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Experimental investigation and optimization of the effect garnet vibratory tumbling as a post-process on the surface quality of 3D printed PLA parts

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Abstract: The method known as additive manufacturing causes high surface roughness between layers depending on the technique used at the end of the product development process. This can be an important problem in three-dimensional (3D) manufacturing depending on the usage area. To solve this problem, this experimental study investigated the effect of vibratory rolling (VT) on surface roughness in 3D printed Polylactic Acid (PLA) parts using garnet abrasive particles. Optimization with the best parameters was also performed and the results were analyzed. The surface roughness (Ra) values were measured at different vibration durations for each mesh size. The study involved subjecting the printed parts to vibratory tumbling using garnet abrasive particles of various mesh sizes (80, 90, 100, 120, 150, 180, and 220 mesh). Surface roughness measurements were taken at different vibration durations (2, 4, 6, 8, 10, and 12 hours) for each mesh size. A surface roughness measuring device was used to obtain the roughness values. The findings reveal that vibratory tumbling with garnet abrasive particles effectively reduces surface roughness in 3D printed parts. As the vibration duration increased, smoother surfaces were achieved. The surface roughness of the printed samples was reduced by 60% on average by using the optimum values after post-process.

Keywords: 3D printing, surface roughness, vibratory tumbling, garnet abrasive, additive manufacturing, polylactic acid part.

1. Introduction

Additive Manufacturing (AM), also known as 3D printing, is a revolutionary process that enables the creation of parts layer by layer directly from 3D model data. This method offers advantages over traditional manufacturing processes, mainly when producing complex, customized, or low-volume parts. As a result, AM has gained widespread adoption and significantly impacted various industries, including aerospace, automotive, defense, and healthcare. AM's benefits include advanced customization options, reduced inventory costs, faster delivery times, and less material waste than traditional manufacturing methods. However, one of the significant challenges associated with AM is the need for better surface quality of printed parts. This issue has prompted the development of pretreatment techniques to minimize errors and determine optimal printing parameters [1-5]. Unfortunately, these preprocessing methodologies often have limited effectiveness. Additional finishing techniques, such as surface treatment and machining, are often necessary to improve AM parts' dimensional and surface quality. Traditional methods like sanding, dremel tools, abrasive blasting, and barrel tumbling have been employed to achieve improved surface finishes. However, these techniques often come at the expense of dimensional accuracy [6]. For precision machining of complex parts, unconventional processes are required. One such process is Abrasive Flow Machining (AFM), which uses a flexible abrasive-based medium to achieve fine finishing of AM parts. AFM provides uniform, predictable, and repeatable results, making it well-suited for finishing complex geometries [7]. It has numerous industrial and material applications. Nevertheless, post-processes also have their limitations. Damage during the post-process can compromise the accuracy of the parts, and the chemicals used in specific processes may pose health risks to operators. To overcome these challenges, one approach is to design AM parts with finishing in mind. Potential issues can be addressed upfront by considering the finishing processes during the part design phase. Furthermore, better integration between AM technologies and

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post-processes could unlock additional opportunities for improving the quality of parts. In conclusion, AM holds tremendous potential despite the challenges of achieving high surface quality. Various pre-treatment and post-process techniques can enhance the surface quality of AM parts, making them suitable for a broader range of applications. The integration and better understanding of these techniques are crucial for the continued growth and evolution of AM.

There are studies on optimizing process parameters, improving surface quality, and providing dimensional accuracy in Fused Deposition Modeling (FDM) and other AM processes. Mohamed et al., 2015: This article reviews current research and future perspectives on optimizing FDM process parameters. It discusses various approaches for optimizing process parameters for improved surface quality and dimensional accuracy [8]. Pandey et al., 2003: Authors investigate ladder-like machining method to enhance the surface quality in FDM. They analyze the effect of machining parameters on surface roughness and dimensional accuracy [9]. Sood et al., 2009: This article proposes to use the gray Taguchi method to improve the dimensional accuracy of FDM parts. It explores optimizing process parameters to minimize dimensional errors [10]. Ahn et al., 2009: The authors propose a method for estimating surface roughness in AM processes, including FDM, using measurement data and interpolation techniques [11]. Mohamed et al., 2016: This article focuses on mathematical modeling and optimizing FDM process parameters. They use the Q-optimization design approach to optimize the process parameters using the response surface methodology [12]. Ahn et al., 2009: The authors work on the representation of surface roughness in FDM and propose a model to explain the roughness properties of FDM fabricated surfaces [13]. Ibrahim et al., 2014: This article investigates the effect of process parameters on surface quality and estimating the roughness of FDM-produced surfaces [14]. Reddy et al., 2018: The authors examine the surface texture of FDM parts and analyze the effect of process parameters on surface roughness [15]. Akande, 2015: This article focuses on preferred ability function analysis to optimize the dimensional accuracy and surface quality of FDM parts [16]. Boschetto et al., 2016: This article explores machining using CNC machining to improve the surface quality of FDM parts [17].

Adel et al., 2018: This article evaluates the surface roughness of FDM parts after hot air jet machining and analyzes the effect of the process on the surface roughness [18]. Taufik and Jain, 2017: The authors propose a laser-assisted machining process to improve the surface quality of FDM parts [19]. Lalehpour et al., 2017: This article examines the surface roughness of FDM parts after an acetone steam bath straightening treatment [20]. Galantucci et al., 2009: The authors conducted an experimental study to improve the surface quality of FDM parts [21]. Galantucci et al., 2010: This article quantitatively analyzes a chemical process to reduce the roughness of parts produced with FDM [22]. Garg et al., 2016: The authors examine the chemical vapor treatment of ABS parts made with FDM and analyze the effect of the treatment on surface quality and mechanical durability [23]. Singh et al., 2017: This article explores improving the surface quality of FDM parts by a steam straightening process [24]. Farbman and McCoy, 2016: Authors guide mechanical design by conducting material tests on 3D-printed ABS and PLA samples [25]. Singh et al., 2019: This article discusses multi-material AM of sustainable, innovative materials and structures involving FDM processes [26]. These references cover a broad knowledge of optimizing process parameters, improving surface quality, and dimensional accuracy in FDM and other AM processes.

When the literature is examined, no study has been found to improve the surface roughness by performing post-processing at different mesh sizes and at different times. In the experimental setup in this study, a vibratory post-processing application was carried out between 80 and 220 mesh and up to 12 hours. In addition, after the optimization process in which the best results were obtained, experimental verification was ensured by manufacturing. Thus, the target of successfully reducing the surface roughness to more acceptable levels has been achieved.

2. Material and Method

In the experimental study, geometries were chosen to represent samples where surface roughness is important. It is aimed to make the results obtained by printing in the parameters most preferred by 3D users more comprehensive. Printing parameters of parts produced from PLA material are seen in Table 1.

Table1. Production parameters of 3D printed parts with PLA material

Parameters	Units	Value
Layer height	(mm)	0.3
Shell thickness	(mm)	1.6
Bottom thickness	(mm)	1.6
Top thickness	(mm)	1.6
Fill density	(%)	20
Print speed	(mm/s)	50
Bed temperature	(°C)	60
Printing temperature	(°C)	220

A vibration tumbler was utilized in this experimental study to investigate the effect of vibratory tumbling (VT) on surface roughness in 3D printing PLA part using garnet abrasive particles (Figure 1.a). The vibration tumbler employed for this research had been specifically designed for this purpose and has been previously described in the literature [27,28]. The vibration tumbler consisted of a bowl or chamber, an electric motor, and an eccentric weight. The abnormal weight was carefully calibrated to provide the desired vibration intensity. A bowl/pool with a capacity of 5 liters (Leegol Electric 5LBs

PG-LG-003) made of steel material was used (Figure 1.b). Garnet abrasive particles with various mesh sizes (80, 90, 100, 120, 150, 180, and 220 mesh) were selected for the experiments. These garnet abrasive particles were commercially available and sourced from reputable suppliers. To perform the VT process, a predetermined amount of 3D printed parts was evenly distributed into the chamber of the vibration drum without using any fluid. The pieces were carefully placed to ensure consistent tumbling conditions. Subsequently, the appropriate garnet abrasive particles were added to the bowl according to the specific mesh size being tested. The VT, with the 3D printed parts and garnet abrasive particles, was operated for a predetermined duration for each experiment (Figure 1.c). The vibration duration varied for each mesh size and was carefully controlled to maintain consistency across the experiments. The duration of the VT process ranged from 0 to 12 hours, with specific time intervals (2, 4, 6, 8, 10, and 12 hours) chosen for measurement purposes. After the VT, the 3D-printed parts were carefully removed from the vibration tumbler for surface roughness measurement (Figure 1.d). Surface roughness (Ra) values were obtained using a surface roughness device (Mitutoyo Surftest SJ-210 Portable Surface Roughness Tester), following standard measurement procedures. The measurements were taken on multiple areas of each part to ensure representative data. The experimental design included ten replicates for each garnet mesh size, resulting in a total of 70 samples tested. The measurements of surface roughness were recorded for further analysis.

3. Results

The experimental results presented in the study demonstrate the effect of VT with garnet abrasive particles on the surface roughness of 3D-printed parts. The roughness measurements were conducted at different time intervals for each mesh size (80, 90, 100, 120, 150, 180, and 220). For the 80 mesh, the initial roughness Ra value was 24.45 µm, consistently decreasing as the vibration duration increased. At the end of the 12-hour vibration period, the roughness Ra value reached 16.8 µm (Figure 2.a). Similarly, for the 90 mesh, the initial roughness Ra value was 24.00 µm, gradually decreasing with longer vibration durations. After 12 hours of vibration, the roughness Ra value fell to 12.00 µm (Figure 2.b). In the case of the 100 mesh, the initial roughness Ra value was 23.8 µm. As the vibration duration increased, the roughness decreased progressively, reaching a value of 11.2 µm after 12 hours (Figure 2.c). For the 120 mesh, the initial roughness Ra value was 23.2 µm, consistently decreasing with longer vibration durations. At the end of the 12 hours, the roughness Ra value reached 10.0 µm (Figure 2.d). The 150 mesh exhibited an initial roughness Ra value of 22.9 µm. Increasing the vibration duration resulted in a gradual decrease in roughness, with a value of 9.6 µm achieved after 12 hours (Figure 2.e). For the 180 mesh, the initial roughness Ra value was 22.6 µm. The roughness decreased as the vibration duration increased, reaching a value of 9.2 µm after 12 hours (Figure 2.f). Finally, the 220 mesh also displayed an initial roughness Ra value of 22.6 µm. With longer vibration durations, the roughness decreased, reaching a value of 9.2 µm after 12 hours (Figure 2.g). These results highlight the effectiveness of VT with garnet abrasive particles in reducing surface roughness in 3D printed parts. The findings indicate that longer vibration durations lead to smoother surfaces, suggesting optimizing the vibration duration to achieve the desired surface quality. Overall, this study contributes to understanding the relationship between VT and surface roughness in 3D printing, and it emphasizes the potential of this method for improving surface quality in AM applications. Further investigations could explore additional parameters and materials to gain deeper insights into surface roughness in 3D printing processes.

For 80 Mesh, the equation is $y = -0.63x + 24.45$. This equation represents measurement data for the “80 Mesh” size. The negative slope (-0. 63) indicates that an increase in time results in a decrease in roughness Ra. In other words, as time progresses for this mesh size, roughness Ra decreases, starting at 24.45 µm when time is zero (Figure 2.a). For 90 Mesh, the equation is $y = -1.00x + 24.50$. This equation also signifies measurement data for “90 Mesh.” The negative slope (-1.00) indicates that an increase in time leads to a decrease in roughness Ra, with an initial value of 24.50 (Figure 2.b). For 100 Mesh is represented by the equation $y = -1.05x + 24.30$. The negative slope (-1.05) suggests that roughness Ra decreases as time increases, with an initial value of 24.30 (Figure 2.c). For 120 Mesh, the equation is $y = -1.10x + 23.70$, signifying data for “120 Mesh.” The negative slope (-1.10) indicates a decrease in roughness Ra with increasing time, starting at 23.70 (Figure 2.d). For 150 Mesh is represented by the equation $y = -1.11x + 23.35$. The negative slope (-1.11) suggests that roughness Ra decreases with time, with an

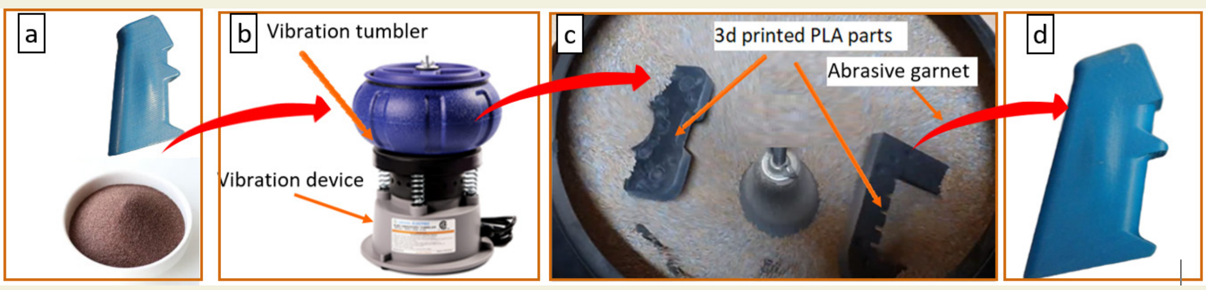

Figure 1. Post-process cycle (a) Garnet abrasive sand and PLA part (b) Experimental setup (c) The vibration tumbler with the 3D-printed parts is in progress (d) Processed part

initial value of 23.35 (Figure 2.e). The equation for 180 Mesh is y = -1.11x + 22.99. This equation represents data for "180 Mesh," and the negative slope (-1.11) indicates that roughness Ra decreases with time, starting at 22.99 (Figure 2.f). Finally, for 220 Mesh, the equation is y = -1.11x + 22.99. This equation represents "220 Mesh" data, and like the others, it has a negative slope (-1.11), indicating a decrease in roughness Ra as time increases, starting at 22.99 (Figure 2.g). All these equations express the linear relationship between time and roughness Ra for each mesh size. The slope reveals how steep or shallow this relationship is, while the intercept represents the initial roughness Ra when time is zero.

Figure 3 displays macro surface roughness views of 3D-printed parts after undergoing VT processes. The figure showcases the surface roughness of parts processed with different mesh sizes and vibration durations. Specifically, the figure illustrates the surface roughness of parts processed with the following parameters: 80 mesh for 2 hours of vibration (Figure 3.a), 100 mesh for 4 hours of vibration (Figure 3.b),120 mesh for 2 hours of vibration (Figure 3.c), and 220 mesh for 12 hours of vibration (Figure 3.d). The purpose of Figure 3 is to provide a visual representation of the surface roughness achieved for each combination of mesh size and vibration duration. By comparing the macro surface roughness views, one can observe the effects of different processing parameters on the surface quality of 3D-printed parts.

Figure 4 presents macro surface roughness views, comparing untreated 3D-printed parts with those subjected to vibrational tumbling using 80 mesh abrasive particles for different durations, specifically 6 and 12 hours. The untreated parts serve as a baseline reference (control surface), allowing us to assess the impact of the tumbling

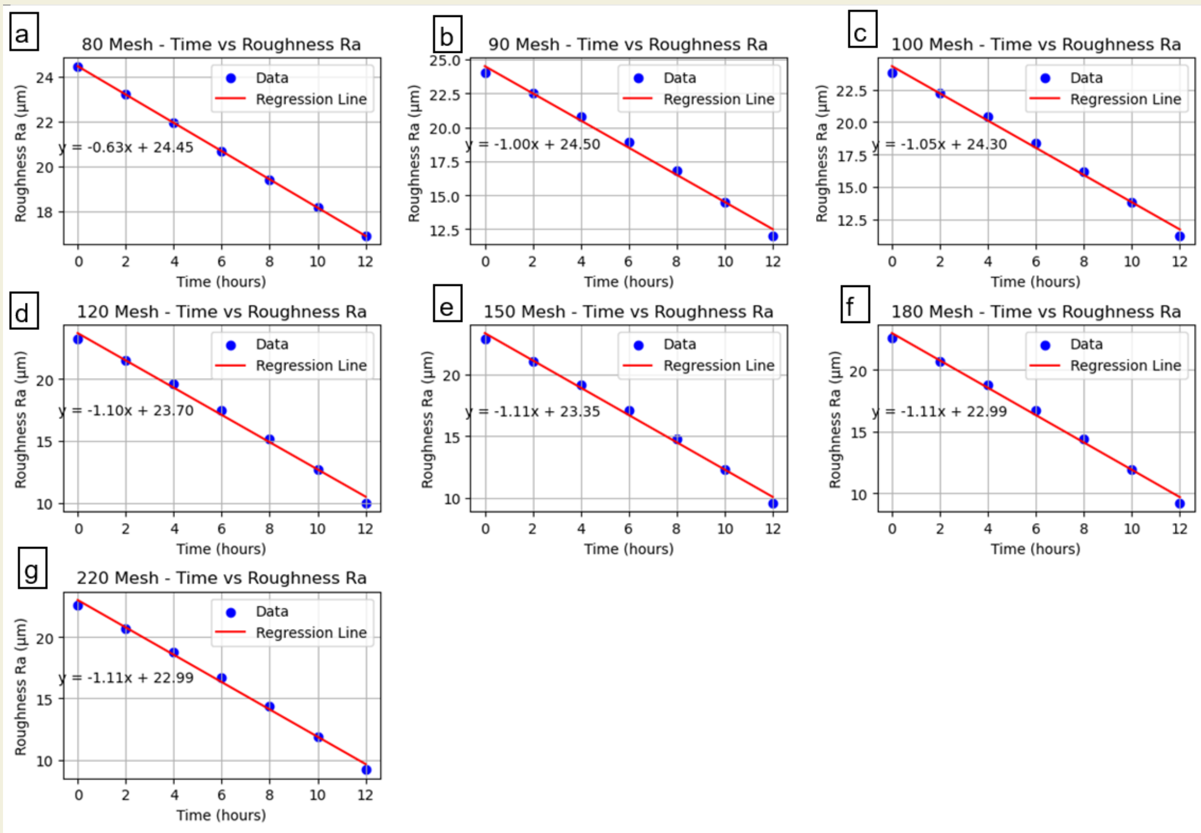

Figure 2. Results for different mesh sizes over various time intervals. (a) 80, (b) 90, (c) 100, (d) 120, (e) 150, (f) 180, and (g) 220 mesh

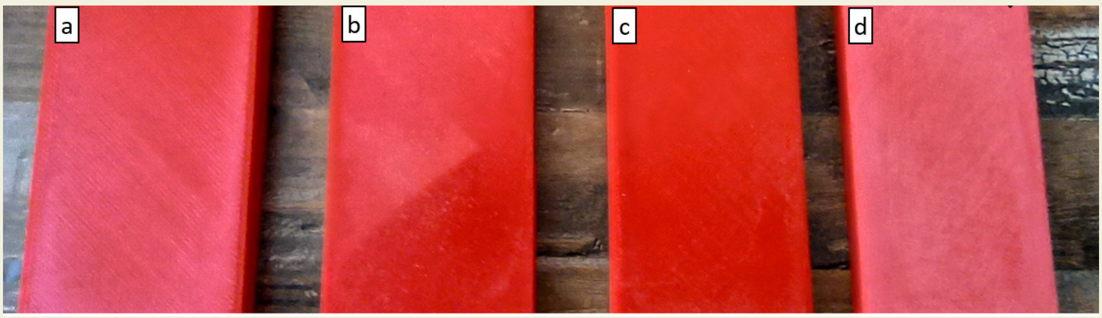

Figure 3. Randomly selected samples of a vibrated tumbler PLA part after the post-process (a) 80 mesh and 2 h, (b) 100 mesh and 4 h, (c) 120 mesh and 2 h, (d) 220 mesh and 12 h.

process on surface roughness (Figure 4.a). The images show clear surface texture and quality differences between the untreated and treated parts. As the tumbling duration increases from 6 to 12 hours, a noticeable improvement in surface smoothness is observed, indicated by a reduction in surface roughness (Figure 4.b and Figure 4.c). The findings underscore the effectiveness of vibrational tumbling with 80 mesh abrasive particles in enhancing the surface quality of 3D printed parts and highlight the importance of optimizing tumbling duration for achieving desired surface characteristics. These results contribute valuable insights for enhancing surface finish in AM applications and emphasize the significance of post-processing methods for improving overall part quality.

Figure 5 shows the optimal mesh sizes and corresponding durations that yield the most favorable surface roughness results in the context of the experimental study. The analysis shows that utilizing 180 mesh abrasive particles combined with a duration of 12 hours in the VT process leads to the lowest average surface roughness values among all evaluated combinations. Thus, it has been determined that the sandblasting process provides an average of 60% improvement in the surface roughness value. This finding underscores the significance of careful mesh size selection and duration optimization to achieve enhanced surface quality in 3D printed parts. Manufacturers can effectively minimize surface roughness by employing the recommended mesh size and duration, ensuring improved overall part quality and reinforcing the relevance of VT as a viable post-processing method in AM applications.

Figure 6 shows a scanning electron microscope (SEM) image of the micro-surface appearance of the 3D-printed parts after undergoing VT. The idea would provide a magnified view of the surface at a micro-scale, allowing for a detailed examination of the surface features and morphology. The SEM image would reveal the effects of

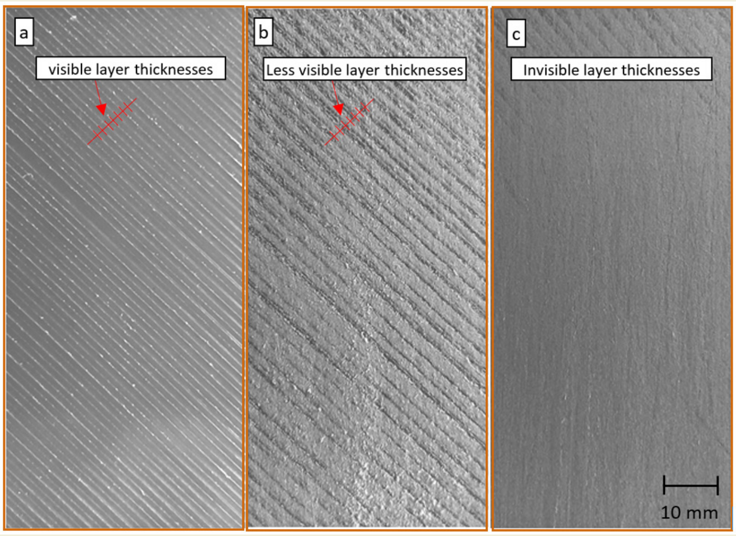

Figure 4. (a) Control surface (b) 80 mesh 6 h, (c) 80 mesh 12 h.

Figure 5. Optimization of surface roughness Ra (µm) best mesh size and duration

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the VT process on the surface of the 3D-printed parts. It may show the removal of layer lines or the presence of smaller-scale roughness features resulting from the tumbling action. The image could also highlight any changes in surface texture, such as smoothing or the formation of new surface structures. The purpose of Figure 6 would be to provide visual evidence and a closer examination of the micro-surface appearance after the VT process. It would aid in understanding the surface modifications and improvements achieved through this post-process method. The SEM images provide a high-resolution view of the microstructure of the surfaces, allowing for a detailed examination of the changes induced by the tumbling process.

Figure 6.a presents a surface roughness appearance of 21.93 µm after 80 mesh and 4 hours of application. Figure 6.b shows the surface roughness of 17.5 µm after 120 mesh and 6 hours of application, and Figure 6.c shows the surface roughness of 9.2 µm after 180 mesh and 12 hours of application. Figure 6.c also gives the SEM image of the surface roughness obtained according to the optimized results. Comparing the photos for each mesh size, distinctive surface features and topography variations can

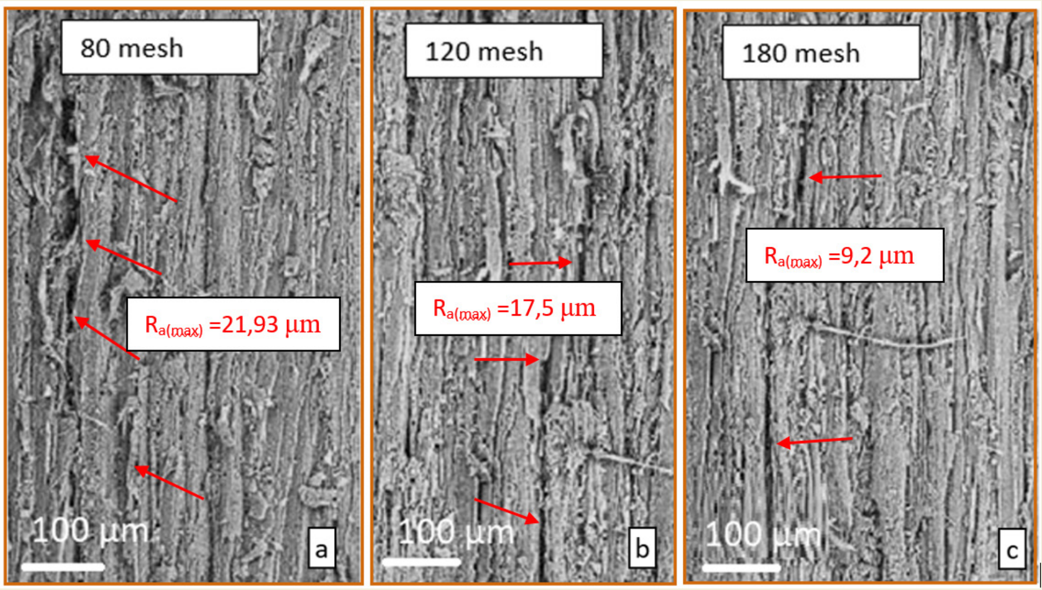

Figure 6. SEM image of the micro-surface of PLA parts. (a) 80 mesh and 4 h, (b) 120 mesh and 6 h, (c) 180 mesh and 12 h.

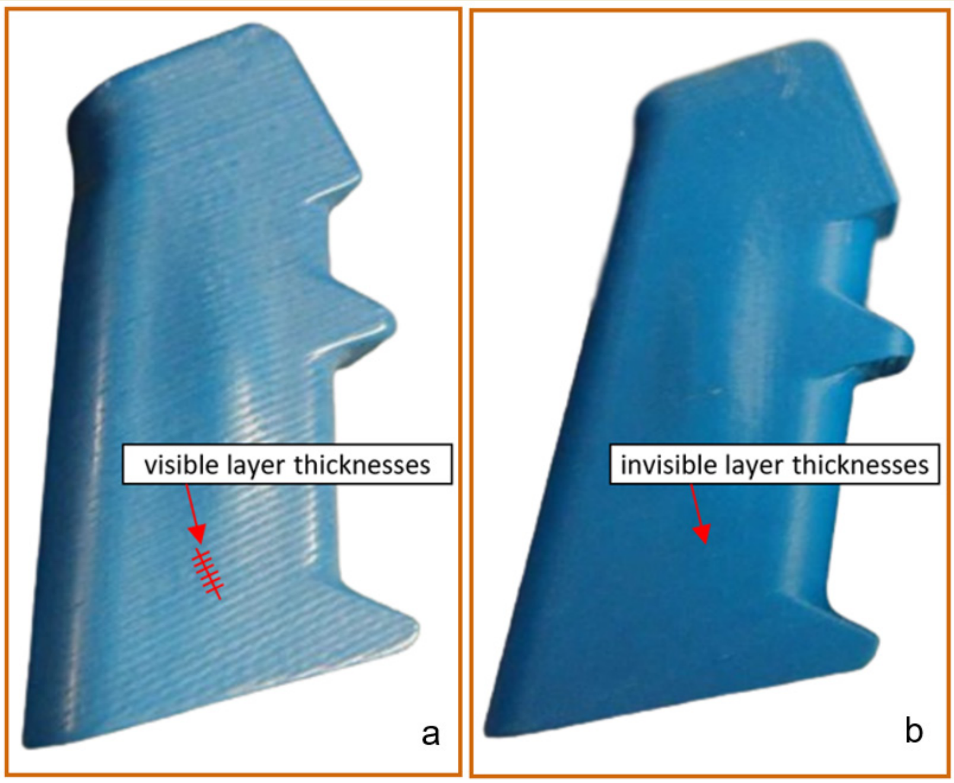

Figure 7. The comparison between 3D printed parts VT with (a) No post-process applied and (b) Post-processed according to optimized parameters.

be observed, revealing the impact of different abrasive particles on the micro-surface characteristics. The SEM images offer valuable insights into the effectiveness of VT with varying mesh sizes, shedding light on how specific mesh sizes influence the microstructural alterations of the 3D-printed parts. This analysis contributes to a comprehensive understanding of the relationship between mesh size and micro-surface quality, further advancing the knowledge of surface enhancement techniques in 3D-printing applications. The SEM images serve as a valuable visual aid, supporting the study's findings and emphasizing the significance of optimizing abrasive particle selection to achieve desired micro-surface properties in AM processes.

Figure 7 shows an example of a 3D-printed gun grip made of PLA material. Figure 7.a shows the no post-processing applied sample, and Figure 7.b shows the same sample as post-processed with optimized parameters. The purpose of this figure is to visually demonstrate the impact of VT on the surface quality of the 3D-printed parts. In image (Figure 7.b), which represents the 3D printed parts after VT with the optimized parameters, the surface appears smoother and more refined compared to the untreated parts in the image (Figure 7.a). The tumbling process using the optimal mesh size and duration has effectively reduced surface roughness, resulting in a more even and polished appearance. Additionally, any visible layer lines or surface defects that may have been present in the untreated parts are less apparent in the vibratory tumbled parts. By comparing both images, it becomes evident that VT with the optimized parameters has significantly improved the surface quality of the 3D-printed parts. This visual representation reinforces the findings presented in the results and discussion sections, highlighting the effectiveness of the VT process in achieving superior surface characteristics and enhancing overall part quality in AM applications.

4. Discussions

The experimental findings presented in this study shed light on the impact of VT with garnet abrasive particles on the surface roughness of 3D-printed parts. The results of roughness measurements conducted at various time intervals for each mesh size (80, 90, 100, 120, 150, 180, and 220 mesh) provide valuable insights into the effectiveness of this post-processing method. The initial roughness Ra values ranged from 24.45 μm to 22.6 μm (Figure 5, first line). They are notably, increasing the vibration time in all mesh sizes from 80 to 220 mesh decreases the surface roughness inversely. At the end of the 12-hour vibration period, the roughness Ra values reached their lowest points, measuring 16.8 μm for 80 mesh, 12.00 μm for 90 mesh, 11.2 μm for 100 mesh, 10.0 μm for 120 mesh, 9.6 μm for 150 mesh, and an impressive 9.2 μm for both 180 mesh and 220 mesh (Figure 5, last line). These findings demonstrate the efficacy of VT with garnet abrasive particles in reducing surface roughness, and they emphasize the importance of optimizing the vibration duration to achieve the desired surface quality. The graphical representation in Figure 2 further confirms the trend of decreasing roughness Ra values with longer vibration durations. The graphs clearly illustrate that extending the vibration time results in lower roughness Ra values for all mesh sizes, reinforcing the effectiveness of VT in enhancing surface smoothness. Figure 3 provides macro surface roughness views, visually illustrating the surface roughness achieved for different mesh sizes and vibration durations. This visual representation supports the experimental data, providing additional evidence of the positive effects of VT in enhancing surface quality. Comparing macro surface roughness views in Figure 4, it is evident that untreated 3D-printed parts show higher surface roughness than parts subjected to vibrational tumbling with 80 mesh abrasive particles. Notably, increasing the tumbling duration from 6 to 12 hours results in a significant improvement in surface smoothness, highlighting the importance of optimal tumbling time to achieve desired surface characteristics. Finally, Figure 5 illustrates that the optimal mesh sizes and durations yield the most favorable surface roughness results. Utilizing 180 mesh abrasive particles combined with a 12-hour vibration period led to the lowest average surface roughness values among all combinations tested. This finding underscores the importance of careful mesh size selection and duration optimization in achieving enhanced surface quality in 3D printed parts. In Figure 6, the SEM image provides a detailed examination of the micro-surface appearance of 3D-printed parts after undergoing VT. The SEM image reveals the tumbling process's effects on the parts' microstructural properties. The distinct variations in surface topography observed for different mesh sizes underscore the influence of abrasive particle selection on the micro-surface characteristics, further enhancing our understanding of surface enhancement techniques in 3D-printing applications. In conclusion, the results from this experimental study demonstrate the effectiveness of VT with garnet abrasive particles in reducing surface roughness in 3D printed parts. The findings highlight the relationship between vibration duration, mesh size, and surface roughness, indicating the potential of this post-processing method for enhancing surface quality in AM. Further research could explore additional parameters and materials to gain deeper insights into surface roughness in 3D printing processes, contributing to continuous advancements in AM applications.

In addition, the following main inferences can be made about the VT method.

- It is more preferable if it is aimed to improve the surface roughness of the entire part in the sandbox/pool during processing. However, if it is to be used for improvements in the surface roughness on partial areas, it is not necessary to spend time and energy for these surfaces as well. For example, while the surface quality is important for the hand-touched area of a gun's grip, as in Figure 7, the interior of the grip is not. However, since the whole part is processed in the sandbox, this can be said as the limitation of the VT method.

- In addition, the printed parts are contaminated during use. As a result of the difficulty of cleaning the residues accumulated in the recesses of the rough surfaces, it will cause negative results for terms of health. For this reason, the formation of these deposits on parts with lower surface roughness will become more difficult and it will be easier to clean. Thus, it can be said that VT is a helpful method in achieving antibacterial results.

- On the other hand, during the production of 3D-printed parts, it is inevitable to find burr residues after the parts added to hold the table well or after the support parts, if any, are separated from the main part. In order to remove these burrs from the part, the VT process helps to obtain more effective results in places where it is not very possible to perform burr removal with other methods, especially in narrow areas, depending on the geometry of the part.

- Many finishing methods result in chemical waste or tool wear. However, in the VT method, there are no such wastes or abrasions, and if the PLA particles in the garnet sand are added to the surface, the garnet sand can be cleaned by removing it from the surface due to the density difference. Garnet sand can be reused as a result of re-drying.

- When many post-process methods are started, they need to wait until they are completed. For example, in surface treatment, the part must be connected, and in order for the processing machine to be used for other works, the part must be disassembled and the machine must be unloaded. However, the sandblasting process not only requires cheap processing equipment, but also allows the process to be kept on hold when desired (or in cases such as power cuts), and then to continue the process from where it was left off.

- Since the sandblasting method in the industrial area is mostly done by spraying the garnet sand on the surface of the part under pressure, it is known that the dust inhaled during this application causes "*silicosis*" disease in the lungs of the operator. Since the VT process is carried out without pressure in a closed pool in the current study, it will not create such a problem. Another advantage of performing the process in a closed environment is that the garnet sand does not scatter around and does not cause environmental pollution.

- Another way to improve the surface roughness of 3D printed parts is to keep the layer thickness value low during the manufacturing phase. However, this will not only increase the printing time but also keep the printers busy, as well as reduce the total lifetime of the printer due to longer working hours. At the same time, there will be long-term energy consumption to keep the nozzle temperature around ~200 °C. By using the VT method as a post-process, larger layer heights can be preferred during the manufacturing phase and economical results can be achieved.

- Another advantage of the method is that a large number of parts can be placed in the sandbox and subjected to an all-in-one surface roughness improvement. If this improvement was tried to be achieved with printer parameters (layer thickness etc.), it would cost long production times for each part separately.

- On the other hand, in cases where different values of surface roughness are needed, some of the parts processed in the same pool can be taken from the sandbox/pool and their processes can be completed. In order for the remaining parts in the sandbox/pool to reach better values, the experiment can be continued by adding the parts that need new processing to the empty places.

5. Conclusions

The experimental findings of this study provide valuable insights into the effectiveness of VT with garnet abrasive particles in reducing surface roughness in 3D-printed parts. The results demonstrate a consistent decrease in roughness Ra values as the vibration duration increases for all mesh sizes investigated. Notably, the optimal mesh size and time combination yielded the lowest average surface roughness values was 180 mesh with a 12-hour vibration period. These results hold significant implications for the AM industry. The reduction in surface roughness achieved through VT can directly impact the overall quality and performance of 3D-printed parts. Smoother surfaces contribute to enhanced aesthetics, improved functionality, and increased longevity of the printed components. As surface roughness is known to influence mechanical properties, wear resistance, and friction characteristics, the findings of this study emphasize the potential of VT as an effective post-processing technique for enhancing part quality in AM.

Based on the experimental results, the following key points can be recommended for conclusions and practical applications:

- *Optimization of Vibration Duration:* The results indicate that longer vibration durations lead to smoother surfaces, as evidenced by decreased roughness Ra values. However, further investigations could explore specific vibration duration ranges for different mesh sizes to identify the ideal duration that maximizes surface quality while minimizing processing time. Fine-tuning the vibration duration can offer an efficient and cost-effective approach to achieving the desired surface finish.

- *Tailoring Mesh Size Selection:* The influence of mesh size on surface roughness was evident in this study, with different mesh sizes resulting in distinct surface characteristics. Further research could explore the relationship between abrasive particle size and its impact on microstructural modifications. Understanding how different mesh sizes affect the surface properties of specific materials can guide material-specific post-processing strategies.

- *Characterization of Mechanical Properties:* While this study focused on surface roughness as a primary measure of surface quality, future investigations could explore the relationship between surface roughness and mechanical properties, such as tensile strength, hardness, and fatigue resistance. This comprehensive approach will provide a more holistic understanding of the influence of VT on part performance.

- *Alternative Abrasive Particles and Materials:* Exploring the efficacy of different abrasive particles and materials in the VT process may offer new insights into surface enhancement techniques. Investigating materials with varying hardness and particle size distributions can better understand how different materials interact with 3D-printed parts during tumbling.

- *Process Integration and Automation:* As the AM industry advances, streamlining post-processing techniques, including VT, becomes essential for scalability and efficiency. Integrating VT into automated post-processing systems can further enhance the reproducibility and consistency of surface post-process results.

In conclusion, the results of this study highlight the potential of VT as a viable post-processing method for reducing surface roughness in 3D-printed parts. The findings contribute to understanding the relationship between VT parameters and surface quality in AM. Manufacturers can achieve smoother surfaces and improved part performance by optimizing vibration duration and mesh size selection. These insights are valuable for researchers and practitioners seeking to enhance the surface quality of 3D printed components and advance the capabilities of AM technologies.

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