since several processing parameters influence the mechanical properties of parts manufactured by FDM process, recent research has focused on studying these parameters. Christiyan et al. [2] investigated the effect of a few process parameters on the mechanical properties of acrylonitrile butadiene styrene (ABS) + hydrous magnesium silicate composite material and suggested that low printing speed and low layer thickness can improve the mechanical properties of the material. Chacón et al. [3] studied the effect of build orientation, layer thickness and feed rate on the tensile and flexural properties of Polylactic acid (PLA) material and concluded that upright orientation resulted in the poorest mechanical performance, whereas the edge and flat orientations resulted in the highest strength and stiffness. Ziemian et al. [4] studied the dependence of the mechanical properties of ABS parts produced by FDM on raster orientation and concluded that the mechanical properties display anisotropic behavior with the orientation of rasters and directionality of polymeric molecules. Durgun and Ertan [5] investigated the influence of different raster angles and build orientations on the surface roughness, tensile strength and flexural strength of ABSplus-P430 parts and suggested that the build orientation has a more significant effect than the raster angle on the surface roughness and mechanical behavior of the parts. Wu et al. [6] carried out an investigation into the influence of layer thickness and raster angle on the mechanical properties of Polyether ether ketone (PEEK) parts. They reported that the optimal mechanical properties were found at a layer thickness of 300 μm and a raster angle of 0º. Dawoud et al. [7] investigated the effect of raster angle and air gap on the mechanical properties of ABS materials, comparing their mechanical properties with injection-molded parts. They suggested that appropriate selection of FDM parameters could result in mechanical properties comparable to those of injection molded parts.

Akessa et al. [8] investigated the influence of process parameters – air gap, raster width and raster angle – on the tensile and flexural properties of ABS-M30. Their investigation concluded that the lower process parameter values have a significant impact on tensile and flexural properties. Onwubolu and Rayegani [9] studied the effect of five important FDM process parameters on the tensile strength of ABS samples and reported the optimal process parameters. Deng et al. [10] explored the effects of printing speed, layer thickness, printing temperature and filling ratio on the tensile properties of FDM-produced PEEK and obtained optimal process parameter combinations.

Furthermore, specific to ULTEM 9085 material, Motaparti et al. [11] investigated the effect of parameters on the flexural properties of ULTEM 9085 parts with solid and sparse build styles. Their investigation revealed that the vertical (edge) build direction could result in greater flexural yield strength. Gebisa and Lemu [12] carried out an extensive investigation into the effect of process parameters on the flexural property of ULTEM 9085 material, considering five processing parameters. From their investigation, they concluded that raster angle and raster width have the greatest effect on the flexural properties of the material. Motaparti et al. [13] also studied the effect of build parameters on the compressive property of ULTEM 9085 parts. They concluded that the interaction between two parameters, build direction and raster angle, significantly affects the compressive yield strength of the material. Bagsik et al. [14] investigated the influence of build orientations, flat (XY) and upright (XZ), on the compressive property of ULTEM 9085 parts. Their study concluded that the upright build orientation improves the compressive strength of the material. Bagsik and Schöppner [15] performed an extended investigation, considering more parameters. Their study showed that the highest tensile strength was achieved for all build directions using a negative raster air gap and also disclosed that using thick filaments for both edge and upright build directions could improve the tensile properties of the parts.

The above literature shows that FDM technology has undergone considerable progress in the last three decades, with regard to investigating the effects of process parameters on the mechanical performance of FDM materials. However, further investigation is still required, as new systems and new materials with different properties are being developed. Furthermore, those studies specific to the mechanical property of ULTEM 9085 are limited in number, and most of the studies have considered only a few process parameters. Investigating the effect of process parameters on mechanical properties is essential for industries to use this material in their product development. The objective of the current study is to investigate the effect of FDM process parameters (air gap, raster width, raster angle, contour number and contour width) on the tensile property of ULTEM 9085. The paper is structured as follows: Section 2 discusses the materials and methods used in the study; Section 3 discusses the results of the study, followed by Section 4, which draws some conclusions.

2. Materials and methods

2.1. 3D printer and material

The 3D printer used for the production of sample coupons is Fortus 450 mc, (Stratasys, Eden Prairie, MN). The printer has a build envelope of 406 x 355 x 406 mm and can build parts within an accuracy of ± 0.127 mm. The material considered for the investigation was Polyether Imide (PEI), known by the commercial name of ULTEM 9085. The material is relatively new and not very thoroughly investigated. Moreover, the material has huge potential for application in the aerospace, military and automotive sectors, due to its high strength-to-weight ratio, flame retardant, chemical resistant and FST (flame, smoke and toxicity) ratings [16].

2.2. Design of experiment

Full factorial design of experiment with five factors (parameters) illustrated in Figure 1 at two levels, given in Table 1, is used to investigate the effects of each of the factors on the tensile properties of the material. This is to screen out the most important from the less important effects. Commercial software, Design-Expert version 11, was employed for the investigation. The actual levels in the table are coded to -1 and 1, using Eqs. (1) and (2) [17], respectively.

The low and high levels of the parameters are assigned considering the 3D printer used (the extreme low and high values) and the test coupon dimensions. The low and high levels of the air gaps between (raster and raster, raster and contour, and contour and contour) are selected to be -0.0254 mm and 0.00 mm, respectively, based on recommendations from other studies [12, 18]. The low and high levels for raster width and contour width were selected to be 0.4064 mm and 0.7814 mm, respectively, since these are the available minimum and maximum values in the Fortus 450 mc 3D printing machine. The contour number levels to fit the size of the test coupon dimension were selected as one and five for low and high, respectively. The two levels of raster angle were the two extreme values, 0º and 90º. With the full factorial design of experiment considering five factors (processing parameters) at two levels, the total number of runs is given by 2^k, i.e. $2^5 = 32$ runs. The design matrix, with the experimental results obtained for the tensile test are not included here due to the page limitation.

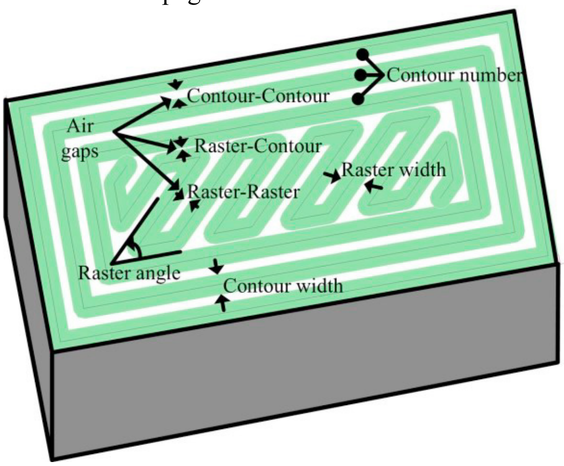

Fig. 1. Fused deposition modelling process parameters

$$X_{low\ coded}\,(-) = \frac{A_{low} - (A_{low} + A_{high})/2}{(A_{high} - A_{low})/2} \quad (1)$$

$$X_{high\ coded}\,(+) = \frac{A_{high} - (A_{low} + A_{high})/2}{(A_{high} - A_{low})/2} \tag{2}$$

where A_{low} is the low-level value of the factors, and A_{high} is the high-level value for the factors.

Table 1. FDM process parameters and their respective values

Factors			Levels	
Name	Units	Symbol	Low (-)	High (+)
Air gap	mm	A	-0.0254	0.0000
Raster width	mm	B	0.4064	0.7814
Raster angle	degree (º)	C	0.0000	90.0000
Contour number	--	D	1.0000	5.0000
Contour width	mm	E	0.4064	0.7814

2.3. Sample preparation

With the selected process parameters, samples for the investigation are prepared in the four steps listed below.

1. A three-dimensional (3D) model of the test coupons is prepared; using commercial computer aided design (CAD) software (Inventor) and saved as a stereolithography (.stl) file.
2. The .stl file is then exported into an operation software package (Insight 11) and customized groups are created. At this stage, the part is sliced at a given layer thickness: in this case, 0.254 mm. The parameter combinations, tool path generation, support generation and contour curves writing are also carried out at this stage and a CMB (Chromeleon Backup Archive) file that is ready for printing is generated.
3. The sample is produced after adjusting the machine setup (adjusting building sheet, installing material, etc.).
4. The built sample is removed from the machine, and the support material is removed if applicable.

2.4. Experimental procedure

The experiment was performed on Instron 5895, a universal testing machine with a load cell of 250 kN, adopting ASTM D3039 standard [19]. The test coupons shown in Figure 2 (a) and (b) were prepared as per the dimensions recommended in the standard. This standard was adopted as per the recommendation in [20], as the sample geometry in other tensile testing standards such as in ASTM D638 form a region with high stress concentration. This is because the filaments do not reach and fill to the ends of the curved region, as shown in Figure 2 (c). The geometry of the 3D printed specimens was modeled using Inventor software, exported as a .stl file and imported to Insight (3D printing software). The tensile test was carried out by inserting the specimen into the grips of the test machine, as shown in Figure 2 (d). The grips were tightened and then the tension load was applied at a constant recommended strain rate of 0.01 mm/mm/min.

3. Results and Discussion

The study was carried out to investigate the influence of process parameters on the tensile properties of ULTEM 9085 thermoplastic material. For the analysis of the experimental results, Design-Expert 11 (Stat-Ease, Minneapolis MN, USA) software was employed. A regression model given in Eq. (3) was proposed for the prediction of the tensile properties of the material, based on the experimental results. The model was developed by fitting the experimental data in a two-factor interaction (2FI) model with significant and insignificant parameters and interaction between factors, identified using an ANOVA technique. The ANOVA table with detailed analysis is given in Table 2. Based on the proposed model Eqs. (4) and (5) were developed. The positive and negative signs in the equations show the respective positive and antagonistic effects of the parameters.

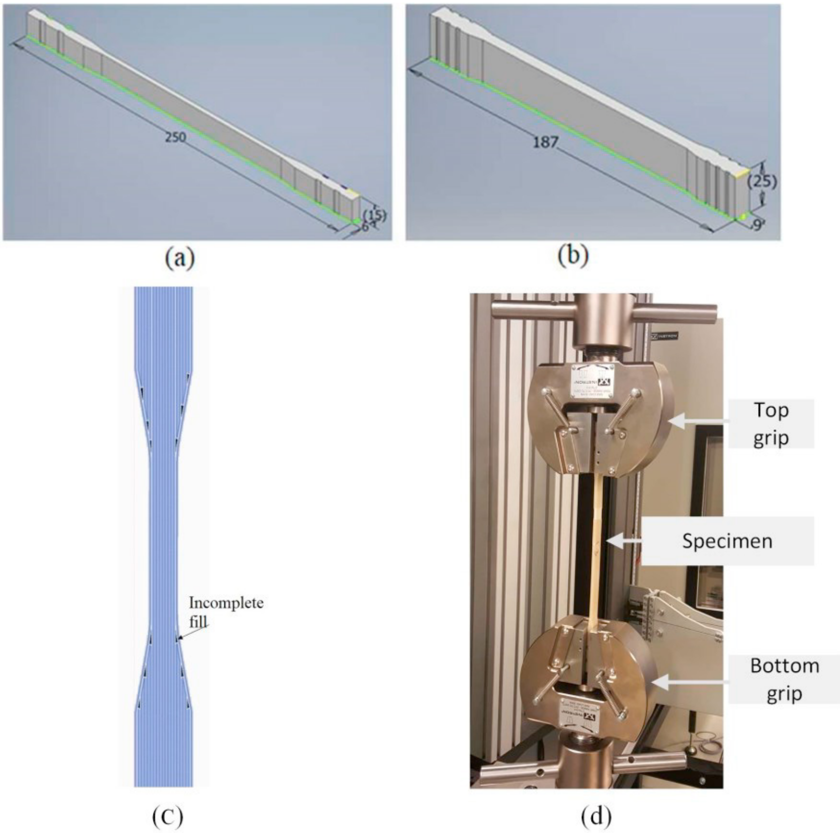

Fig. 2. 3D models of test coupons ((a) 0º, (b) 90º) (all dimensions are in mm), (c) Incomplete fill in samples, (d) Experimental setup

$$Y = \beta_0 + \sum_{i=1}^{5} \beta_i X_i + \sum_{i<j}^{5} \beta_{ij} X_i X_j + \varepsilon \quad (3)$$

where Y is the predicted response, βs are the regression coefficients, Xs represent the coded factors (parameters), and ε is the random error.

$$(Tensile\ strength)^{0.68} = 16.0318 - 0.558528 \times A - 0.384408 \times B - 3.91853 \times C - 0.546049 \times AC - 0.302355 \times BC \quad (4)$$

$$(Tensile\ strain)^{1.49} = 0.0141467 - 0.000264903 \times A - 0.00853997 \times C - 0.000910101 \times AC \quad (5)$$

In the ANOVA table, factors with very small probability (Prob > F value lower than 0.05) are regarded as significant and included in the regression model, whereas, factors with probability (Prob > F value) greater than 0.1 are regarded as insignificant and excluded from the model. However, insignificant single factors that are involved in the significant interaction effects are included in the model. Furthermore, good agreement is seen between adjusted and predicted R^2, i.e., within 0.2 between each other, and adequate precisions of over four also show the significance of the models. Fisher's assumptions tests; normal probability, equality of variance and run order independence are all valid for the models developed. However the plots are not included due to the page limitation.

Table 2. ANOVA tables of regression models for the responses

Source	Sum of Squares	Degree of Freedom	Mean Square	F-value	p-value	remark
Tensile strength (1)						
Model	518.54	5	103.71	372.82	< 0.0001	significant
A-Air gap	9.98	1	9.98	35.89	< 0.0001	significant
B-Raster width	4.73	1	4.73	17	0.0003	significant
C-Raster angle	491.36	1	491.36	1766.37	< 0.0001	significant
AC	9.54	1	9.54	34.3	< 0.0001	significant
BC	2.93	1	2.93	10.52	0.0032	significant
Residual	7.23	26	0.2782			
Cor Total	525.77	31				
Tensile strain (2)						
Model	0.0024	3	0.0008	240	< 0.0001	significant
A-Air gap	2.25E-06	1	2.25E-06	0.6843	0.4151	insignificant
C-Raster angle	0.0023	1	0.0023	711.24	< 0.0001	significant
AC	0	1	0	8.08	0.0083	significant
Residual	0.0001	28	3.28E-06			
Cor Total	0.0025	31				

(1) $R^2 = 0.9862$, Adjusted $R^2 = 0.9836$, Predicted $R^2 = 0.9792$, Adequate Precision = 42.5735
(2) $R^2 = 0.9626$, Adjusted $R^2 = 0.9586$, Predicted $R^2 = 0.9511$, Adequate Precision = 29.5112

3.1. Influence of process parameters on tensile properties

Five FDM process parameters are considered for the investigation. The first plots from the left in Figure 3 (a) and (b) show the main effects of air gap on the tensile strength and tensile strain, respectively. It is observed that this parameter (air gap) has less significant influence on the responses than the raster angle (given in the middle plot). Moreover, the influence of air gap is more visible in samples with 90º raster angle than in samples with 0º raster angle, as can be seen in Figure 3. Comparing counterparts with low-level and high-level air gap in Figure 3, such as runs 7 and 8, 15 and 16, 23 and 24, and 29 and 30, it is evident that low-level air gap improves the tensile strength of the material. This could be due to the low-level air gap forming a dense structure by overlapping adjacent filaments, thus making the part much stronger.

The effect of raster width on the tensile properties of the material can be seen in the second plots from the left in Figure 3 (a) and (b). Similar to the air gap, the influence of this parameter is more noticeable in the samples with 90º raster angle than in those with 0º raster angle. The effect of this parameter on the tensile properties is not that substantial. However, a comparison of counterparts, such as runs 6 and 8, 14 and 16 and 22 and 24, reveals that low-level raster width, in a way, improves the tensile strength of the material.

The tensile properties are influenced significantly by the raster angle, as evidenced from the middle plots in Figures 3 (a) and (b). Samples with 0º raster angle are stronger than samples with 90º raster angle. This could be attributed to the fact that samples with 0º raster angle are produced in such a way that the filaments are oriented in the longitudinal direction (length of the sample), which is parallel to the tensile load application direction. This makes the part more resistant to the applied tensile load, thus improving the tensile properties of the material. This effect is also noticeable in Figure 4, in which the runs with 0º raster angle (runs 1 to 4, 9 to 12, 17 to 20, and 25 to 28) show superior tensile strength to that of the samples with 90º raster angle (runs 5 to 8, 13 to 16, 21 to 24, and 29 to 32). The highest tensile strength of 86.92 MPa is registered for the parameter combination of low air gap (-0.0254 mm), low raster width (0.4064 mm), low raster angle (0º), high contour number (five) and high contour width (0.7814 mm). This value is much higher than the values reported in the factory data sheet [2] and other similar studies [14, 15].

The other two parameters (contour number and contour width) do not have much influence on the tensile properties, as shown in Figure 3 (a) and (b). However, comparing the counterparts with low and high levels of contour numbers from Figure 4, such as runs 6 and 14, 7 and 15, 8 and 16, 22 and 30, and 24 and 32, the positive effect of the high-level contour number on the tensile strength can be evidenced. This could be due to the addition of longitudinal filaments (contours) oriented parallel to the load application direction, which improves the resistance of the part to the applied load. Furthermore, a comparison of runs 8 and 24, 13 and 29, 14 and 30, and 15 and 31 reveals that thicker contour width improves the tensile strength of the material.

Generally, when comparing the current study to a similar study reported by the authors on the flexural properties of the same material [12], only raster angle shows a significant influence on the tensile properties of the material, whereas, in the previous study, all parameters except air gap showed a significant effect on the flexural properties of the materials.

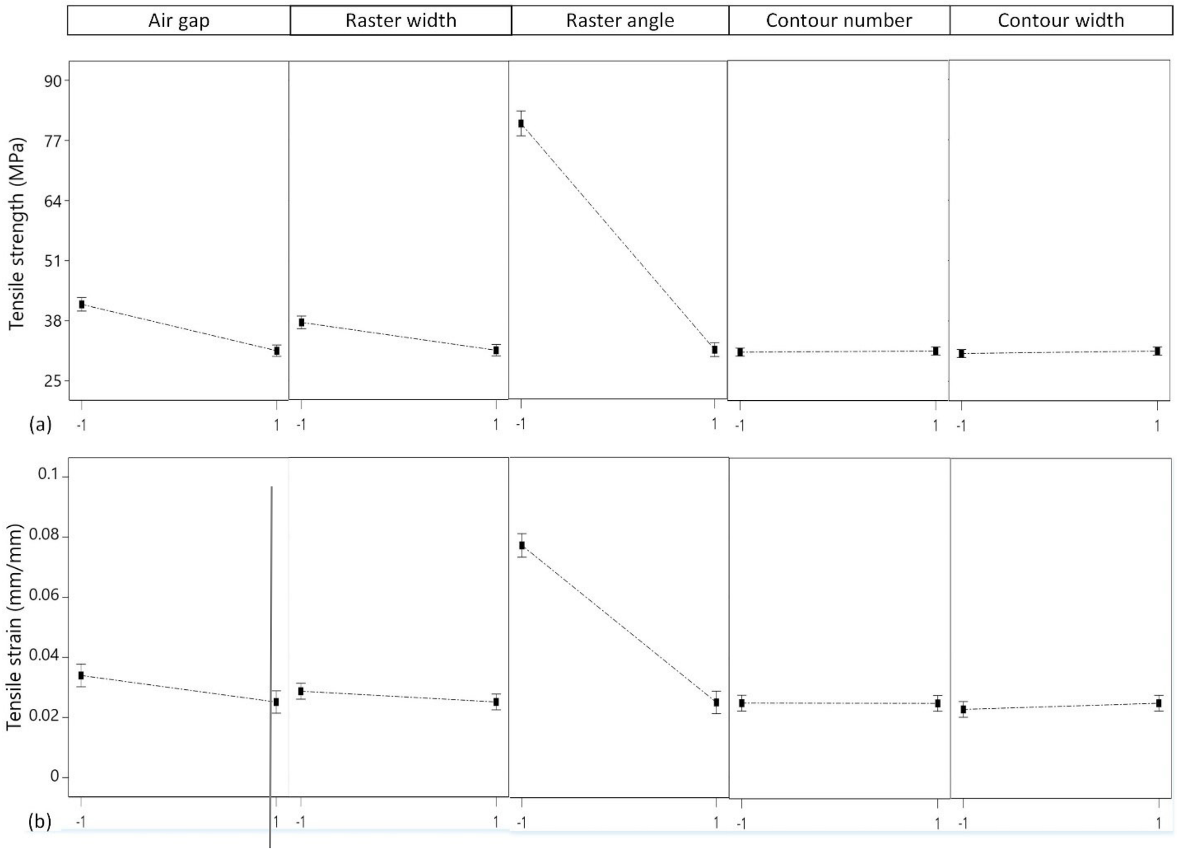

Fig. 3. Plots of main effects showing influence of process parameters on (a) tensile strength and (b) tensile strain

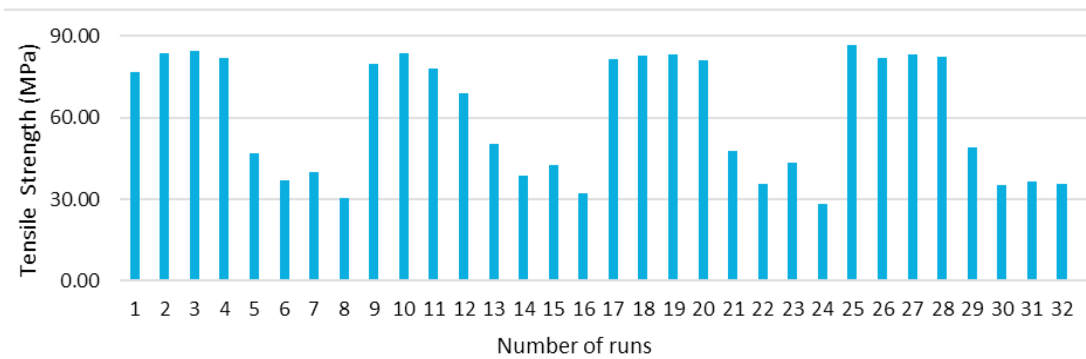

Fig. 4. Tensile strength vs. number of runs

4. Conclusions

The current study investigated the effects of FDM process parameters on the tensile properties of ULTEM 9085 material. Full factorial design of experiment was used for the investigation. Five process parameters, namely: air gap, raster width, raster angle, contour number and contour width, are considered in the investigation. Among the parameters considered, the influence of raster angle was the highest. For low levels of this parameter, the lowest tensile strength of about 30 MPa was registered, whereas about 87 MPa was registered for the high level of this parameter, although other parameters also participated. Since the current study is limited to the investigation of process parameters at two levels, it is recommended that future studies increase the number of levels, so that a more accurate result can be obtained.

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