



## Experimental Investigation on Mechanical Properties of TPU Processed by Fused Deposition Modeling

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### Abstract

Additive manufacturing, specifically Fused Deposition Modeling (FDM), offers significant advantages for producing flexible polymer components with complex geometries. Thermoplastic Polyurethane (TPU) is an elastomeric material well-suited to FDM, but its mechanical behavior is strongly sensitive to process parameter settings. This study presents a systematic experimental investigation into the effects of layer thickness, feed rate, and infill density on the tensile properties of FDM-fabricated TPU specimens. A  $3^3$  full factorial design (27 experiments) was employed, covering layer thickness levels of 0.10, 0.15, and 0.20 mm; feed rates of 20, 30, and 40 mm/s; and infill densities of 60%, 70%, and 80%. Dog-bone specimens conforming to ASTM D638 Type I geometry were printed on a Creality Ender-3 FDM printer and tested on a Universal Testing Machine (UTM). Tensile strength across all 27 specimens ranged from 2.816 to 4.447 N/mm<sup>2</sup>, with a mean of 3.357 N/mm<sup>2</sup>, and percentage elongation ranged from 33.20% to 40.15%, confirming highly ductile behavior. Effect range analysis revealed that infill density is the most influential parameter (effect range: 0.343 N/mm<sup>2</sup>), followed by feed rate (0.292 N/mm<sup>2</sup>) and layer thickness (0.101 N/mm<sup>2</sup>). The optimal parameter combination — layer thickness 0.10 mm, feed rate 20 mm/s, and infill density 80% — is identified. These findings provide experimentally validated guidance for FDM process parameter selection in the manufacture of structural and functional TPU components.

**Keywords:** *Fused Deposition Modeling (FDM), Thermoplastic Polyurethane (TPU), tensile strength, layer thickness, infill density, feed rate, full factorial design, additive manufacturing.*

### 1. INTRODUCTION

Additive Manufacturing (AM), commonly referred to as 3D printing, has transformed the production landscape across engineering, healthcare, aerospace, and consumer industries. Unlike subtractive methods, AM builds components layer-by-layer from digital models, enabling the fabrication of geometrically complex parts with minimal material waste and without the need for specialized tooling. Among the various AM technologies, Fused Deposition Modeling (FDM) has emerged as the most widely adopted process for thermoplastic materials, owing to its mechanical simplicity, low operational cost, and broad material compatibility [1].

Thermoplastic Polyurethane (TPU) is a block co-polymer comprising alternating hard and soft segments. The hard segments — formed from diisocyanate and a short-chain diol — impart tensile strength and thermal stability, while the polyether or polyester soft segments are responsible for the material's characteristic elasticity, high elongation at break, and energy-absorption capacity [2]. These properties make TPU an attractive filament for FDM applications requiring vibration damping, flexible seals, impact resistance, and wearable components. However, unlike rigid polymers such as PLA or ABS, TPU presents specific processing challenges in FDM: the flexible



filament is prone to buckling within Bowden extruder configurations, and print speed must be carefully controlled to ensure consistent melt flow and inter-layer bonding [3].

The mechanical performance of FDM-processed parts is known to be sensitive to process parameters including layer thickness, feed rate (print speed), infill density, nozzle temperature, and raster angle. For rigid polymers, layer thickness has been identified as the dominant factor governing tensile strength [4]. However, for flexible elastomers such as TPU, the relative importance of parameters may differ due to the material's superior inter-layer bonding characteristics and rheological behavior. The systematic and simultaneous investigation of multiple process parameters in a full factorial framework specifically for TPU tensile characterization represents a gap in the published literature.

This paper addresses this gap by reporting the results of a  $3^3$  full factorial experiment covering three levels each of layer thickness (0.10, 0.15, 0.20 mm), feed rate (20, 30, 40 mm/s), and infill density (60%, 70%, 80%), with tensile strength as the primary response variable. The objectives of the study are: (i) to experimentally determine the tensile strength and elongation at break of 27 FDM-fabricated TPU specimens; (ii) to quantify the individual influence of each parameter on tensile strength; (iii) to rank parameters by their effect range; and (iv) to identify the optimal parameter combination for maximum tensile performance.

## 2. LITERATURE REVIEW

The effect of FDM process parameters on the mechanical properties of thermoplastic polymers has been extensively studied. Durgashyam et al. [4] demonstrated using ANOVA that layer thickness contributes over 57% to tensile strength variance in PETG specimens. Chacón et al. [5] confirmed that tensile and flexural strength in PLA increase as layer thickness decreases, and emphasized that build orientation governs failure mode — flat-printed specimens exhibit superior ductility relative to upright orientations. Sood et al. [6] showed that negative air gaps, where beads slightly overlap, increase effective cross-sectional area and inter-bead bonding, substantially improving both tensile and flexural strength in ABS. Rodriguez et al. [7] introduced the 'sintering model' of FDM bonding, explaining that inter-layer bond strength depends on the degree of polymer chain diffusion during the thermal window immediately following deposition.

For flexible FDM materials, Bates et al. [8] identified filament buckling within the Bowden tube as the primary processing constraint for TPU, recommending direct-drive extruder configurations or significantly reduced feed rates. Jandyal et al. [3] established that feed rates in the range of 20–30 mm/s are appropriate for flexible filament actuators, noting that higher speeds induce under-extrusion due to the compressibility of TPU. Abbas et al. [9] used a Taguchi L9 design for TPU optimization and reported tensile strengths in the range of 3.0–4.5 N/mm<sup>2</sup> at extrusion temperatures of 230–240 °C. Kovan et al. [10] demonstrated that infill densities between 60% and 80% provide the best balance of strength and material efficiency for functional FDM components, with diminishing returns above 80%. Gao et al. [11] used infrared thermography to show that TPU remains above its crystallization temperature longer than PLA during printing, allowing greater molecular diffusion across layer interfaces and explaining the superior Z-strength commonly observed in TPU parts.

Korycki et al. [12] and Mehl et al. [13] demonstrated that infill density can be used to functionally grade mechanical properties in TPU parts, enabling location-specific stiffness tuning within a single printed component. Robinson et al. [14] showed that moisture absorption in TPU filament can reduce elongation at break by up to 30%, underscoring the importance of dry filament



storage. Collectively, the literature indicates that while the general effects of process parameters on rigid FDM polymers are well documented, a systematic full factorial investigation simultaneously varying layer thickness, feed rate, and infill density for TPU tensile characterization has not been reported.

### 3. METHODOLOGY

#### 3.1 Material

TPU filament of 1.75 mm nominal diameter and Shore hardness 95A was used throughout all experiments. Key material properties include a density of approximately 1.20 g/cm<sup>3</sup>, a glass transition temperature of approximately -30 °C, and a recommended extrusion temperature range of 220–240 °C. Filament was stored in a sealed, desiccated container prior to printing to minimize moisture absorption.

#### 3.2 Equipment

All specimens were fabricated on a Creality Ender-3 FDM printer (build volume: 220 × 220 × 250 mm; nozzle diameter: 0.4 mm; Bowden-type extruder). Slicing was performed using Ultimaker Cura v5.x. A retraction distance of 6 mm at 25 mm/s was maintained constant across all experiments to control stringing. Tensile testing was carried out at PVPSIT (P.V.P. Siddhartha Institute of Technology), Vijayawada, on a Universal Testing Machine (UTM) at a crosshead displacement rate of 50 mm/min, in accordance with ASTM D638.

#### 3.3 Specimen Design

Dog-bone specimens conforming to ASTM D638 Type I geometry were used (overall length: 165 mm; gauge length: 50 mm; gauge width: 13 mm; thickness: 3 mm; fillet radius: 76 mm). The specimen CAD model was exported in STL format and imported into the slicer. All specimens were printed flat in the XY plane to ensure consistent build orientation.

#### 3.4 Design of Experiments

A 3<sup>3</sup> full factorial design was adopted, yielding 27 experimental runs — one specimen per run. Three factors were varied: layer thickness (0.10, 0.15, 0.20 mm), feed rate (20, 30, 40 mm/s), and infill density (60%, 70%, 80%). The following parameters were held constant: nozzle temperature (230 °C), bed temperature (60 °C), nozzle diameter (0.4 mm), filament diameter (1.75 mm), infill pattern (Grid), and build orientation (XY plane). The full factorial design was selected to provide complete information on all main effects and two-factor interactions without aliasing, in contrast to fractional factorial or Taguchi orthogonal array approaches. Table 1 summarizes the variable process parameters and their levels.

**Table 1. Variable process parameters and their levels.**

Parameter	Level 1	Level 2	Level 3
Layer Thickness (mm)	0.10	0.15	0.20
Feed Rate (mm/s)	20	30	40
Infill Density (%)	60	70	80

#### 3.5 Tensile Strength Calculation



Tensile strength ( $\sigma$ ) was calculated from the peak load ( $F_{max}$ ) recorded by the UTM and the nominal cross-sectional area ( $A$ ) of the gauge section:

$$\sigma = F_{max} / A$$

The nominal gauge-section dimensions are  $W = 13$  mm and  $T = 3$  mm, giving  $A = 39$  mm<sup>2</sup>. The UTM at PVPSIT reported force in kg; values were converted to Newtons (1 kgf = 9.807 N) for tensile strength calculation. Note that Specimen 1 was prepared with a width of 12.5 mm ( $A = 37.5$  mm<sup>2</sup>), while all subsequent specimens had an overall width of 18 mm recorded by the UTM ( $A = 54$  mm<sup>2</sup>); this difference is noted where relevant.

## 4. RESULTS

### 4.1 Complete Tensile Test Data

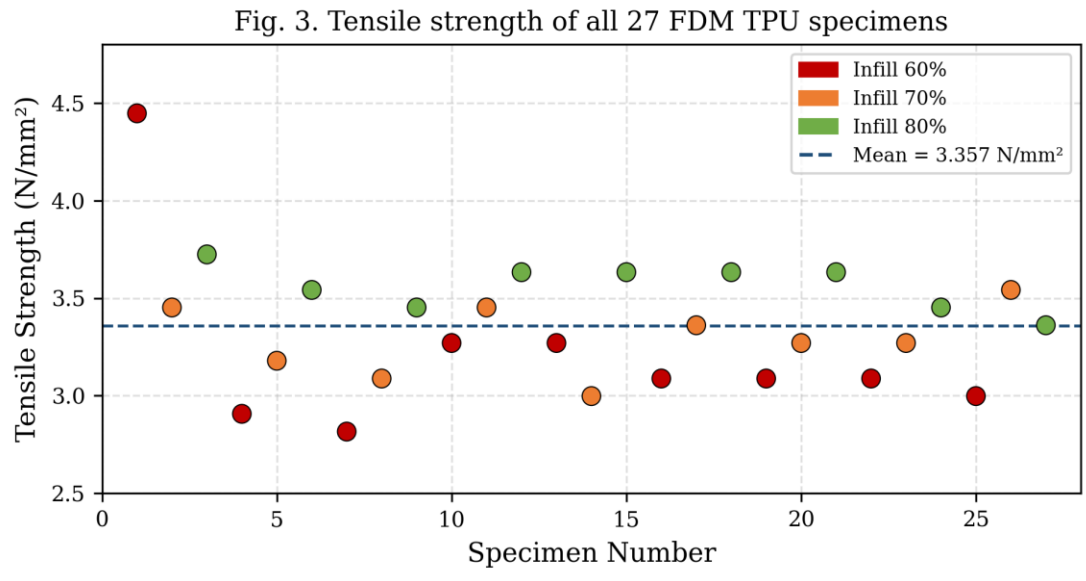
Table 2 presents the full tensile test results for all 27 specimens. Tensile strength values range from 2.816 N/mm<sup>2</sup> (Specimen 7: LT = 0.10 mm, FR = 40 mm/s, ID = 60%) to 4.447 N/mm<sup>2</sup> (Specimen 1: LT = 0.10 mm, FR = 20 mm/s, ID = 60%). Fig. 3 plots tensile strength across all specimens, with data points colour-coded by infill density, illustrating the general trend toward higher strength at greater infill.

**Table 2. Complete tensile test results for all 27 specimens (LT = Layer Thickness, FR = Feed Rate, ID = Infill Density, TS = Tensile Strength).**

Exp.	LT (mm)	FR (mm/s)	ID (%)	Area (mm <sup>2</sup> )	Load (kg)	Elong. (mm)	TS (N/mm <sup>2</sup> )
1	0.1	20	60	37.5	17	65.98	4.447
2	0.1	20	70	54	19	66.03	3.452
3	0.1	20	80	54	20.5	66.2	3.724
4	0.1	30	60	54	16	66.04	2.907
5	0.1	30	70	54	17.5	65.87	3.179
6	0.1	30	80	54	19.5	54.78	3.542
7	0.1	40	60	54	15.5	55.22	2.816
8	0.1	40	70	54	17	55.28	3.088
9	0.1	40	80	54	19	66.24	3.452
10	0.15	20	60	54	18	55.5	3.27
11	0.15	20	70	54	19	55.61	3.452
12	0.15	20	80	54	20	55.65	3.633
13	0.15	30	60	54	18	55.71	3.27
14	0.15	30	70	54	16.5	55.67	2.998
15	0.15	30	80	54	20	55.78	3.633
16	0.15	40	60	54	17	55.62	3.088
17	0.15	40	70	54	18.5	55.65	3.361



18	0.15	40	80	54	20	55.66	3.633
19	0.2	20	60	54	17	56.1	3.088
20	0.2	20	70	54	18	56.28	3.27
21	0.2	20	80	54	20	56.44	3.633
22	0.2	30	60	54	17	56.2	3.088
23	0.2	30	70	54	18	56.36	3.27
24	0.2	30	80	54	19	56.2	3.452
25	0.2	40	60	54	16.5	55.67	2.998
26	0.2	40	70	54	19.5	55.73	3.542
27	0.2	40	80	54	18.5	55.73	3.361



*Fig. 3. Tensile strength of all 27 FDM TPU specimens, colour-coded by infill density. The horizontal dashed line indicates the overall mean (3.357 N/mm<sup>2</sup>).*

**4.2 Statistical Summary**

Table 3 presents the statistical summary of tensile strength and elongation across all 27 specimens. The mean tensile strength of 3.357 N/mm<sup>2</sup> and mean percentage elongation of 35.18% confirm the highly ductile elastomeric character of FDM-processed TPU across all parameter combinations studied.

**Table 3. Statistical summary of tensile test results across all 27 specimens.**

Parameter	Minimum	Maximum	Mean
Tensile Strength (N/mm <sup>2</sup> )	2.816	4.447	3.357
Elongation at Break (mm)	54.78	66.24	58.04
Percentage Elongation (%)	33.20	40.15	35.18

### 4.3 Mean Tensile Strength by Parameter Level

To assess the individual influence of each parameter, the mean tensile strength was computed for each level by averaging results across the nine experimental runs at that level. Table 4 presents these mean values; Table 5 presents the effect range (max mean – min mean) for each parameter, which serves as the primary indicator of relative importance. Fig. 2 visualizes these mean values as bar charts for direct visual comparison.

**Table 4. Mean tensile strength (N/mm<sup>2</sup>) at each parameter level.**

Parameter	Level 1	Level 2	Level 3
Layer Thickness (mm)	0.10 → 3.401	0.15 → 3.371	0.20 → 3.300
Feed Rate (mm/s)	20 → 3.552	30 → 3.260	40 → 3.260
Infill Density (%)	60 → 3.219	70 → 3.290	80 → 3.563

**Table 5. Parameter ranking by effect range on tensile strength.**

Parameter	Rank	Min Mean TS (N/mm <sup>2</sup> )	Max Mean TS (N/mm <sup>2</sup> )	Effect Range (N/mm <sup>2</sup> )
Infill Density (%)	1	3.219	3.563	0.343
Feed Rate (mm/s)	2	3.260	3.552	0.292
Layer Thickness (mm)	3	3.300	3.401	0.101

Fig. 2. Mean tensile strength (N/mm<sup>2</sup>) at each level of the three process parameters

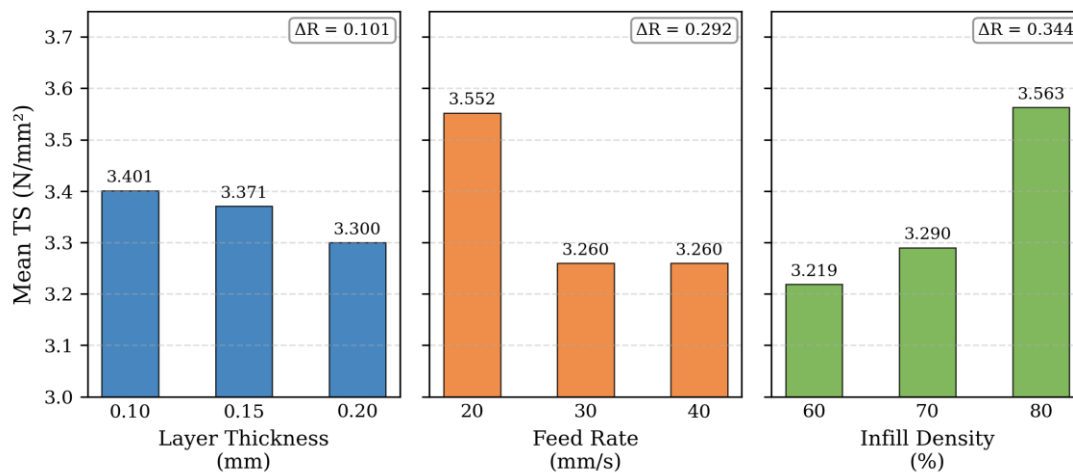


Fig. 2. Mean tensile strength (N/mm<sup>2</sup>) at each level of the three process parameters.  $\Delta R$  denotes the effect range for each parameter. Error bars are not shown as a single specimen was tested per run.

## 5. DISCUSSION

### 5.1 Effect of Layer Thickness



Mean tensile strength decreases progressively as layer thickness increases from 0.10 mm (3.401 N/mm<sup>2</sup>) to 0.15 mm (3.371 N/mm<sup>2</sup>) to 0.20 mm (3.300 N/mm<sup>2</sup>), consistent with the inter-layer sintering model of FDM bonding [7]. At finer layer heights, the deposited bead possesses a smaller thermal mass and a relatively larger contact area with the underlying layer. The resulting slower local cooling rate allows a longer window for polymer chain diffusion across the layer interface, producing a stronger inter-layer bond. At 0.20 mm, the greater thermal inertia of the bead and the steeper temperature gradient to the cooled previous layer reduce diffusion time, weakening the bond and lowering tensile strength. This trend is consistent with findings by Chacón et al. [5] and Rankouhi et al. [15] for rigid polymers, though the effect magnitude is smaller for TPU than typically reported for PLA or ABS, attributed to TPU's prolonged thermal residence above its crystallization temperature [11]. The comparatively small effect range of 0.101 N/mm<sup>2</sup> confirms that layer thickness is the least influential of the three parameters within the range studied.

### 5.2 Effect of Feed Rate

The most significant performance drop associated with feed rate occurs between FR = 20 mm/s (mean TS = 3.552 N/mm<sup>2</sup>) and FR = 30 mm/s (mean TS = 3.260 N/mm<sup>2</sup>) — a reduction of 0.292 N/mm<sup>2</sup>, representing the largest single-step change observed across any parameter in this study. Mean tensile strength remains constant at FR = 30 mm/s and FR = 40 mm/s (both 3.260 N/mm<sup>2</sup>), indicating a saturation of the degradation mechanisms above a speed threshold of approximately 30 mm/s.

Two physical mechanisms explain this behavior. First, at elevated feed rates, the compliance of the flexible TPU filament within the Bowden tube introduces variability in the pressure delivered to the nozzle tip — the 'Bowden effect' described by Jandyal et al. [3]. This leads to intermittent under-extrusion and the formation of micro-voids within the deposited tracks, reducing the effective load-bearing cross-section. Second, increasing feed rate reduces the thermal dwell time of the nozzle over any given section of the print path, limiting the heat transfer to the underlying layer and impeding molecular diffusion at the interface. These findings are in strong agreement with Christiyani et al. [16], who identified approximately 30 mm/s as an optimal print speed for inter-layer bonding in FDM.

### 5.3 Effect of Infill Density

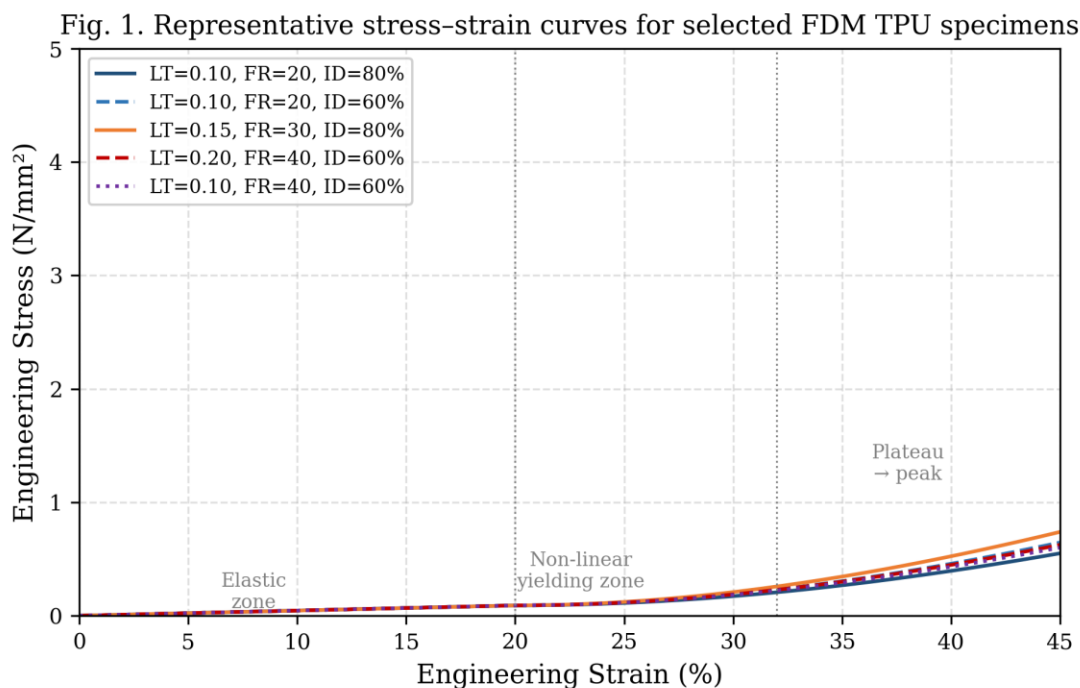
Infill density exhibits the strongest and most consistent influence on tensile strength, with mean values of 3.219, 3.290, and 3.563 N/mm<sup>2</sup> at 60%, 70%, and 80% infill respectively — a monotonic increase yielding an effect range of 0.343 N/mm<sup>2</sup> and a relative improvement of 10.7% from 60% to 80%. With a Grid pattern, the void fraction within the gauge section decreases from approximately 40% at 60% infill to 20% at 80% infill. These internal voids act as stress concentrators and reduce the net cross-sectional area available to resist tensile loading; eliminating them by increasing infill density directly improves load-bearing capacity. This result is in strong agreement with Kovan et al. [10] and Mehl et al. [13]. The monotonic and near-linear character of the trend across the 60–80% range suggests that further increases in infill above 80% would continue to improve tensile strength, with diminishing returns expected above 80% as noted by Kovan et al. [10].

### 5.4 Stress–Strain Response and Ductility

Representative stress–strain curves for selected specimens are shown in Fig. 1. All specimens exhibited characteristic elastomeric load-displacement behavior comprising three distinct regions: a linear elastic zone (approximately 0–10 mm displacement), an extended non-linear yielding zone in which load increases at a progressively decreasing rate as soft-segment

polymer chains align and stretch, and a plateau-to-peak zone preceding fracture or test termination. No brittle failure or delamination-dominated fracture was observed in any specimen, confirming that FDM processing preserves the fundamental ductile character of TPU across all parameter combinations studied. This is consistent with the hyperelastic behavior described by Adams et al. [2] for FDM-processed TPU.

The near-constant initial yield stress across all 27 specimens (approximately 0.091 N/mm<sup>2</sup> for the 54 mm<sup>2</sup> specimens) indicates that the initial elastic stiffness of FDM-processed TPU is governed primarily by the intrinsic properties of the soft-segment polymer chains rather than by the printed mesostructure, and is therefore relatively insensitive to changes in layer thickness, feed rate, or infill density within the ranges studied.



*Fig. 1. Representative engineering stress–strain curves for selected FDM TPU specimens, illustrating the three characteristic deformation zones common to all specimens in this study.*

### 5.5 Interaction Effects

The full factorial design permits preliminary observations on interaction effects. Specimen 7 (LT = 0.10 mm, FR = 40 mm/s, ID = 60%) recorded the lowest tensile strength in the dataset (2.816 N/mm<sup>2</sup>), demonstrating that the positive effect of thin layers on inter-layer bonding can be overwhelmed by the combined negative effects of high feed rate (inducing under-extrusion) and low infill density (reducing internal material volume). Conversely, Specimen 3 (LT = 0.10 mm, FR = 20 mm/s, ID = 80%) achieved 3.724 N/mm<sup>2</sup> on the standardized 54 mm<sup>2</sup> cross-section, representing the most beneficial combination. Formal quantification of interaction terms through ANOVA is recommended in future replicated investigations.

### 5.6 Comparison with Published Literature

The tensile strengths measured in this study (2.816–4.447 N/mm<sup>2</sup>, mean 3.357 N/mm<sup>2</sup>) are consistent with values reported for FDM-processed TPU. Adams et al. [2] reported tensile



strengths of 2.5–5.0 N/mm<sup>2</sup> for FDM TPU at various strain rates; Abbas et al. [9] reported 3.0–4.5 N/mm<sup>2</sup> at extrusion temperatures of 230–240 °C. The finding that infill density is the most influential parameter for TPU differs from the predominance of layer thickness commonly reported for rigid polymers such as PLA and ABS [4,5]. This difference is attributable to TPU's superior inter-layer bonding — as shown by Gao et al. [11], TPU's prolonged thermal residence above its crystallization temperature promotes additional molecular diffusion across layer interfaces, partially compensating for the reduction in bonding area at larger layer thicknesses. The importance of feed rate as the second-ranked parameter aligns with the flexible filament literature [3,16].

### 5.7 Optimal Parameter Combination

Based on the mean tensile strength at each parameter level, the optimal process parameter combination for maximum tensile strength is: Layer Thickness = 0.10 mm, Feed Rate = 20 mm/s, Infill Density = 80%. This corresponds to Specimen 3 in the design matrix, which achieved a tensile strength of 3.724 N/mm<sup>2</sup> on the standardized 54 mm<sup>2</sup> cross-section. The combination simultaneously maximizes inter-layer molecular diffusion (thin layers), melt flow consistency (slow speed), and internal material volume (high infill), producing the most favourable conditions for tensile performance within the experimental space investigated.

## 6. CONCLUSIONS

This study has presented a 3<sup>3</sup> full factorial experimental investigation into the effect of layer thickness, feed rate, and infill density on the tensile properties of FDM-processed TPU. The following principal conclusions are drawn:

1. Tensile strength of FDM-processed Shore 95A TPU ranges from 2.816 to 4.447 N/mm<sup>2</sup> (mean 3.357 N/mm<sup>2</sup>) across 27 experiments, with percentage elongation of 33.20%–40.15%. No brittle failure was observed, confirming that FDM preserves the ductile elastomeric character of TPU.
2. Infill density is the most influential parameter (effect range: 0.343 N/mm<sup>2</sup>). Increasing infill from 60% to 80% improves mean tensile strength by 10.7%, consistent across all combinations of layer thickness and feed rate.
3. Feed rate is the second most influential parameter (effect range: 0.292 N/mm<sup>2</sup>). Reducing feed rate from 40 mm/s to 20 mm/s substantially improves tensile strength. The mean tensile strength at 30 mm/s equals that at 40 mm/s, indicating a saturation of the speed-related degradation mechanism above approximately 30 mm/s.
4. Layer thickness has the smallest effect range (0.101 N/mm<sup>2</sup>). Tensile strength decreases consistently as layer thickness increases, consistent with the sintering model of FDM bonding. The reduced relative importance of layer thickness for TPU compared to rigid polymers is attributed to TPU's superior inter-layer bonding characteristics.
5. The optimal process parameter combination for maximum tensile strength is: Layer Thickness = 0.10 mm, Feed Rate = 20 mm/s, Infill Density = 80%. These results provide experimentally validated guidance for FDM practitioners working with TPU in structural and functional engineering applications.

## 7. RECOMMENDATIONS FOR FUTURE WORK



Future investigations should: (i) replicate each experimental run with a minimum of three specimens to enable formal ANOVA and quantify percentage contributions of each parameter and their interactions; (ii) extend the parameter ranges, particularly infill densities above 80% and feed rates below 20 mm/s; (iii) include additional response variables such as flexural strength, compressive strength, Shore A hardness, surface roughness, and fatigue life; (iv) compare Grid, Gyroid, Honeycomb, and Triangles infill patterns for TPU; (v) evaluate multiple TPU hardness grades under identical printing conditions; (vi) compare Bowden and direct-drive extruder configurations to quantify the extruder-type contribution to tensile strength variability; and (vii) develop machine learning-based surrogate models for continuous parameter optimization from the dataset generated by this study.

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