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Mechanical Characterization of Stereolithography (SLA) 3D Printed Components using Multiple Photopolymer Resins

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Abstract - This study investigates the influence of build orientation, layer thickness, and infill density on the Charpy impact performance of Stereolithography (SLA) components fabricated using ABS-like and Flexible600 photopolymer resins. Utilizing a Taguchi L9orthogonal array, specimens were produced on an industrial ELEGOO Saturn 4 Ultra 16K printer according to ASTM D6110 standards. Statistical validation through Signal-to-Noise (S/N) ratio analysis and ANOVA identifies infill density as the most statistically significant parameter governing energy absorption for both materials. Experimental results reveal that the ABS-like resin achieves a peak impact strength of 0.641 J/mm at a 50 µm layer thickness, 45° orientation, and 70% infill. In contrast, the Flexible600 resin demonstrates superior impact resistance, recording a maximum value of 1.791 J/mm due to its elastomeric molecular architecture and high-strain energy dissipation. The findings establish that while rigid resins require high structural continuity, flexible resins benefit from specific parametric configurations that optimize volumetric deformation. This research provides a definitive framework for material-specific parametric optimization to enhance the structural reliability of multifunctional SLA components.

Keywords - Stereolithography (SLA), ABS-like Resin, Flexible600 Resin, Charpy Impact Strength, Taguchi L9 Optimization, ANOVA, Infill Density, Anisotropic Behavior, Energy Absorption.

1. INTRODUCTION

ISO/ASTM 52900 defines Additive Manufacturing (AM) as “the process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies.”(ASTM, 2021). Unlike conventional subtractive manufacturing methods, additive manufacturing minimizes material wastage and enables the production of highly complex geometries. Stereolithography (SLA), one of the earliest additive manufacturing technologies developed by Charles Hull, belongs to the vat photopolymerization family. In SLA printing, ultraviolet laser light selectively cures liquid photopolymer resin into solid layers to create the desired object.

SLA printing is widely used in medical, aerospace, dental, automotive, and prototyping industries because of its superior surface quality and dimensional precision. Despite these advantages, SLA printed components exhibit anisotropic mechanical behavior because of the layer-wise fabrication mechanism. Mechanical properties are significantly influenced by process parameters such as layer thickness, orientation angle, and internal structural density.

Build orientation determines the direction of layer deposition and directly affects interlayer bonding, residual stress distribution, and support generation. Similarly, layer thickness controls printing resolution and bonding quality, while infill density influences internal structural integrity and mechanical strength. Therefore, optimization of process parameters becomes essential to achieve reliable mechanical performance.

The present work focuses on investigating the effect of layer thickness, orientation, and infill density on the impact strength of SLA printed specimens manufactured using ABS-like and Flexible600 photopolymer resins.

2. LITERATURE REVIEW

Stereolithography (SLA) has revolutionized modern manufacturing by enabling the fabrication of complex geometries directly from digital models with minimal material waste. Among various additive manufacturing (AM) techniques, SLA occupies a critical position due to its high dimensional accuracy, smooth surface finish, and capability to produce intricate features. Beyond rapid prototyping, the process has become a viable manufacturing method for functional applications in aerospace, biomedical engineering, dentistry, and electronics (Husna et al., 2024).

Recent advancements in desktop SLA and DLP printing technologies have further evolved with improvements in printing speed, resin formulations, and curing systems (Kantaros et al., 2024). The mechanical performance of SLA-printed parts is a critical factor for functional suitability and is influenced by both resin chemistry and processing parameters. Research indicates that SLA components exhibit significant anisotropic behavior primarily governed by printing orientation. Experimental investigations have demonstrated that tensile strength decreases linearly with increasing printing orientation angle, while Young's modulus remains relatively unaffected (Li and Teng, 2024). This anisotropy arises from the layer-by-layer curing mechanism; previously cured layers experience lower temperatures than newly deposited ones, resulting in incomplete interlayer bonding (Li and Teng, 2024). Consequently, horizontally oriented specimens often exhibit higher tensile strength because the applied load is parallel to the layer planes, whereas vertical orientations are more susceptible to failure along layer interfaces. Optimization of parameters such as layer thickness and post-curing is essential for achieving enhanced strength and accuracy (Alghauli et al., 2024).

Thinner layers generally improve mechanical performance by reducing internal voids and increasing curing overlap (Husna et al., 2024). Furthermore, post-processing operations, including isopropyl alcohol (IPA) cleaning and UV post-curing, are vital to complete polymerization and improve stability (Kantaros et al., 2024). While UV exposure increases crosslink density, modulus, and hardness, excessive post-curing can increase brittleness by reducing chain mobility (Husna et al., 2024). A diverse materials palette now exists for SLA, ranging from standard and tough resins to rigid and flexible formulations. However, a significant gap remains in the literature regarding systematic, comparative studies that analyze multiple different photopolymer resin systems under identical processing conditions.

Most published work focuses on the properties of an individual resin, while there is limited research providing a direct comparative mechanical characterization across distinct material types fabricated with the same parameters. Material-specific guidelines for printing in SLA are necessary, and there is a distinct gap for materials like ABS-like and Elastic600 resins regarding material-specific parametric optimization. This research addresses these limitations through the Mechanical Characterization of the SLA Printed Multiple Photopolymer Resins.

3. MATERIALS AND EXPERIMENTAL METHODOLOGY

Material Selection and Specifications For this comparative investigation, two distinct commercially available photopolymer resins from ELEGOO were utilized: ABS-like resin and Flexible600 resin. The ABS-like resin was selected for its high-modulus, rigid characteristics, making it suitable for structural engineering applications. In contrast, the Flexible600 resin was chosen for its high-strain elastomeric properties, which facilitate superior kinetic energy absorption and impact resistance. These materials represent two functional extremes of the photopolymer spectrum, allowing for a comprehensive analysis of parametric influence across differing molecular architectures. Digital Modeling and Pre-processing The impact test specimens were designed in strict accordance with the ASTM D6110 standard to ensure the validity and reproducibility of the Charpy impact results. Geometric modeling was performed using PTC CREO®, a high-fidelity parametric CAD suite, and subsequently exported as Standard Tessellation Language (STL) files. The digital models were then processed in Chit box slicing software, where the specific process parameters—Layer Thickness, Part Orientation, and Infill Density—were assigned according to the generated Taguchi L9 Design of Experiments (DOE) matrix. Fabrication and Post-Processing Protocols Fabrication was executed on an industrial-grade ELEGOO Saturn 4 Ultra (16K) SLA 3D printer, which ensures high dimensional precision and consistent layer adhesion. The printing environment was maintained under controlled conditions to mitigate the influence of thermal fluctuations on the curing kinetics. Following the build cycle, a standardized post-processing protocol was implemented to ensure structural stability

Solvent Cleaning: Specimens were submerged in an isopropyl alcohol (IPA) bath to remove uncured residual resin from the surface Post-Curing: Cleaned specimens were subjected to a controlled ultraviolet (UV) light exposure cycle to maximize the degree of conversion and achieve full polymerization. Mechanical Characterization and Statistical Validation Charpy impact testing was conducted as per ASTM D6110 to quantify the energy absorption capacity of each specimen. To systematically analyze the resulting data, statistical validation was performed using the Taguchi Signal-to-Noise (S/N) ratio analysis, employing the "larger-is-better" characteristic to determine the optimal parametric combinations for maximum toughness. Furthermore, Analysis of Variance (ANOVA) was utilized to quantify the percentage contribution of each individual process parameter to the total variance in the impact response, ensuring the results are statistically significant.

4. DESIGN OF EXPERIMENTS (DOE)

Taguchi L9 Orthogonal Array Selection

In this study, a Taguchi L9 orthogonal array was employed to systematically evaluate the influence of critical Stereolithography (SLA) processing parameters on the impact strength of printed specimens. The Taguchi method was selected over a full-factorial design as it significantly reduces the number of experimental runs—from 27 (3^3) to 9—while maintaining a high degree of statistical reliability and providing sufficient data for Analysis of Variance (ANOVA) and Signal-to-Noise (S/N) ratio calculations.

The experimental design focuses on three primary factors, each varied across three levels to capture potential non-linear relationships:

1. **Layer Thickness (A):** Determines vertical resolution and interlayer fusion.
2. **Part Orientation (B):** Governs the anisotropic stress distribution during impact.
3. **Infill Density (C):** Controls the structural continuity and cross-sectional mass of the specimen.

Table 1: Taguchi L9 Orthogonal Array with Coded Parameter Levels

Part ID	Layer Thickness	Part Orientation	Infill Density
A1B1C1	30	30	30
A1B2C1	30	45	50
A1B3C3	30	60	70
A2B1C2	50	30	50
A2B2C3	50	45	70
A2B3C1	50	60	30
A3B1C3	70	30	70
A3B2C1	70	45	30
A3B2C2	70	60	50

The selection of these specific parameters and levels is justified by the inherent mechanics of the SLA process:

- **Layer Thickness (30, 50, 70 µm):** These levels represent the functional range of high-precision desktop SLA printers. Thinner layers (30 µm) are hypothesized to enhance interlayer bonding through increased curing overlap, while thicker layers (70 µm) facilitate faster production with potentially different energy absorption characteristics.
- **Part Orientation (30°, 45°, 60°):** Prior literature suggests that 0° and 90° orientations represent extreme anisotropic boundaries. By selecting intermediate angles (30°–60°), this study aims to quantify the complex stress-shielding effects occurring within the most common functional build envelopes.

- **Infill Density (30%, 50%, 70%):** Unlike traditional solid SLA prints, varying the infill density allows for a comparative analysis of structural efficiency. This range was selected to investigate the threshold where internal porosity ceases to be a "damper" and starts to compromise structural continuity.

The implementation of two replicates for each of the 9 runs (totalling 18 specimens per material) ensures that the experimental error can be accurately quantified during ANOVA testing, thereby strengthening the validity of the material-specific optimization for **ABS-like** and **Flexible600** resins.

5. RESULTS AND DISCUSSION

The experimental investigation into the impact performance of stereolithography (SLA) printed components reveals a fundamental divergence in energy absorption mechanisms between rigid and flexible photopolymer systems. For the ABS-like resin, the peak impact strength was recorded at 0.641 J/mm, whereas the Flexible600 resin exhibited a significantly higher maximum impact resistance of 1.791 J/mm. This substantial difference is primarily attributed to the intrinsic molecular architecture of the resins; the ABS-like material functions through a rigid polymer matrix that resists deformation until brittle failure occurs, while the Flexible600 resin utilizes a long-chain elastomer structure capable of extensive viscoelastic energy dissipation. These findings underscore that the transition from a rigid to a flexible resin system facilitates a nearly threefold increase in kinetic energy absorption capacity under high-strain-rate loading conditions.

Statistical analysis using the Taguchi L9 orthogonal array identified infill density as the most statistically significant parameter governing the mechanical response for both material systems. For the ABS-like resin, a direct correlation was observed between increasing infill density and impact toughness, with the optimal strength achieved at 70% infill. This suggests that higher structural density provides a greater cross-sectional area to resist crack initiation and propagation within the rigid matrix. Conversely, the Flexible600 resin reached its optimal performance at a moderate infill of 50%, indicating that a degree of internal porosity may actually enhance the material’s ability to "dampen" impact forces through volumetric compression. This highlights a critical research gap: material-specific parametric optimization is essential, as the high-density strategies favorable for rigid resins do not necessarily translate to the performance of elastic photopolymers like Flexible600.

The influence of part orientation further elucidates the anisotropic nature of SLA-printed components. The experimental data demonstrates that orientations of 45° and 60° consistently yield superior impact resistance compared to the 30° orientation. At lower orientation angles, the impact load often aligns with the layer interfaces, increasing the probability of interlayer delamination. However, at the optimized 45° (ABS-like) and 60° (Flexible600) build directions, the applied stress is distributed across multiple printed layers, forcing the crack to navigate a more tortuous path across the cross-linked network. Furthermore, ANOVA results confirmed that while layer thickness influences surface morphology, its contribution to bulk impact strength is lower than that of infill density and orientation. Ultimately, these results confirm that the mechanical integrity of SLA components is a synergistic result of intrinsic resin chemistry and optimized fabrication strategies, specifically regarding structural continuity and orientation-controlled stress distribution.

6. CONCLUSION

The experimental results lead to the definitive conclusion that SLA fabrication parameters are primary determinants of mechanical integrity, rather than resin chemistry alone. Statistical validation through ANOVA identifies infill density as the most statistically significant contributor to impact resistance, as it governs the cross-sectional structural continuity required to arrest crack propagation. Part orientation and layer thickness follow as secondary influential factors, primarily modulating the quality of interlayer bonding and the distribution of stress relative to the anisotropic layer planes.

A comparative assessment reveals that the Flexible600 resin provides superior energy absorption, recording a peak impact strength of 1.791 J/mm—nearly threefold that of the ABS-like resin’s 0.641 J/mm. This performance disparity is attributed to the elastomer-based molecular architecture of Flexible600, which facilitates viscoelastic dissipation. Ultimately, the study confirms that achieving optimized mechanical performance in SLA-fabricated components requires material-specific parametric strategies to maximize structural reliability and energy absorption.

7. FUTURE SCOPE

The future scope of this research lies in the transition from discrete material characterization toward the development of functionally graded additive manufacturing systems. Future investigations should explore the integration of machine learning algorithms, such as Artificial Neural Networks (ANN), to predict impact performance across a continuous spectrum of parameters beyond the discrete levels of the Taguchi L9array. Additionally, there is a significant opportunity to evaluate the long-term structural durability of optimized ABS-like and Flexible600 components under dynamic environmental stressors, including cyclic loading, thermal aging, and moisture absorption. Further research could also examine the mechanical synergy of hybrid reinforcement strategies, such as embedding continuous high-strength fibers or structural cores within the SLA resin matrix to push energy absorption thresholds for industrial applications. Such advancements will facilitate the development of standardized engineering guidelines for multifunctional and biomimetic SLA designs.

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