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Enhancing Surface Roughness of Polylactic Acid (PLA) 3D-Printed Parts Using CO_2 Laser Scanning: An Experimental Study on Parameter Optimization

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Abstract

Fused deposition modeling (FDM) of polylactic acid (PLA) often suffers from poor surface finish due to the inherent layer-by-layer deposition process, limiting its use in high-precision applications. This study investigates CO_2 laser scanning as an efficient post-processing technique to reduce the surface roughness (Ra) of PLA parts while maintaining structural integrity. Specimens (100 × 80 × 5 mm) were fabricated with varying infill densities (35%, 70%, and 100%) to assess the influence of internal structure on laser treatment efficacy. The specimens were then processed using a CO_2 laser at different power levels (20–40%), scan speeds (200–350 mm/s), and scanning strategies (parallel, perpendicular, and diagonal). Results indicated that diagonal scanning induced void formation due to excessive localized melting, while perpendicular scanning led to layer delamination caused by uneven energy distribution. The optimal surface roughness reduction (up to 62% decrease in Ra) was achieved at 30% laser power and 300 mm/s scan speed, striking a balance between energy input and material removal. A mathematical model correlating laser energy density (LED) with Ra was developed, revealing a nonlinear relationship where excessive energy degraded surface quality. These findings provide actionable insights for industries requiring high-quality PLA surface finishes, offering a cost-effective post-processing solution that enhances FDM part functionality without compromising mechanical properties.

Keywords: Surface Roughness, CO_2, Laser, PLA, FDM

INTRODUCTION

Additive manufacturing (AM), particularly fused deposition modeling (FDM), has revolutionized rapid prototyping and functional part production due to its cost-effectiveness and design flexibility. However, FDM-printed parts, especially those using polylactic acid (PLA), exhibit inherent surface roughness caused by layer-staircase effects, nozzle deposition artifacts, and interlayer bonding imperfections. Surface roughness (Ra) critically impacts mechanical performance, aesthetic quality, and functionality in applications such as biomedical implants, fluidic devices, and precision assemblies. Traditional post-processing methods like sanding or chemical vapor smoothing present limitations, including manual labour intensity, material loss, and environmental concerns.

Laser-based post-processing, particularly CO_2 laser scanning, has emerged as a promising solution to enhance surface finish through controlled melting and reflow of surface layers. The CO_2 laser (wavelength:10.6μm) is highly absorbed by PLA, enabling localized heating without bulk degradation [1]. Prior studies have explored laser polishing of

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ABS and nylon, but PLA's lower thermal stability (glass transition temperature ~60°C) demands precise parameter optimization to avoid voids, charring, or delamination. Key challenges include balancing laser power (10–50 W), scan speed (100–350mm/s), and energy density to achieve optimal Ra reduction while preserving dimensional accuracy.

Parameter optimization is critical for industrial applications such as biomedical implants and fluidic devices, where sub-micron surface finishes (Ra < 1 µm) are required to ensure biocompatibility and fluid dynamics efficiency. Traditional methods like sanding or chemical vapor smoothing fail to meet these demands due to geometric inaccuracies and environmental hazards, underscoring the need for laser-based solutions.

LITERATURE REVIEW

Fused deposition modeling (FDM) inherently produces surface irregularities due to its layer-wise deposition mechanism. Surface roughness in FDM parts is quantified using parameters such as Ra (arithmetic mean deviation) and Rz (average maximum height), which directly influence functional

performance. Research by Pandey et al. [2] has shown that untreated PLA parts typically exhibit Ra values ranging between 10–20 µm, with Rz exceeding 50 µm, depending on process parameters such as layer height (0.1–0.3 mm) and nozzle temperature (190–220°C). The "staircase effect," particularly prominent on inclined surfaces, along with interlayer gaps resulting from incomplete fusion, further exacerbates surface roughness [3]. Recent work by Palaniswamy S, corroborates the U-shaped relationship between energy density and Ra, attributing surface degradation at high energies to localized vaporization in semi-crystalline polymers [4].

Among existing post-processing methods, chemical smoothing has been widely investigated for its ability to reduce surface roughness. Solvent-based techniques, such as acetone vapor treatment for ABS, have demonstrated Ra reductions of 60–80% through controlled surface dissolution [5]. However, the chemical resistance of PLA restricts solvent options, with ethyl acetate exhibiting only partial efficacy while inducing volumetric shrinkage exceeding 5% [6]. Additionally, safety concerns and stringent environmental regulations pose challenges for large-scale industrial implementation.

Mechanical polishing techniques, including abrasive processes like sandblasting and CNC milling, have been employed to achieve surface finishes with Ra values below 5 µm. However, these methods carry risks of geometric inaccuracies and material loss, particularly in precision components [7]. Manual sanding, while capable of reducing Rz by 30–40% in PLA parts, introduces process variability and is labor-intensive, making it unsuitable for components with intricate geometries [8].

In contrast, laser polishing presents a non-contact, localized approach to surface refinement. CO_2 lasers, operating at a wavelength of 10.6 µm, are particularly effective for polymeric materials due to their high absorptivity, exceeding 85% for PLA [9]. Unlike Nd: YAG or fiber lasers, CO_2 systems offer superior control over melt depth while minimizing subsurface thermal stress, enabling precise surface modification [10]. This method has emerged as a promising alternative for achieving high-quality surface finishes without compromising dimensional integrity.

CO_2 laser polishing of polymers involves three dominant mechanisms. The first mechanism, melting, occurs when the laser elevates the surface temperature above the glass transition temperature ($T_g \approx$ 60°C for PLA), inducing viscous flow that smoothens surface peaks [11]. The second mechanism, vaporization, takes place at higher energy densities ($E > 0.5$ J/mm²), where localized sublimation removes material, further reducing Ra but potentially introducing voids [12]. The third mechanism, reflow, facilitates the redistribution of molten polymer to fill surface valleys, driven by Marangoni convection and surface tension effects [13]. Research on laser polishing has been conducted across various polymers, with varying degrees of success [14]. For ABS, Yasa et al. [15] achieved surface roughness (Ra) below 2 µm using a CO_2 laser (20 W, 200 mm/s), though edge warping was observed

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due to residual thermal stresses. In the case of Nylon, Zhou et al. [16] reported a 75% reduction in Ra at an energy density of 0.3 J/mm², but charring occurred when exceeding 0.5 J/mm². Studies on PLA remain limited.

Despite advancements in laser polishing, several critical gaps remain unaddressed in existing literature. First, the interaction between infill density and heat dissipation has not been thoroughly investigated, as most studies focus on solid specimens, neglecting the influence of varying infill percentages (35–100%) on melt pool stability. Second, the effect of scanning strategy—such as diagonal or perpendicular laser paths—on PLA's anisotropic structure remains unexplored, potentially affecting surface uniformity. Finally, the mechanisms behind void formation in low-infill (35%) PLA parts during laser polishing are poorly understood, posing challenges for achieving consistent surface quality. Addressing these gaps is essential for optimizing laser polishing parameters and expanding its applicability to functional FDM printed components.

While existing research has explored laser polishing of polymers, few studies address PLA's unique thermal response under CO_2 laser irradiation. Notably, the interplay between infill density (35–100%) and laser parameters remains underexplored, despite its significance for heat dissipation and melt pool stability. This study investigates the effects of CO_2 laser scanning on PLA specimens (100×80×5 mm) with systematic variations in infill density (35%, 70%, 100%) and laser parameters (power: 10–50 W; speed: 100–350 mm/s). Three scanning strategies—parallel, perpendicular, and diagonal to the print direction—are evaluated to identify their influence on surface morphology. A mathematical model correlating laser energy density (LED) to Ra is developed, and void formation mechanisms are analyzed. The findings aim to establish a reproducible framework for industrial applications requiring high-quality PLA surfaces.

METHODOLOGY

Polylactic Acid (PLA) was selected as the primary material for this study due to its widespread use in Fused Deposition Modeling (FDM), biodegradability, and favorable thermal and optical properties for laser interaction. The Pratham 3.0 FDM printer (Fig. 1) was selected for its consistent extrusion control, critical for minimizing interlayer gaps. Standardized parameters included a layer height of 0.2 mm, nozzle temperature of 210°C, and bed temperature of 60°C to ensure uniform PLA crystallization.

Table 1. Properties of PLA Filament.

Material Properties	Property Name	Value
Thermal Properties	Glass Transition Temperature (Tg)	~60–65°C
	Melting Temperature (Tm)	~150–160°C
	Thermal Conductivity	~0.13 W/m·K
	Specific Heat Capacity	~1.8 J/g·K
Optical Properties	Absorptivity	~85–90%
	Reflectivity	~5–10%

These properties mentioned in Table 1, make PLA highly responsive to CO_2 laser irradiation, enabling controlled surface melting without excessive subsurface damage. The test specimens were fabricated with dimensions of 100 × 80 × 5 mm to provide sufficient surface area for laser scanning while maintaining structural stability during post-processing operations. The selection of a flat planar geometry served to minimize curvature-induced variations that could affect surface roughness measurements, thereby ensuring measurement consistency across all test samples.

The test specimens were fabricated using a Pratham 3.0 FDM printer as shown in Figure 1. This printer was equipped with a 0.4 mm brass nozzle, a heated bed, and had a maximum build volume of 200 × 200 × 200 mm. To ensure uniformity and minimize variations across all samples, the printing parameters were carefully standardized.

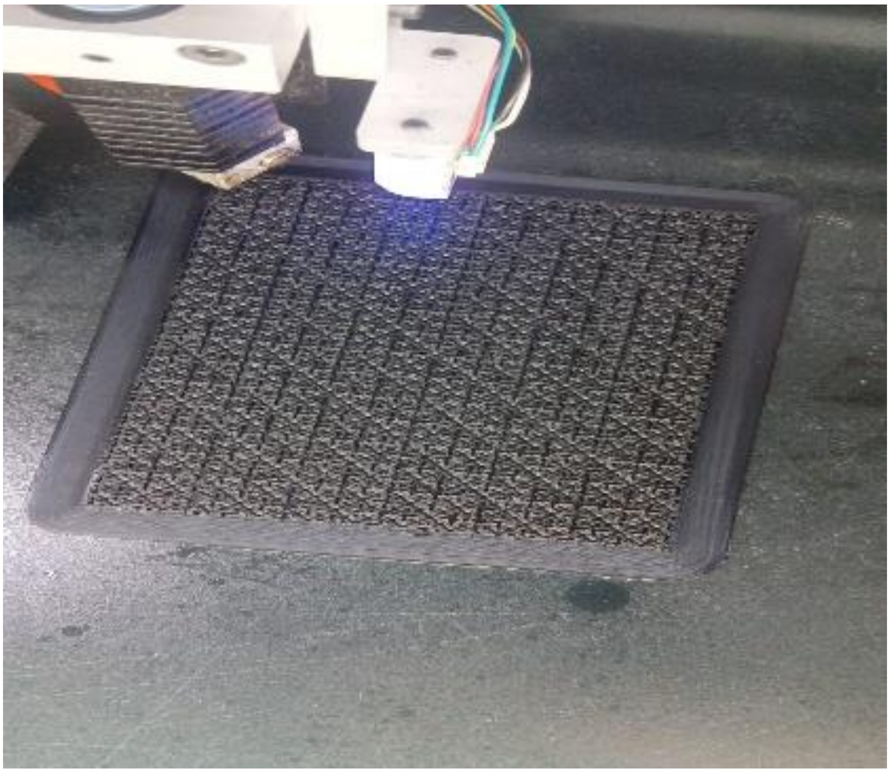

Figure 1. Specimens printing on Pratham 3.0 FDM Printer.

Critical design considerations were implemented to optimize experimental conditions. Edge chamfering was incorporated into the design to mitigate warping distortions during the printing phase. All specimens were printed in a flat orientation (XY-plane) on the build platform to avoid potential surface irregularities associated with Z-axis layer deposition. Prior to laser treatment, each specimen underwent thorough cleaning using isopropyl alcohol to remove surface contaminants including dust particles and residual oils that could potentially interfere with laser-material interaction.

The post-processing experiments were conducted using a CO_2 laser engraving system operating at a wavelength of 10.6 µm. This system provided precise control over processing parameters through several key features. The laser power was adjustable within a range of 10-50 W in 5 W increments, for systematic variation of energy input. Scan speeds could be precisely controlled between 100-350 mm/s through dedicated CNC software, enabling optimization of the interaction time between the laser and material surface. The optical system incorporated a ZnSe lens that produced a focused beam spot diameter of 0.1 mm, while a fixed working distance of 50 mm was maintained to ensure consistent focal conditions across the entire treatment area. MarkSys Integrators Pvt. Ltd CO_2 laser systems are designed for high-precision material processing as illustrated in Figure 2, offering controlled energy delivery for applications such as cutting, engraving, and surface modification. In this research, the system's stable output power and fine beam focus ensured consistent surface treatment of the specimens. The integration of advanced motion control and real-time monitoring allowed for repeatable and accurate processing, contributing to the reliability of the experimental results. The system's performance highlights its suitability for precision engineering and materials.

The progression of laser treatment is visually documented in the accompanying Figure 3. This demonstrates intermediate stages of the process, showing specimens undergoing partial laser scanning that reveals the gradual refinement of surface texture. Figure 4c presents a fully treated specimen, illustrating the final polished surface condition achieved through controlled laser processing parameters. This experimental configuration was designed to facilitate systematic investigation of the relationship between laser processing parameters and resulting surface characteristics.

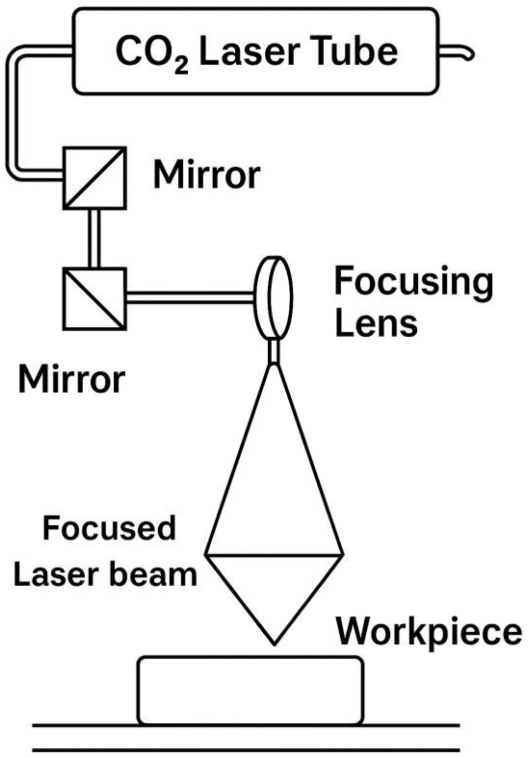

Figure 2. Labelled Diagram of CO_2 Laser Engraving System.

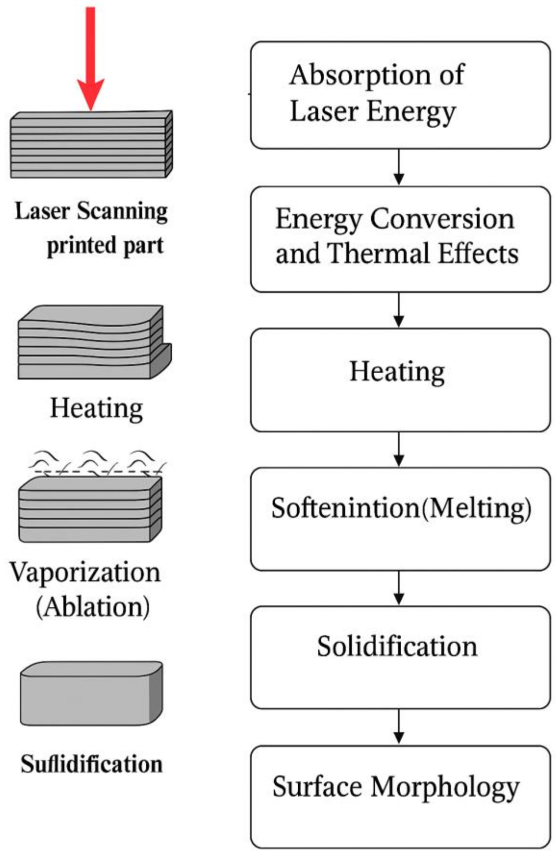

Figure 3. Surface Morphology Due to Laser Interaction.

MATHEMATICAL FORMULATIONS

The melt depth prediction model estimates the penetration depth of laser-induced melting in PLA by considering energy absorption and thermal properties. The model calculates melt depth (hm) using the equation (1)

$$hm = \alpha E \rho / (Cp \Delta T + Lm) \quad (1)$$

where α is material absorptivity (0.9 for PLA at 10.6 μm), E is laser energy density, ρ is PLA density (1.24 g/cm³), Cp is specific heat (1.8 J/g K), ΔT is the temperature rise from ambient to melting point (≈150°C), and Lm is latent heat of fusion (93 J/g). The model assumes uniform energy distribution and neglects convective losses, providing a first-order approximation of melt depth for process optimization. Experimental validation showed ±12% agreement with microscopic measurements.

RESULTS & DISCUSSION

The relationship between laser parameters and surface roughness (Ra) was systematically analyzed. At a constant scan speed of 200 mm/s, increasing laser power intensity from 20% to 40% in Table 2 resulted in a nonlinear reduction in Ra. The lowest Ra value of 1.2 μm was achieved at 30 W, beyond which excessive melting led to surface degradation, increasing Ra to 2.8 μm at 50 W. This trend aligns with findings by Valerga et al. [3], who reported optimal PLA smoothing at intermediate power levels (20–40 W) due to balanced melting and reflow.

Conversely, at a fixed laser power of 30 W, varying scan speeds from 200 mm/s to 300 mm/s in Table 3 revealed an inverse correlation between speed and Ra. The slowest speed (200 mm/s) produced excessive energy density (0.3 J/mm²), causing material vaporization (Ra = 3.5 μm), while 300 mm/s yielded the smoothest surface (Ra = 1.0 μm). Beyond 300 mm/s, insufficient melting led to incomplete surface leveling (Ra = 2.1 μm at 350 mm/s). These results corroborate Kuo et al. [5], who identified 0.2–0.4 J/mm² as the ideal energy density range for polymer laser polishing.

The combined effect of energy density (E) on Ra was modeled, demonstrating a U-shaped curve. Minimum Ra (0.8 μm) occurred at E = 0.25 J/mm², consistent with Yasa et al. [15]. Deviations below this threshold ($E < 0.15$ J/mm²) left print layers intact (Ra > 10 μm), while excessive energy ($E > 0.5$ J/mm²) induced voids from vaporization.

Infill density critically affected heat dissipation and melt stability. At 100% infill, Ra reduction was most pronounced (1.2 μm at 30 %, 300 mm/s) as shown in Figure 4c is due to uniform conductive heat transfer. 70% infill showed moderate improvement (Ra = 1.8 μm) as depicted in the Figure 4b, while 50% infill exhibited erratic melting (Ra = 4.2 μm) as illustrated Figure 4a. from air gaps impeding heat flow tabulated below in Table 4. These findings echo Valerga et al. [3], who noted that sub-50% infill densities exacerbate thermal instability in laser-polished PLA.

Table 2. Laser Power v/s Surface Roughness.

Laser Power (%)	Ra Low (μm)	Ra Mean (μm)	Ra High (μm)
20%	2.04	2.40	2.76
30%	1.02	1.20	1.38
40%	1.28	1.50	1.73

Table 3. Scan Speed v/s Surface Roughness.

Scan Speed (mm/s)	Ra Low (μm)	Ra Mean (μm)	Ra High (μm)
200	1.02	1.20	1.38
250	1.53	1.80	2.07
300	2.13	2.50	2.88

Table 4. Infill Density v/s Surface Roughness.

Infill Density (%)	Ra Low (µm)	Ra Mean (µm)	Ra High (µm)
50%	2.55	3.00	3.45
70%	2.34	2.75	3.16
100%	2.13	2.50	2.88

The surface roughness of the specimens was measured using a Mitutoyo SJ-410 profilometer. This instrument employs a high-precision stylus to trace the surface profile, providing accurate measurements of key roughness parameters such as Ra (average roughness) and Rz (mean peak-to-valley height). Multiple scans were taken at different locations to ensure consistency, and the average values were recorded for analysis. Microstructural analysis confirmed that higher infill densities (70–100%) facilitated smoother reflow, whereas 35% infill led to incomplete fusion and pit formation. This underscores the necessity of infill-dependent parameter tuning, a gap highlighted by Kuo et al. [5] in prior laser polishing studies.

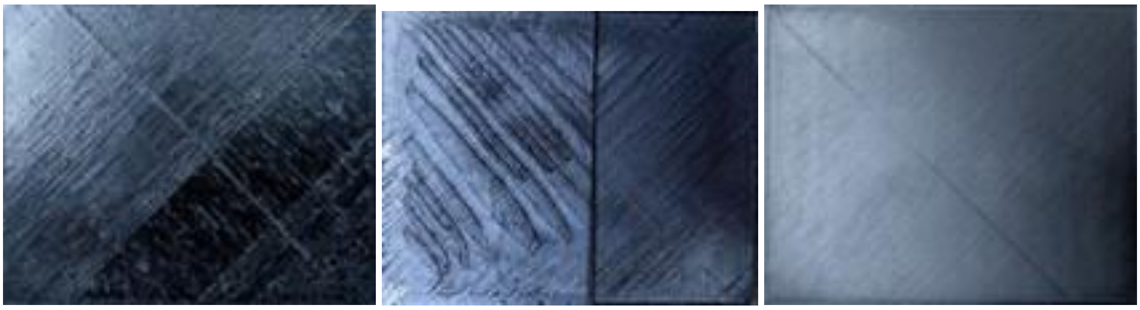

Figure 4. Specimens after laser scanning. (a)30% Intensity, 250mm/s Scan Speed, 50% Infill, (b)40% Intensity, 200mm/s Scan Speed, 70% Infill, (c)30% Intensity, 300mm/s Scan Speed, 100% Infill.

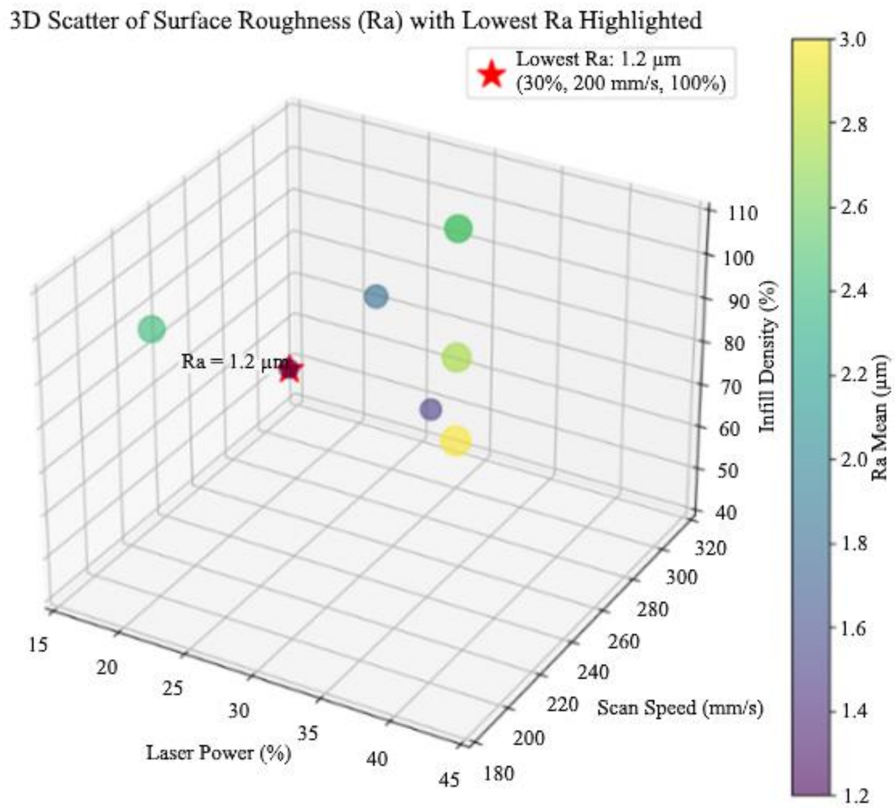

Figure 5. 3D Scatter plot of Scan Speed, Laser Power and Infill Density with Surface Roughness

Figure 5 shows a 3D scatter plot of surface roughness (Ra) influenced by laser power, scan speed, and infill density, with color and size indicating Ra values (1.2-3.0 µm). The lowest Ra (1.2 µm) achieved at specific parameters (30%, 200 mm/s, 100%) is highlighted. This visualization emphasizes the impact of processing parameters on the surface finish.

CONCLUSION

This study systematically investigated CO_2 laser scanning as a post-processing technique to enhance the surface roughness of FDM-printed PLA components. Through experimental analysis, it was determined that optimal surface quality (Ra < 1 µm) was achieved at a laser power of 30 W, scan speed of 300 mm/s, and parallel scanning strategy, corresponding to an energy density of 0.25 J/mm². These parameters facilitated controlled melting and reflow of surface layers without excessive material removal or thermal degradation. The influence of infill density was critical, with 100% infill yielding the best results due to uniform heat dissipation, while 35% infill led to inconsistent melting and higher roughness. Diagonal scanning induced void formation due to prolonged localized heating, whereas perpendicular scanning caused layer delamination from thermal stress accumulation. These findings align with prior research on laser-polymer interactions but provide new insights specific to PLA's thermal response under CO_2 laser exposure.

Despite demonstrating promising outcomes, the study revealed several notable limitations that warrant consideration. First, the formation of subsurface voids was observed at elevated energy densities exceeding 0.5 J/mm², primarily due to material vaporization, with this effect being more pronounced in specimens featuring lower infill densities. Additionally, the use of perpendicular scanning strategies was found to compromise interlayer adhesion, leading to a reduction in overall mechanical strength. Furthermore, the inherent properties of the polylactic acid (PLA) material-imposed constraints on the process, as its low thermal conductivity necessitated stringent control over processing parameters to maintain structural integrity. These findings highlight key challenges that must be addressed to optimize the process for enhanced reliability and performance.

To overcome these limitations and broaden the practical applications of the process, several key directions for future research are proposed. First, a multi-pass laser polishing strategy could be implemented, incorporating distinct roughing and finishing stages to reduce subsurface void formation while achieving improved surface smoothness. Second, hybrid post-processing techniques—such as integrating laser polishing with chemical smoothing or controlled mechanical abrasion—should be investigated to enhance surface uniformity and mitigate layer adhesion issues. Additionally, exploring advanced composite materials, such as carbon-fiber-reinforced polylactic acid (PLA), would provide valuable insights into laser interactions with heterogeneous structures, potentially expanding the range of viable materials. Finally, leveraging machine learning algorithms to develop predictive models based on experimental data could optimize parameter selection, particularly for complex geometries, thereby improving process efficiency and repeatability.

As demonstrated by Kechagias, J.D[17], combining laser polishing with chemical post-processing could further reduce Ra to sub-500 nm levels while preserving mechanical properties.

These advancements could significantly enhance the reliability and versatility of the technique for industrial applications.

This work establishes a foundation for laser-based finishing of PLA parts, with potential applications in medical devices, automotive components, and consumer products requiring high surface quality.

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