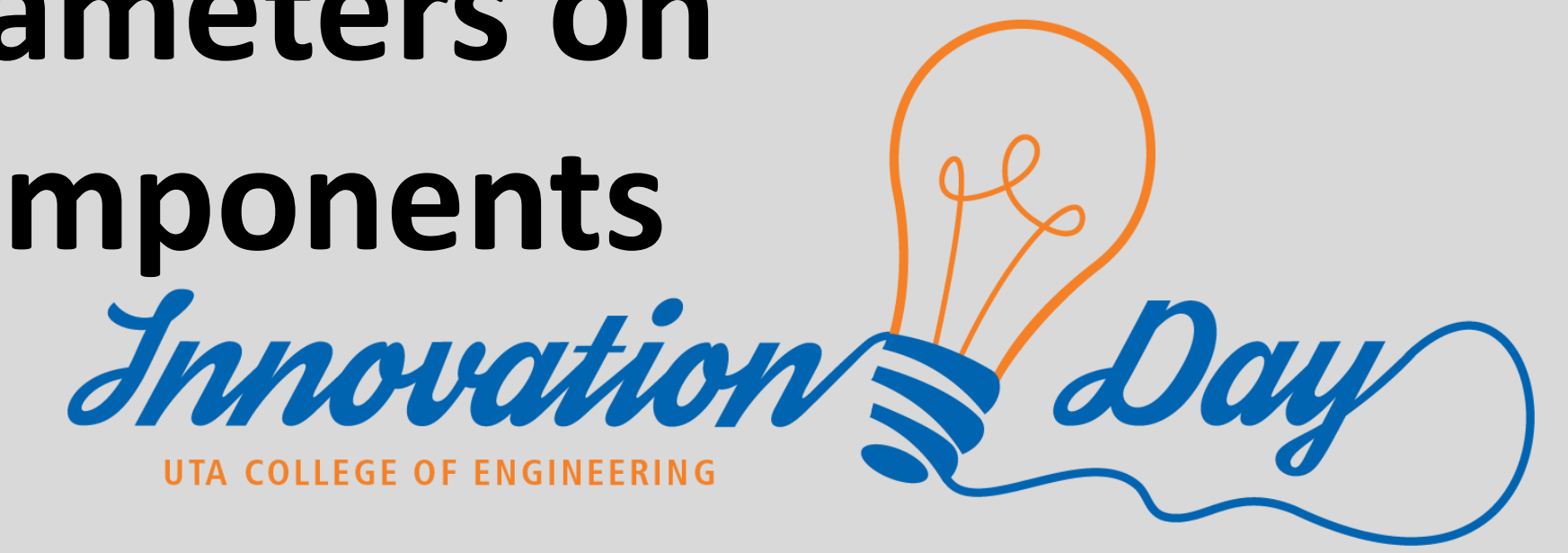


58: Investigating the Effect of Additive Manufacturing Parameters on Surface Roughness of High-Performance Thermoplastic Components

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Executive Summary

- This study investigates how FDM parameters affect the surface roughness of Polyetherimide (PEI) components.
- PEI is a **high-performance** thermoplastic widely used in aerospace and industrial applications due to its thermal stability and mechanical strength [3].
- A Taguchi L27 design of experiments (DOE) is used to evaluate the effects of **nozzle temperature, chamber temperature, printing speed, and flow rate** [11].
- Experiments are conducted using a Prusa Pro HT90 high-temperature FDM printer.
- Surface roughness is evaluated using optical microscopy and MATLAB-based image analysis.
- Goal:** Identify optimal printing conditions to improve surface quality in high-performance polymer additive manufacturing.

Background

- Additive manufacturing (AM), particularly fused deposition modeling (FDM), enables fabrication of complex geometries with reduced material waste and production time [1].
- FDM is widely accessible and used due to its material versatility and cost-effectiveness [1].
- High-performance thermoplastics such as Polyetherimide (PEI / ULTEM) offer excellent thermal stability, mechanical strength, and chemical resistance [3].
- Surface quality remains a major limitation (**Figure 1**) in FDM, especially for high-temperature polymers, due to layer-by-layer deposition effects [2].
- Process parameters such as nozzle temperature, chamber temperature, and printing speed significantly influence surface finish and part quality [5].
- Design of Experiments (DOE), particularly Taguchi methods, is commonly used to efficiently study parameter effects while reducing experimental effort [10], [11].

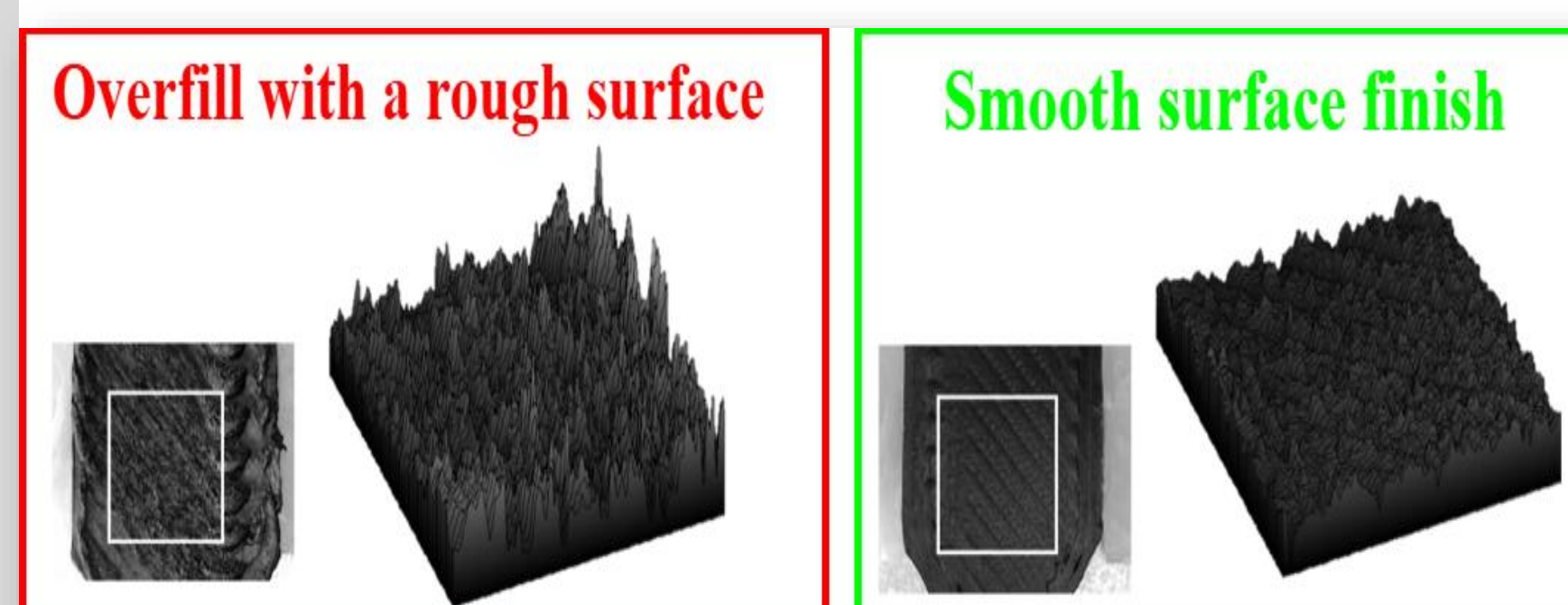


Figure 1. Rough vs Smooth Surfaces

Experimental Setup

- Prusa Pro HT90** high-temperature FDM printer, see **Figure 2**.
- Material: **PEI** (high-performance thermoplastic).
- ADXL345** sensors used for vibration monitoring.
- Surface roughness evaluated using **optical microscopy + MATLAB (Figure 3)**.

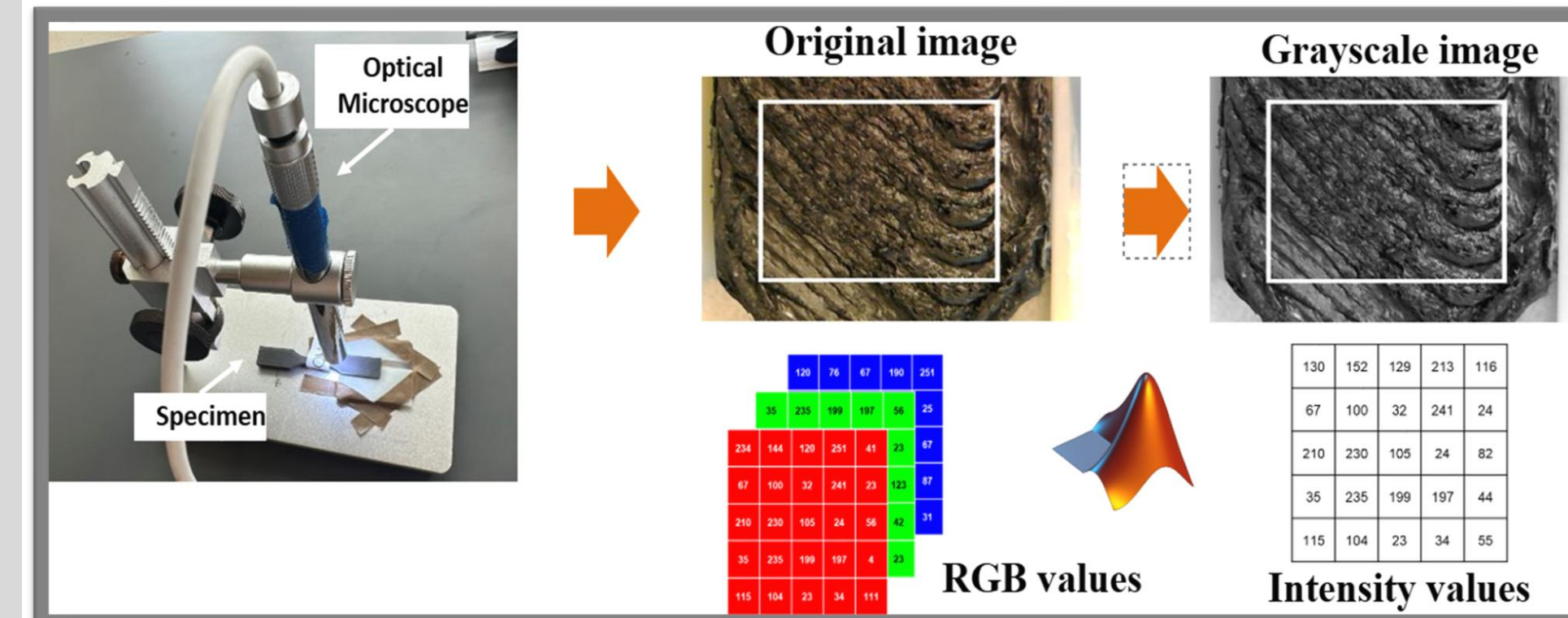


Figure 3. Surface roughness analysis workflow



Figure 2. Prusa Pro HT90 printer

Surface Roughness Metrics

- S_a : Average surface roughness, representing average deviation from the mean intensity.
- S_q : Root mean square roughness, emphasizing larger surface variations and peaks.

$$S_a = \frac{\sum_{n=1}^N \sum_{m=1}^M |I_{nm} - \bar{I}|}{N * M}$$
$$S_q = \sqrt{\frac{\sum_{n=1}^N \sum_{m=1}^M (I_{nm} - \bar{I})^2}{N * M}}$$

Experimental Test Plan

- Taguchi L27 DOE used to study surface roughness across **four FDM parameters** [11].
- Parameters studied: nozzle temperature, chamber temperature, printing speed, and flow rate.
- Each factor was tested at **three levels: low, medium, and high** (**Table 1**).
- The **L27** design reduced testing effort compared with a full factorial study while preserving main effects [11].
- Three replications** were performed for each condition, resulting in **81 printed specimens**.
- Key interactions considered: **nozzle temperature X chamber temperature**, and **nozzle temperature X printing speed**.
- Only half** of the specimen geometry was printed to reduce material use and printing time (**Figure 4**).

Table 1. Process Parameters and Levels

Parameter	Low	Medium	High
Nozzle Temperature (°C)	360 °C	375 °C	390 °C
Chamber Temperature (°C)	Ambient	45 °C	90 °C
Printing Speed (mm/s)	30 mm/s	45 mm/s	60 mm/s
Flow Rate %	90%	100%	110%

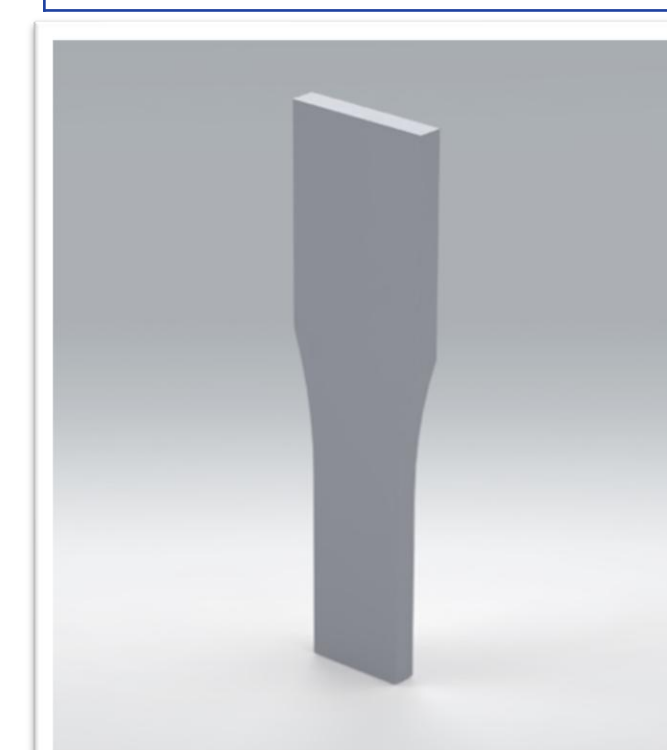


Figure 4. Half-specimen geometry

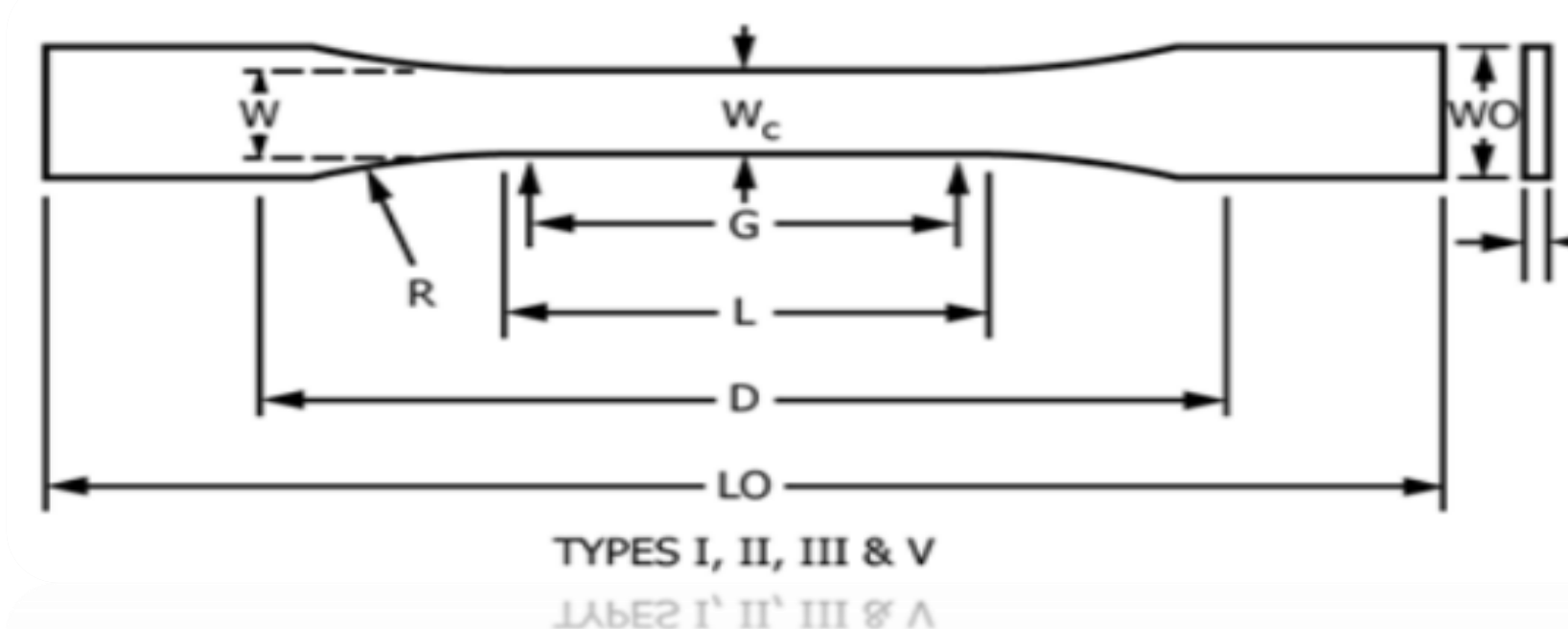


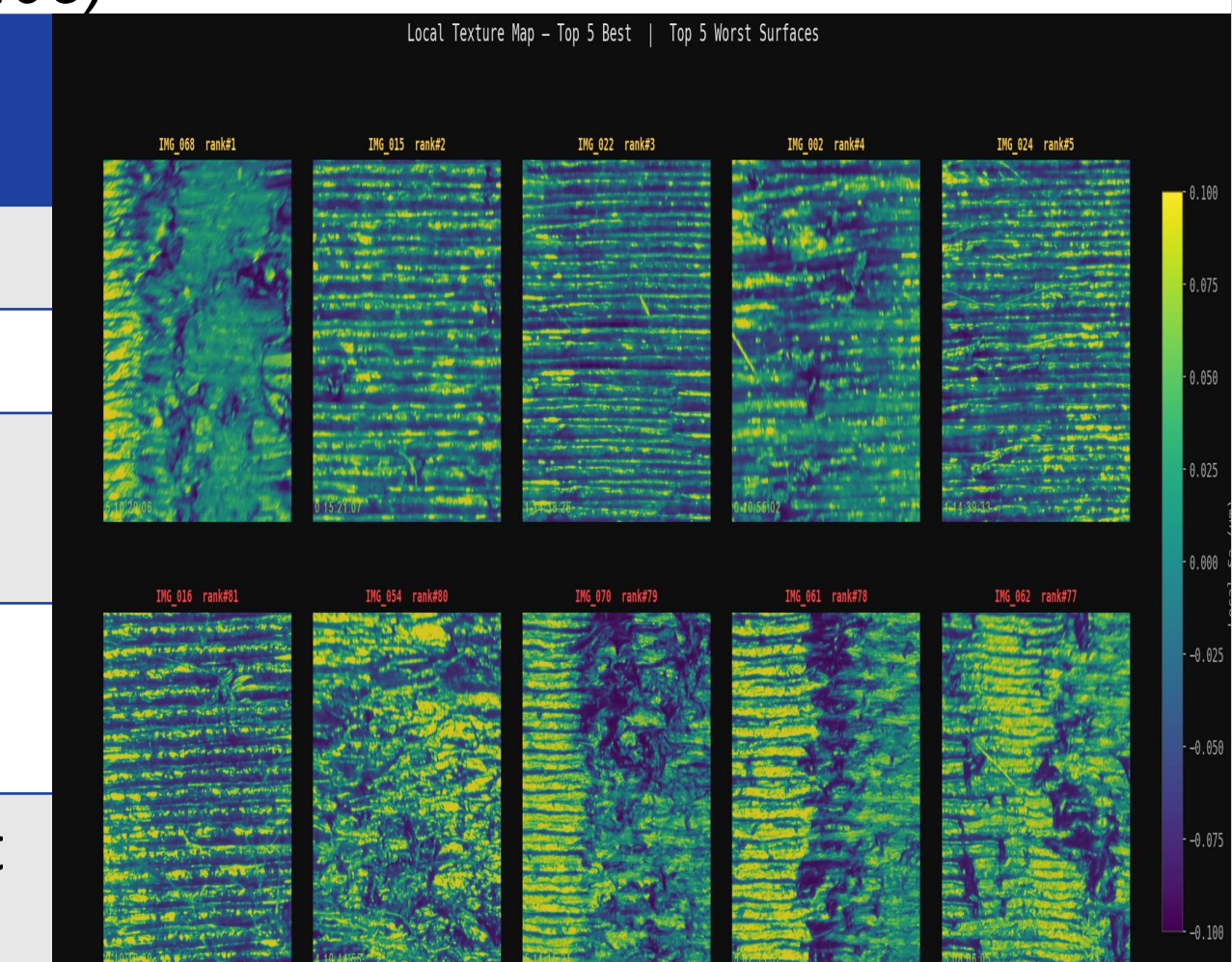
Figure 5. 2-D Drawing

Experimental Results

- Nozzle Temperature: Strong effect** ($p = 0.0012$); higher temperatures improve surface.
- Printing **Speed: Highly significant** ($p = 0.0037$); higher speeds increase roughness.
- Chamber Temperature: Moderate effect** ($p = 0.0343$); need thermal control.
- Interaction (Nozzle x Chamber): Significant** ($p = 0.0127$); parameters should be optimized together.
- Flow Rate: Not significant** ($p = 0.0877$); minor influence in tested range.

Table 2. ANOVA Significance Summary ($\alpha = 0.05$)

Factor	P-value	Significance
Nozzle Temperature	0.0012	Significant ✓
Printing Speed	0.0037	Significant ✓
Chamber Temperature	0.0343	Significant ✓
Nozzle Temp x Chamber Temp	0.0127	Significant ✓
Flow Rate	0.0877	Not Significant ✗



- Heatmaps show **smoother** textures under optimal conditions and **rough** patterns in poor settings.

Figure 6. Top 5 best and worst surface texture maps.

Conclusions

Highlights:

- Nozzle temperature and printing speed significantly impact surface roughness.**
- Chamber temperature also affects surface quality.**
- The **strong interaction: (nozzle x chamber)** temperatures suggests they should be optimized together.
- Flow rate shows no significant effect** within the tested range.

- K-means (k = 2)** identified distinct surface quality groups, with k selected using the **Silhouette Score**.

Future work:

- Explore **vibration data correlation** with roughness for real-time quality monitoring.
- Further refine **optimal printing conditions** by expanding parameter ranges.
- Assess effects of **half vs. full specimen geometry** on surface quality.
- Enhance print stability and **adhesion consistency** for improved reliability.

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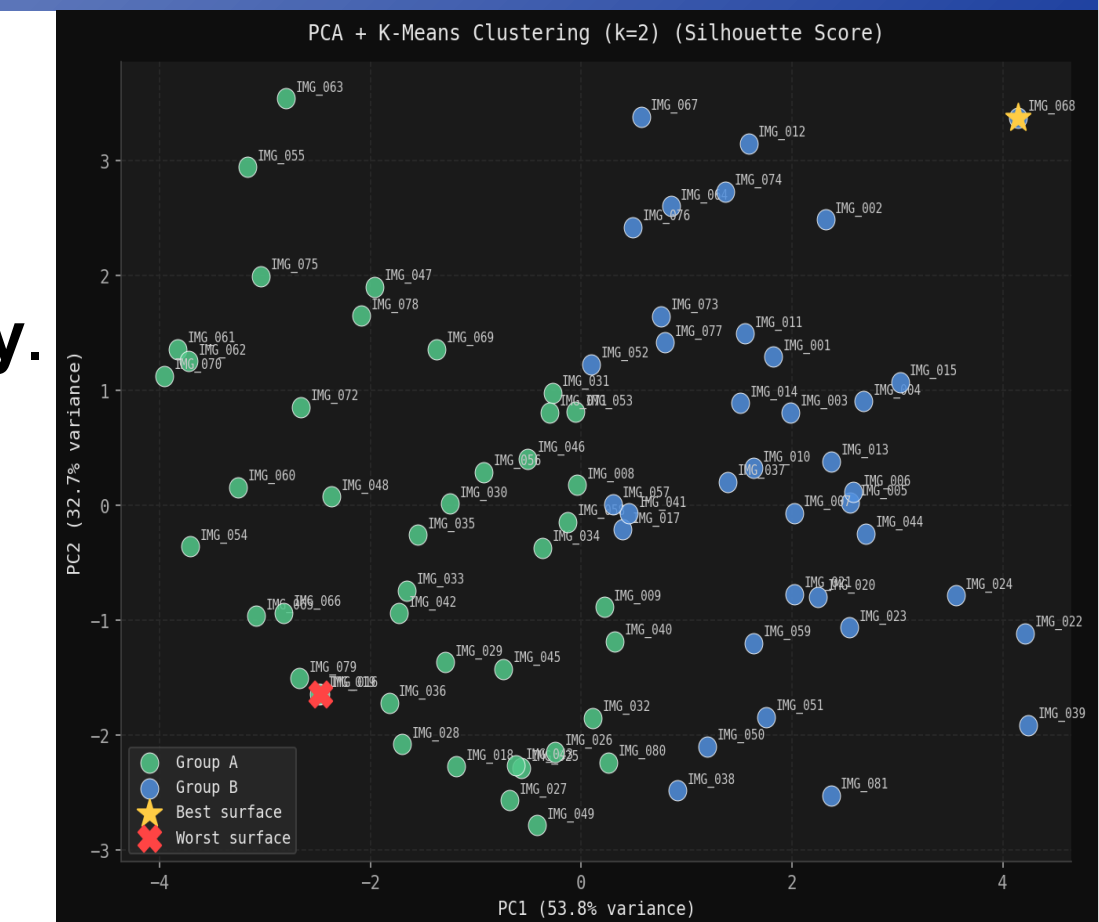


Figure 7. PCA + K-means clustering for smooth vs. rough surfaces.