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Improvement of Surface Quality by Reducing the Part's Surface Roughness Texture

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Abstract: Polyamide (PA) materials are extensively used in Selective Laser Sintering (SLS) for producing functional components. Among them, DuraForm PA and DuraForm GF from 3D Systems, along with PA 2200 and PA 3200 GF from EOS, are widely adopted for their favourable mechanical and thermal properties. Glass-filled (GF) composites, composed of a polymer matrix reinforced with glass particles, provide enhanced stiffness and dimensional stability compared to unfilled PA materials.

This study focuses on improving the surface quality of laser-sintered (LS) parts and mitigating the rough surface texture characteristic of the SLS process. Experiments were conducted using a 2500 HiQ 3D System, employing a fractional factorial design of experiments (DOE) with five factors at two levels. The melt flow rate (MFR) was used as an indicator of recycled powder quality, with PA 2200 powder exhibiting an MFR range of 15–20. Results reveal that surface texture is strongly affected by scan spacing and interactions among laser power, scan speed, and scanning strategy. The proposed approach offers a systematic framework for optimizing LS process parameters for recycled PA 2200 powder, enhancing surface finish and overall part quality.

Keywords: Selective Laser Sintering (SLS), Polyamide 12 (PA12), Glass-Filled Composite, Rapid Manufacturing, Surface Quality Optimization

الخلاصة:

تُعدّ مواد البولي أميد (PA) من أكثر البوليمرات استخدامًا في تقنية التلبيد الانتقائي بالليزر (SLS) نظرًا لقدرتها على إنتاج مكوّنات وظيفية عالية الأداء. ومن أبرز هذه المواد DuraForm PA و DuraForm GFمن شركة D Systems3، بالإضافة إلى PA 2200 و PA 3200 GFمن شركةEOS ، لما تتميّز به من خصائص ميكانيكية وحرارية متفوّقة.

تتميّز المواد المركّبة المملوءة بالألياف الزجاجية — (GF) والمكوّنة من مصفوفة بوليمرية مُعزّزة بجزيئات زجاجية دقيقة — بزيادةٍ ملحوظة في
الصلابة والاستقرار البُعدي مقارنةً بمواد PA غير المملوءة، مما يجعلها
خيارًا مثاليًا للتطبيقات التي تتطلّب دقّة هندسية واستدامة ميكانيكية.

تهدف هذه الدراسة إلى تحسين جودة الأسطح المعالجة بالليزر (LS) وتقليل خشونة السطح الناتجة عن عمليةSLS ، وذلك من خلال تحليل منهجي للعوامل المؤثّرة على خصائص السطح. أُجريت التجارب باستخدام نظام D Systems 2500 HiQ3، وفق تصميم تجارب عاملي جزئي (DOE) خماسي العوامل على مستويين. استُخدم معدل تدفّق الذوبان (MFR) كمؤشرٍ تقويمي لجودة المسحوق المُعاد تدويره، حيث تراوحت قيم MFR لمسحوق PA 2200 بين 15 و20. أظهرت النتائج أن خصائص السطح النهائي تتأثّر تأثّرًا جوهريًا بكلٍّ من مسافة المسح والتفاعلات المتبادلة بين طاقة الليزر وسرعة المسح واستراتيجية المسح. يُقدّم هذا البحث إطارًا منهجيًا متكاملاً لتحسين معايير عملية التلبيد بالليزر لمسحوق PA 2200 المُعاد تدويره، بما يسهم في رفع جودة تشطيب السطح وتحسين الخصائص الوظيفية والموثوقية العامة للمكونات المنتجة. الكلمات المفتاحية: التلبيد الانتقائي بالليزر(SLS) ، البولي أميد 12(PA12) ، المواد المركّبة المملوءة بالألياف الزجاجية، التصنيع السريع، تحسين جودة السطح.

الكلمات المفتاحية: التلبيد الانتقائي بالليزر(SLS) ، بولي أميد 12(PA12) ، مادة مركّبة مدعّمة بالألياف الزجاجية، التصنيع السريع، تحسين جودة السطح.

1-Introduction:

One of the most effective and versatile rapid prototyping (RP) techniques is Selective Laser Sintering (SLS), also known as the Laser Sintering (LS) process. In this technology, objects are fabricated layer by layer from heat-fusible, fine powdered materials using thermal energy generated by a CO_2 laser [1]. Among the materials used, Polyamide 12 (PA12) or Nylon 12 powders are the most common due to their excellent mechanical performance, thermal stability, and processability. Some variants are composite formulations reinforced with glass, metal (e.g., copper or aluminium), or carbon fibres. Other polymeric materials such as polystyrene (PS), polycarbonate (PC), acrylonitrile butadiene styrene (ABS), ceramics, and metals have also been employed in the SLS process [2]. The particle size of the powder plays a crucial role in the fabrication quality; finer particles allow the formation of thinner layers, resulting in improved resolution and smoother surface finishes [3]. All PA12 powders are processed in a similar manner during the LS procedure, undergoing prolonged heating and cooling cycles at temperatures close to their melting point. These thermal conditions can induce both physical and chemical changes in the powder, leading to degradation of its mechanical and thermal properties over time.

Non-sintered powder can be recycled and reused; however, excessive reuse without sufficient addition of virgin powder can adversely affect part quality. Components produced from predominantly recycled powder often exhibit dimensional variations, increased shrinkage, and rougher surface textures compared to those fabricated from fresh material (Figure 1).

Figure 1 presents the surface texture of (SLS).

2- LITERATURE REVIEW

The quality of parts produced by the Selective Laser Sintering (SLS) process is governed by a complex interplay of material characteristics, process parameters, and operational conditions. It has been well established that the mechanical and surface properties of SLS-fabricated components are not only dependent on the intrinsic properties of the polymer powders used but are also significantly influenced by parameters such as laser power, scan speed, layer thickness, hatch spacing, and bed temperature [3]. These parameters collectively determine the energy density applied during sintering, which in turn affects the degree of particle fusion, porosity, dimensional accuracy, and surface morphology of the final product.

Kruth et al. [3] highlighted that the interaction between the laser and polymer material is central to understanding the sintering mechanisms in SLS. The absorption of laser energy leads to localized melting of powder particles, followed by solidification and bonding. The extent and uniformity of this melting process dictate the smoothness of the sintered layer and the interlayer adhesion, both of which are critical to surface quality. Improper selection of process parameters often leads to incomplete melting or overheating, resulting in surface irregularities, degradation, and dimensional inaccuracies.

The operational guidelines provided by DTM [4] for the Sinterstation® System 2500 underline the importance of precise control over temperature and laser energy input. These industrial guidelines emphasize that even small deviations in process stability can cause part distortion, curling, or surface roughness—particularly when recycled or aged powders are used. Maintaining consistent thermal gradients is therefore crucial for achieving homogeneous sintering and minimizing surface imperfections.

Ho et al. [5] further demonstrated the correlation between laser energy density and surface roughness in their investigation of polycarbonate materials fabricated through SLS. Their experimental findings showed that insufficient energy results in incomplete particle fusion, leading to porous and rough surfaces, whereas excessive energy promotes over-sintering, causing warping and thermal-induced distortions. The study also noted that optimizing the balance between laser power and scan speed can significantly enhance surface uniformity while minimizing curling and shrinkage.

From a materials perspective, Salmoria et al. [6] investigated the microstructural behaviour of polymer blends such as PA/HDPE during SLS processing and reported that the degree of crystallinity and thermal stability of the material influence the final surface finish. Their work revealed that polymer degradation and uneven melting behaviour, often associated with reused powders, contribute to reduced surface quality and dimensional inconsistency. These findings emphasize the need for a systematic investigation into the behaviour of aged or recycled powders, particularly PA2200 (PA12), which is widely used due to its favourable mechanical and thermal properties.

Complementing these studies, Naim [7] developed a finite element analysis (FEA) model to simulate curl development in SLS, offering insights into the thermal and mechanical stresses that occur during the sintering process. His work demonstrated that uneven heat distribution across the powder bed causes differential shrinkage, leading to warping and surface deformation. This highlights the necessity of optimizing process parameters to control thermal gradients and minimize distortion-related defects.

Despite extensive research on parameter optimization for SLS, there remains a distinct lack of experimental studies focusing specifically on the improvement of surface quality when using deteriorated or recycled PA2200 powders. Powder degradation—manifested through oxidation, molecular weight reduction, or altered flow properties—can significantly influence layer consolidation and surface finish. Therefore, to bridge this research gap, the present study adopts a Design of Experiments (DOE) methodology to systematically evaluate the effects of key process parameters on the surface texture of laser-sintered PA2200 parts. The study aims to identify optimal parameter combinations that enhance surface quality and maintain dimensional precision, even when recycled materials are incorporated into the production process.

3-EXPERIMENTAL DETAILS:

3. Method and Equipment

A Sinterstation 2500 HiQ machine was utilized for all experiments. A fractional factorial design of experiments (DOE) with five factors at two levels and three replications was conducted following an initial screening test. The primary objective was to evaluate how process parameters and powder quality affect the surface finish of laser-sintered parts produced from recycled PA2200 powder.

The powder samples tested included:
Virgin powder (new, supplied by EOS GmbH)
Once-used powder (1× recycled)

Twice-used powder (2× recycled, loose powder)

The melt flow rate (MFR) was measured to assess the quality and flow behaviour of the material after repeated LS cycles. The MFR values, expressed in g/10 min, were determined by extruding molten polymer through a die under controlled conditions of temperature and load.

3.1 Measurement Parameters for Melt Flow Rate (MFR)

The MFR measurements were performed according to ISO 1133 standard testing procedures. The tests were conducted at a temperature of 275°C under a load of 5.0 kg, using 8–10 g of material per test, as recommended by the Material Data Centre [8].

Each sample was tested six times, and the average MFR value was calculated. The recycled PA2200 powder used in the main experiments exhibited an MFR range of 15–20 g/10 min [9, 10]. This parameter served as an indicator of powder degradation and its suitability for reuse in the SLS process.

A qualitative scoring system was employed to evaluate surface quality based on visual inspection and tactile assessment of the fabricated parts.

3.2 DOE Experimental Approach for Surface Texture Reduction

The experimental framework is illustrated in Figure 2. The Design of Experiments (DOE) methodology was employed to determine the optimal combination of process parameters that minimizes surface roughness and improves overall part quality. DOE is an effective statistical tool for identifying the most significant factors affecting material behaviour and process outcomes.

Through this approach, the study seeks to establish the parameter settings that yield the highest-quality and most reliable LS parts, particularly when utilizing recycled PA2200 powder.

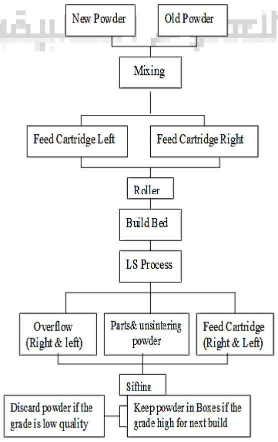


Fig. 2 Flow of powder cycling during HIQ LS process

3.3 Designing the Benchmark Part

The benchmark part was designed to incorporate features of varying thicknesses, shapes, and orientations, including surfaces oriented at different angles relative to the vertical z-axis, as illustrated in Figure 3. The overall dimensions of the part are 110 mm (width) × 110 mm (length) × 48 mm (height).

The final model was converted into STL format and subsequently transferred to the Laser Sintering (LS) machine (Sinterstation 2500 HiQ) for fabrication.

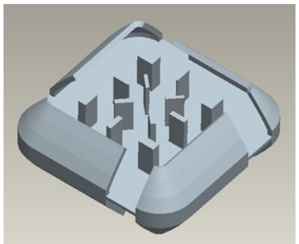


Fig. 3. CAD model of the benchmark part used for laser sintering experiments.

2.4 The score system

A response scoring system was introduced to evaluate the response variable Rv. Each fabricated part was individually inspected to assess its surface quality. The evaluation focused on the presence and severity of the "orange peel" surface texture, following the scoring criteria outlined in Table 1.

Table 1 Scoring system for evaluation of the Rv

Description	Score	Quality
Good surface finish	1	Acceptable
Slightly rougher surface finish, No "orange peel"	0.5	Acceptable
"orange peel" texture	0	Not Acceptable

2.5 Screening Test

In this experiment, all parts fabricated using a laser scan speed (LSp) of 3000 mm/s with laser powers (LP) of 9 W, 12 W, and 15 W exhibited severe surface texture defects. Parts produced at an LSp of 4000 mm/s with 15 W LP showed a slightly brown discoloration and a rough surface finish. These conditions corresponded to energy densities (ED) higher than the default setting. Consequently, the combinations of 3000 mm/s LSp and 15 W LP were excluded from the subsequent DOE.

Benchmark parts fabricated at 4000 mm/s and 5000 mm/s LSp with 9 W and 12 W LP demonstrated improved response values Rv and better surface quality. Following the screening test, a two-level factorial design with three replications was conducted.

The primary LS process parameters identified as significantly influencing surface quality and mechanical properties—and therefore selected for the DOE screening—were as follows:

Scan spacing (SCSP)
Laser power (LP)
Laser scan speed (LSp)
Scanning strategy (SST)

Part bed temperature (Tb)

The experimental runs were randomized to minimize systematic bias, determining the order of testing and the assignment of factor combinations. Figure 4 illustrates the arrangement of benchmark parts with different parameter settings built randomly in the LS chamber.

The build time of each benchmark part was compared with the standard build time based on default LS process parameters. Parts that exhibited the best and worst response values Rv were identified and analyzed. It was observed that the factor levels significantly affected build duration. For instance, parts fabricated at 4000 mm/s LSp required 1.04% to 1.23% longer build times than the standard, due to reduced scan speed. Conversely, parts produced at 5080 mm/s LSp showed negligible differences from the standard build time (less than 1%).

3. Optimization of the LS Process to Reduce Surface Texture:

Based on the surface response analyses and interaction plot results, the optimal combination of process parameters for minimizing surface texture was determined. The optimized LS process settings are summarized in Table 2.

Table 2 the optimum LS process parameter

Powder (MFR)	**15-20 & 15-16**
LP (W)	12
LSp (mm/sec)	5000
SCSP (mm)	0.15
(ºC)	170
SSt	Outline

3.1.1 Optimization of the LS Process Employing 15–20 MFR Powder

In this experiment, a Sinterstation 2500 HiQ Plus machine was used. The default settings—0.225 mm beam offset in both the X and Y directions and one-time (1×) outline scanning—were modified to a 0.38 mm beam offset, with one-time (1×), two-time (2×), and three-time (3×) outline scanning configurations.

Two powder qualities were tested:

Recycled PA2200 powder with a melt flow rate (MFR) of 18–19 g/10 min, used in the DOE optimization test.

Older recycled powder, exhibiting slightly lower flow performance.

The response variable Rv results indicated that adjusting the beam offset to 0.38 mm and modifying the outline scan count significantly improved surface appearance. No distinct surface defects were observed on the benchmark part features. However, the angled surfaces (as shown in Figures 4a and 4b) exhibited slight roughness, which was still considered acceptable in terms of surface quality.

The average Rv value achieved in this optimization experiment was 82%, exceeding the acceptance threshold of 65%. This confirms that the target Rv value was successfully achieved, demonstrating the effectiveness of the optimized process settings.

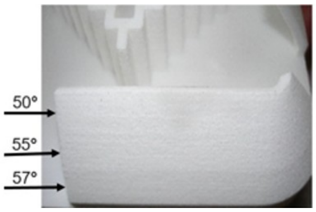


Fig. 4a Angled surfaces

Fig. 4b Vertical plain

3.1.2 Optimization of the LS Process Employing 15–16 MFR Powder

The second optimization experiment was conducted using heavily recycled PA2200 powder with a melt flow rate (MFR) of 15–16 g/10 min, representing significantly aged material. The results indicate that the average response value Rv obtained in this test was lower compared to that achieved with 15–20 MFR powder, and the samples exhibited higher shrinkage levels (ranging from 3.7% to 3.85%). These findings suggest that PA12 powder deteriorates substantially after extensive reuse, reaching a condition where the characteristic "orange peel" surface texture cannot be effectively minimized. Figures 5 and 6 illustrate the conical and angled surfaces along the z-axis (at 90° and 57° orientations), where the "orange peel" texture is prominently visible. Additional signs of surface roughness and textural irregularities were also observed along the z-axis at 50° and 55° angles.

Figure 5: The Characteristic "Orange Peel" Surface Texture Visible on Angled Surfaces (Aged PA2200 Powder).

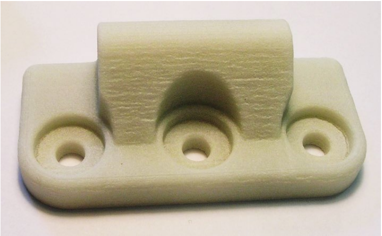


Figure 6: Textural Irregularities and Roughness of Component Printed with Heavily Recycled PA2200 Powder.

3.1.2 The Effects of Temperature and Time on Particle Size Distribution

In this experiment, the particle size distribution (PSD) was analyzed to quantify the changes in the size of unsintered new and aged PA12 powders resulting from prolonged exposure to heat.

The new PA12 powder exhibited an asymmetrical distribution, skewed toward smaller particle sizes, whereas the aged (recycled) PA12 powder also showed an asymmetrical distribution, but skewed toward larger particle sizes, as illustrated in Figures 7 and 8. As shown in Figure 7, the difference in mean particle size between the new and aged PA12 powders was relatively small, despite both distributions being asymmetrical. However, Figure 8 demonstrates that the arithmetic mean, median, and model values were not equal for either powder type. This indicates that temperature and exposure time exert a slight influence on particle size, while particle size itself has a strong impact on the melt flow rate (MFR).

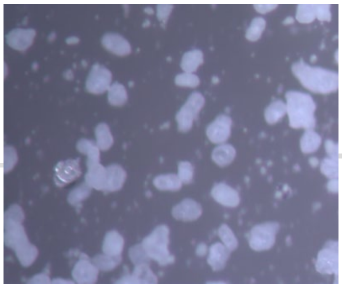
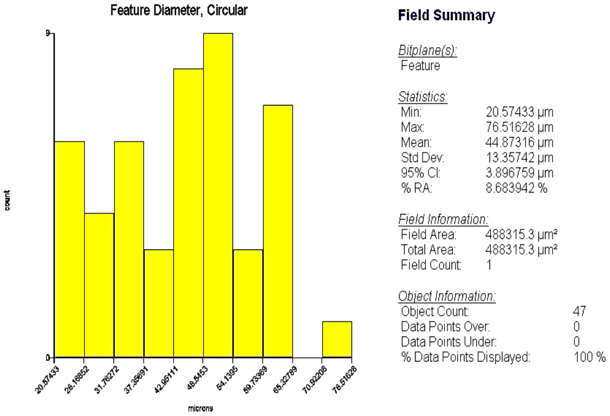


Fig. 7 Microscopic View and Comparative Particle Size Distribution (PSD) of New PA12 Powder.



Field Summary

Bitplane(s):
Feature

Statistics:

Min:	20.57433 µm
Max:	76.51628 µm
Mean:	44.87316 µm
Std Dev:	13.35742 µm
95% CI:	3.896759 µm
% RA:	8.683942 %

Field Information:

Field Area:	488315.3 µm²
Total Area:	488315.3 µm²
Field Count:	1

Object Information:

Object Count:	47
Data Points Over:	0
Data Points Under:	0
% Data Points Displayed:	100 %

Fig. 8 Statistical Analysis of Particle Size Asymmetry in New and Aged PA12 Powders (Comparison of Arithmetic Mean, Median, and Mode).

4. Conclusions

The reuse of PA12 powder in the LS process leads to a deterioration of surface finish, increased shrinkage, and the appearance of an “orange peel” texture. The recommended optimum process parameters—achieved by slightly adjusting the fill and outside beam offsets (X and Y) and applying twice the number of outline scanning cycles—were found to improve the Rv of the benchmark parts. This indicates that applying the correct combination of process parameters and energy density (ED) can significantly enhance viscous flow mechanisms and powder fusion, thereby reducing the “orange peel” texture. In contrast, applying the same optimum parameters to older PA2200 powder (15 MFR–16 MFR) did not eliminate the “orange peel” texture. This may be due to changes in the thermal and sintering properties of the deteriorated powder, which are not easily reversible. For example, a higher degree of chain entanglement in the polymer can increase viscous flow resistance, leading to more efficient packing of polymer chains and resulting in significant shrinkage. Additionally, the arithmetic and median particle sizes of both powders differ from their modal values, indicating that temperature and time have only minor effects on particle size, whereas particle size strongly influences the melt flow rate (MFR).

Acknowledgements

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