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DEVELOPMENT OF LASER POLISHING AS AN AUXILIARY POST-PROCESS TO IMPROVE SURFACE QUALITY IN FUSED DEPOSITION MODELING PARTS

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ABSTRACT

Laser polishing is a highly effective surface treatment process mainly used on metals and optical components, but it can also be used on plastic parts. It requires no manual labor, can be applied on parts of any size, and produces no hazardous or polluting substances on many plastic parts. Fused deposition modeling (FDM) is an additive manufacturing process in which parts are built by extruding thin layers of hot material through a nozzle. It has the advantage of producing complicated part geometries, and the possibility to change a design with no additional cost. This study investigates the use of laser polishing as an auxiliary post-process on Polylactic Acid (PLA) parts produced with FDM to improve the surface quality of final products. Although YAG lasers are commonly used in assisting metal machining processes, a CO_2 laser was utilized in this study to post-process 3D-printed parts in order to reduce the staircase appearance. The main purpose of this study is to demonstrate that instead of reducing step size in 3D printing processes, it is possible to use bigger step sizes and laser treat the surface quickly afterwards to decrease the total process time while not compromising from surface quality. Laser speeds of 43-180 mm/s and laser powers of 0.75-3.75 W were tested on blocks of 3D-printed PLA with a parallelogram prism shape at 0.3 mm layer height. By varying laser speed and power, roughness reductions of up to 97% were achieved resulting in a uniform average surface roughness of 2.02 µm. This presents a fast, automatable, and inexpensive auxiliary post-process to FDM.

INTRODUCTION

Subtractive processes such as machining have dominated the manufacturing industries such as aerospace, automotive, biomedical, and energy production, where precision is important, in the last few decades [1-3]. However, with the development of advanced manufacturing processes such as additive manufacturing and laser polishing, engineers have realized that it is possible to produce some of the parts in these industries with more design freedom. Particularly in applications where mechanical properties of the final product are not as critical, or when prototyping speed is crucial for the process, additive manufacturing techniques are rapidly evolving and have already secured a place in the industry [4].

Additive manufacturing is still a relatively new technique where layers of material are stacked on top of the previous layers to create a part at the end [5]. It is mainly used for the production of parts with customized and complex geometries or for the development of prototypes. The main strength of the process is its design freedom and the opportunity to easily create features that would be difficult, if not impossible, to produce with conventional (subtractive) manufacturing processes [6]. According to the American Society for Testing and Materials (ASTM) standards, additive manufacturing processes are divided into seven subcategories, and material extrusion is one of the most common methods [7]. Fused deposition modeling (FDM) is an additive manufacturing process in this subcategory, in which parts are built by extruding multiple thin layers of molten material (usually plastic) through a nozzle and onto a build plate and allowing them to fuse together while cooling down [8]. It has the advantage of producing complicated part geometries, and the possibility to change a design with no additional cost. Currently, FDM is limited to prototypes and personal use due to the insufficient mechanical properties in end products [9]. The main reason for the poor mechanical properties in parts produced by FDM is having multiple layers bound together providing less structural integrity than a uniform internal structure [10]. Furthermore, in non-vertical (angled or curved) profiles, the layer-by-layer nature of the process creates a staircase appearance, causing small gaps [11]. The staircase appearance might result in dimensional inaccuracies; furthermore, the gaps caused by this appearance act as cracks that lead to fatigue failure [12-13]. In parts that are designed to be prototypes, having the staircase appearance and cracks may not be a serious issue since mechanical properties are not the main priority. However, if additive manufacturing is considered as a potential replacement for subtractive processes, surface quality and dimensional accuracy are important aspects of the process. Therefore, it is essential to minimize this staircase appearance. Using a thinner layer size reduces gap size and therefore the risk of crack initiation and fatigue failure, but it significantly increases process time. This method is also limited by the minimum nozzle diameter available. Therefore, using post-processing techniques to treat the part surface is a more efficient way to eliminate the problem [14-16]. Currently, the most common techniques are:

- Sanding: performed manually, which makes it unsuitable for industrial production.
- Bead / sand blasting: the process is effective and automatic. However, a containment chamber is required which makes it impractical for large parts.
- Chemical post-processing: chemical baths can be used to smooth FDM parts. However, they can alter their mechanical properties and damage thin or fragile features.

As none of these techniques are suitable for large-scale production of non-fragile parts, a different technique is required. To bring FDM to an industrial scale, an auxiliary process that is automatable, adaptable, and does not affect mechanical properties of the part is necessary. To this end, auxiliary assistance after the part is printed can be utilized. Application of heat on the rough surface can be an easy way to achieve a smooth surface; however, it is difficult to control a temperature field to reach desired results. It is challenging to reduce the surface roughness to desired values while not affecting sub-surface features. Therefore, use of focused energy sources instead of energy fields is a necessity in making sure that only desired geometry is removed.

Laser polishing is a post-processing technique where such a focused energy laser beam is used to reduce the surface roughness of a part manufactured through different processes. It is currently used on metals [17], diamonds [18], and micro-optic components [19]. A focused laser is applied to the material surface to melt irregularities, creating a more even surface profile and reducing surface roughness (Figure 1) [20]. The process can be automated and applied to a wide range of sizes and shapes with the help of a robotic arm. When used as an auxiliary process on machined metal parts, it is highly effective in treating the surface to desired quality. In such cases, final average surface roughness values (R_a) of down to 1.2 μm (80% reduction compared to initial roughness) have been achieved [17]. For metals, a YAG laser is usually used whereas for organic materials such as wood, acrylic, and rubber, a CO_2 laser is more suitable. The difference in the wavelength of the two types is what makes them more effective in different materials. The use of laser assistance on plastic parts is relatively unknown, since the quality of the surfaces coming out of injection molding or similar plastic manufacturing processes is usually not as critical. However, if a 3D printed part is of concern, and the dimensional accuracy is of importance, it is essential to evaluate the potential solutions. In this study, the effect of polishing using a CO_2 laser on Polylactic Acid (PLA) parts 3D-printed via FDM to improve the surface quality through reducing the roughness and thus the staircase appearance is investigated. In addition to the increase in surface quality, potential of using laser polishing as an auxiliary process to reduce process time is also explored.

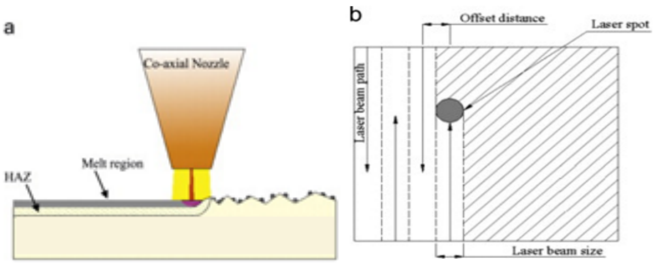

Figure 1: Example of laser polishing process [20]

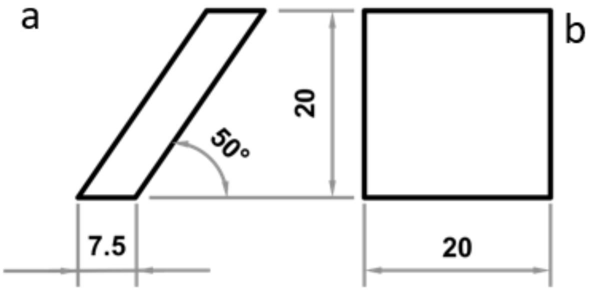

Figure 2: Sample block dimensions (mm). (a) Side (b) Front

EXPERIMENTAL SETUP

In this study, sample blocks of parallelogram prism shape (Figure 2) were produced for the experiments. These samples were 3D-printed using a MakerBot 3D printer with the maximum allowed layer thickness of 0.3 mm, where the width (7.5 mm) would be on the bottom and the top during the build. This way, each layer would be composed of a rectangle of 20 mm x 7.5 mm area, and each layer would shift by a small amount to one side to create the parallelogram prism shape (Figure 2). Since at a 45° angle the block did not print properly, a 50° angle was used. By 3D-printing in this fashion, it was ensured that the sides of the build (20 mm x 20 mm square shape) would include the staircase appearance. Then, the blocks would be flipped 50° so that the rough surface with the staircase appearance would be on the top and the bottom, making it easy for the laser cutter to stay in focus on. The dimensions of the blocks were carefully chosen in order to maximize the initial surface roughness, which would help in observing the percentage reduction and minimizing the noise.

After the samples were 3D-printed via FDM, they were polished using an Epilog Fusion CO_2 laser cutter. The inner side of the block was used in all tests for consistency. This equipment has a P = 75 W maximum power, v = 10 in/s (254 mm/s) maximum speed, and D = 0.006 in (152.4 µm) spot diameter, and allowed the use of any integer percentage of the maximum power and speed values. Unfortunately, any value other than an integer percentage (*e.g.* 12.5%) would not be achievable, so the experiments were designed accordingly. Power values between P = 0.75 to 3.75 W (1-5%) and speed values between v = 120 and 180 mm/s were tested (Table 1). Researchers have also shown that the amount of overlap between laser paths can affect the process [21]. Since two parameters were already being varied, overlap was kept constant at 0%. Finally, although the values of power and speed were determining factors, a combination of both was used to investigate the differences between experiments. In many studies where a pulsed laser is employed, fluence is used as the determining parameter [22]. However, Energy Density (*ED*), the amount of energy applied per surface area, is the determining parameter in laser polishing [22] when a continuous laser is utilized, and it was used for comparison in this study as well (Eq. 1).

$$ED = \frac{P}{vD} \qquad (1)$$

Table 1: Experimental range at constant 0% path overlap

Parameter	Unit	Low Condition	High Condition
Speed	**mm/s**	43 (17%)	180 (71%)
Power	**W**	0.75 (1%)	3.75 (5%)

Surface roughness was measured before and after each laser polishing process using a Mahr PS1 surface profilometer. Three repetitions of each measurement were conducted both parallel and perpendicular to the layer marks on the part. Since it is the most common measure of surface roughness, arithmetic average roughness values (R_a) were used in comparison.

RESULTS AND DISCUSSIONS

After each block was 3D-printed, all surfaces were visually inspected and the surface roughness was measured. These parts had the standard staircase appearance, and few other irregularities. In cases where the surfaces exhibited unusual characteristics due to printing-related and printer-specific issues, test pieces were reprinted to ensure that the experimental results were not biased. After laser polishing, the treated surface of each block was also visually inspected. Blocks had a glossy, reflective appearance, which is an expected outcome of the laser polishing process (Figure 3). It was also possible to observe both the initial layer marks created by the 3D-printing process as well as the laser marks. Since the laser polishing process is known to be precise once the machine is calibrated, tests were not replicated. Roughness measurements were replicated three times and averaged to ensure minimal measurement error.

Figure 3: Blocks partly treated with the laser polishing process

Measuring surface roughness parallel and perpendicular to the layer marks was necessary to evaluate the overall roughness of the part correctly. In a similar way to feed marks in machining, layer marks in FDM parts cause the mechanical properties to vary directionally. Usually, the weakest set of properties is used to calculate engineering requirements and factors of safety. Therefore, the mechanical properties of a material are preferred to be consistent along directions rather than to vary directionally. When the surface roughness was measured on 3D-printed parts, average values of 34.5 µm in the direction perpendicular to 3D-printing layer marks and 1.18 µm in the parallel direction were recorded (Table 2).

Since continuous filament was extruded in the parallel direction, a low surface roughness was expected. The main target in this study of using laser polishing as an auxiliary process was to reduce the surface roughness in the perpendicular direction while not increasing the total process time. Therefore, the small increase in the surface roughness parallel to the layer marks due to laser polishing, which brings the values closer to the perpendicular values, is not of concern in this study. If anything, it is viewed as a positive outcome since the surface quality in two directions is more consistent after the laser polishing (15% difference between the two directions after polishing as opposed to the 97% difference before polishing).

Table 2: Comparison of surface roughness (R_a) before and after laser polishing (ED = 10.6 J/cm^2) perpendicular and parallel to 3D-printing marks

	Perpendicular µm	Parallel µm	Difference %
3D-printed	34.5	1.18	97
Laser polished	2.02	2.33	-15

It was observed that the different laser parameters had a wide range of effects on the test blocks. Energy densities above ED = 11.5 J/cm^2 completely cut through the block surface, and below ED = 4 J/cm^2 had no measureable effect on the part.

Therefore, after calibrating the energy density with minimum and maximum meaningful values, all remaining experiments were conducted within that range. The hypothesis was that the energy density can be utilized as a controlling parameter (by changing the speed and power) to change the surface roughness, as was shown by Chang *et al.* (2016) (Figure 4a) in a study on the effect of laser polishing on H13 tool steel [22]. Supporting this hypothesis, for energy density values between *ED* = 4.3 to 11.1 J/cm^2 at 0% overlap, laser polishing of 3D-printed PLA parts showed a similar trend to the results for tool steel (Figure 4b). Note that due to the use of a pulsed laser, fluence is the independent variable in **Figure 4**a, whereas energy density (*ED*) is the independent variable for the results of this study (Figure 4b) since a continuous laser is utilized. The vast difference between the fluence required to polish tool steel and the energy density required to polish PLA is due to the fact that (1) penetrating into steel requires significantly more laser power than PLA, and (2) a pulsed laser has a smaller time frame to effect the material. However, it is important to see the similarities between the trends in the reactions of PLA and tool steel to laser polishing in terms of surface roughness reduction, since there is a greater amount of research done on laser polishing of metals. The results of this study can play an intermediate role in connecting the behaviors of two different types of materials under laser polishing.

Lowest energy density values achieved by low power and high speed (Figure 4b) reduced the perpendicular surface roughness from approximately 34.5 µm to 32.4 µm (6%), which is not a significant change. However, the laser polishing process quickly started to show its effect after utilizing higher energy densities, supported with a 67% surface roughness reduction from the 3D-printed part at *ED* = 5.54 J/cm^2 to 11.3 µm. From there, the effect of increasing the energy density proved useful until approximately *ED* = 7 J/cm^2 where a reduction of 95% was achieved, at which point surface roughness was measured as 1.89 µm. It can be seen on **Figure 4**b that after *ED* = 7 J/cm^2, the effect of increasing the energy density even further was not significant. The reason for this was that the surface was already fully melted at *ED* = 7 J/cm^2, which was what smoothed the blocks. Measuring comparative surface roughness reduction as well as final roughness was important to determine the efficiency of the process (Table 3 and Figure 5). It can be concluded that similarly, after *ED* = 7 J/cm^2, the effect of using higher energy density is minimal in reducing the surface roughness. It can also be seen from **Figure 4**b and Figure 5 that it is possible to achieve similarly high energy density values with all three power levels. However, at 2% power, one would require to have the lowest speed among the three levels, which would increase the process time for no justifiable reason. Therefore, it is important to keep power at the maximum level that is possible to use with any equipment, where the laser would not cut through the whole surface of the material. For this reason, it is suggested that maximum power among these three values should be used at a maximum speed that would result in an energy density value within the acceptable range (*ED* = 4-11.5 J/cm^2).

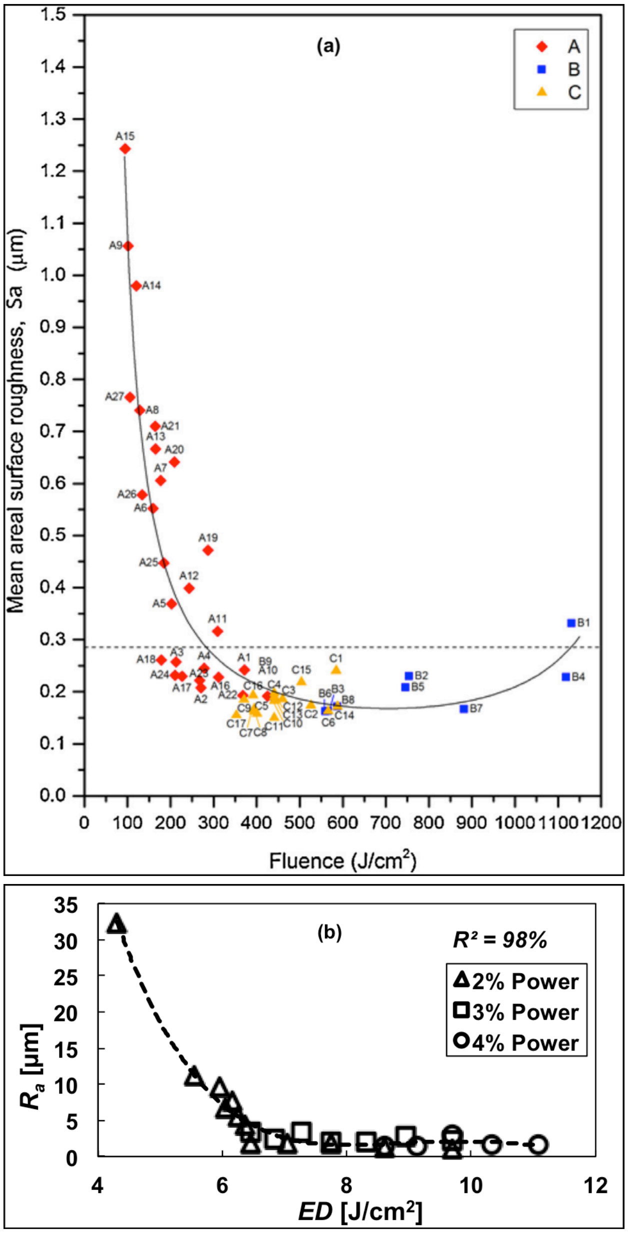

Figure 4: Change in perpendicular surface roughness with (a) fluence in H13 tool steel [22], (b) energy density in 3D-printed (FDM) PLA

Finally, in order to justify the value of laser polishing as an auxiliary process to FDM, a comparative study of process time and final surface roughness was conducted (Table 4). A test block was printed with the smallest available layer height of 0.1 mm (fine printing). Process time for this experiment was measured to be 30 minutes, and it resulted in an average surface roughness of 6.13 µm. Then, thicker layers of material were 3D-printed at a layer height of 0.3 mm (coarse printing), and both surfaces of the part with the staircase appearance were laser polished in full to compare with the test block. The total time for coarse printing and laser polishing measured to be 22 minutes and 40 seconds in total, 24% less than fine printing alone. This shows that even with the additional process time of laser polishing, it is possible to finish the whole process in less time, particularly when the power and speed values are selected carefully to maximize the benefit from surface roughness vs. energy density graph (Figure 4b). In addition, the average surface roughness was measured to be 1.77 µm, a significant 65% smaller than the fine-printed block. Therefore, it was concluded that laser polishing can be utilized as an effective auxiliary process to 3D-printing of PLA parts in order to reduce both the process time and the average surface roughness of the parts.

Table 3: Horizontal roughness (R_a) measurements after polishing and reductions compared to initial roughness

Energy Density **J/cm^2**	**Perpendicular R_a** **µm**	**Reduction** **%**
5.54	11.3	67
5.96	9.6	72
6.15	7.7	78
6.25	5.6	84
6.35	4.4	87
6.46	1.9	95
6.84	2.5	93
7.05	1.9	95
7.75	2.1	94
8.30	2.0	94
9.12	1.6	95
10.30	1.7	95
11.07	1.7	95

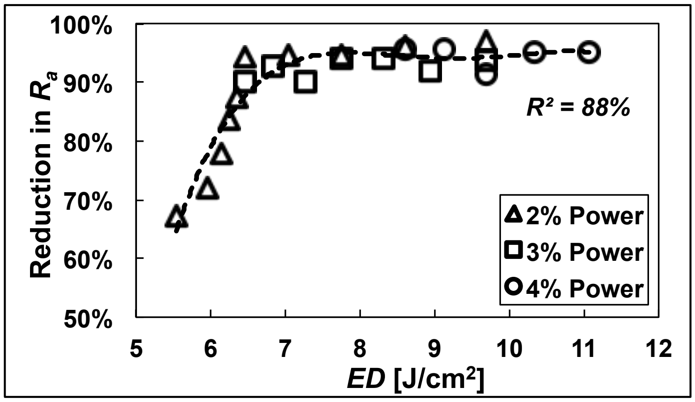

Figure 5: Reduction in perpendicular R_a

The amount of material removed from the part surface remains to be investigated. While it would be logical to expect that the part geometry would not decrease any more than its average surface roughness, the possibility of material flowing away from a certain region or evaporating must be considered. Confirming this is necessary to categorize laser polishing on PLA as a post-process and not an extra process that affects the dimensions of the final part. However, in practice it will most likely not be necessary to know since the tolerance of FDM is above the nano-scale [23].

Table 4: Difference between low-thickness layer process (fine 3D-printing) and process with laser polishing (ED = 7.75 J/cm^2)

Process	**Process time** **min**	**Average R_a** **µm**
Fine printing	30:00	6.13
Coarse printing + laser polishing	22:40	2.15
Change [%]	**-24**	**-65**

Although this study is focused on the change in surface roughness and process time, mechanical properties of the end part should also be included in selection of the appropriate process. Fortunately, reduction in surface roughness and elimination of surface irregularities are known to decrease the possibilities of brittle fracture and fatigue failure [12-13]. However, mechanical testing of the parts after laser polishing will be necessary to confirm these effects on 3D-printed PLA plastic parts. Although laser polishing should, in theory, only affect the surface of the part, it is possible that with the amount of heat created, a laser-affected zone on the subsurface could be a concern. A surface and subsurface microstructural analysis will be performed on these parts to ensure that the laser-affected zone is minimal. Furthermore, the process will be applied to new materials such as Acrylonitrile butadiene styrene (ABS) plastic and different geometries such as curved surfaces with the help of CAD technology to keep the laser focused, so that actual applications of 3D-printing can be simulated more closely.

CONCLUSIONS

In this study, laser polishing was tested as an auxiliary process to reduce the surface roughness of PLA parts produced with FDM. With the best set of laser parameters, roughness reductions of up to 97%, with final R_a = 2.02 µm were achieved, whereas the total process time decreased by 24% compared to 3D-printing with fine layers. This shows laser polishing is a viable method for treating FDM parts, increasing their fracture strength and fatigue resistance by eliminating irregularities and creating a smoother surface. Future work will quantify these effects by performing fatigue and strength tests on parts before and after the process.

The fast and automatable nature of this process makes it ideal for industrial large-scale production of plastic parts. It is inexpensive, fast, and it offers design freedom superior to conventional plastic manufacturing processes. Automating laser polishing with CAD technology could open up the production range of FDM and create a possibility for it to penetrate into new markets. In future research, the process will be applied to new geometries and materials in order to make it useful for a wider range of products.

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