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Combining laser aided ablation and polishing to minimize surface roughness of additively manufactured aluminium components

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COMBINING LASER AIDED ABLATION AND POLISHING TO MINIMIZE SURFACE ROUGHNESS OF ADDITIVELY MANUFACTURED ALUMINIUM COMPONENTS

by

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ABSTRACT

The surface roughness of additively manufactured parts is much higher than the acceptable range for most applications, thus post-processing is needed to qualify these parts for use. Laser polishing can be used to bring the surface roughness in an admissible range, but if the initial roughness is very high then the energy density for the polishing process needs to be very high to achieve a significant reduction in roughness. This high energy density can produce many process defects. Also, laser polishing alone cannot get rid of high wavelength asperities. Any waviness in the part can be linked with initial waviness in the as-built part and to the high energy density used during laser polishing. Waviness makes it harder to achieve dimensional accuracy. In this study, we propose a solution to extensively reduce surface roughness while also mitigating surface waviness, using a combination of laser ablation/machining, laser macro-polishing and laser micro-polishing. Surface roughness (Ra value) of 1.11 μm in one direction and 1.60 μm in another was achieved, which was more than 93% reduction in Ra compared to the as-built part. At the end, a process to achieve dimensional accuracy using pulsed laser ablation/machining is illustrated.

ACKNOWLEDGMENTS

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I would like to thank my parents and my sister for their constant support throughout my pursuit of a master's degree despite the long distance. Finally, I am thankful for all my friends for being there for me through everything.

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1. INTRODUCTION

Additive manufacturing (AM) is emerging as a successful manufacturing process for the production of parts with complex geometries that are otherwise difficult to produce using conventional manufacturing processes [1,2]. In industries such as aerospace, automobile, medical implants, etc., complex, lightweight and/or customizable parts can significantly improve the competence and so AM is increasingly being used in these fields. However, parts produced using most metal AM processes exhibit poor surface roughness and geometric accuracy in their as-built state [3-5]. So post-processing is obligatory to qualify the part for final application.

Many factors account for dimensional inaccuracy and poor surface quality of metal additive manufactured parts. Surface tension associated with temperature gradients of the melt pool can cause rapid hydrodynamic motions known as Marangoni flow, resulting in the ‘dishing’ or ‘humping’ as explained in [6,7]. ‘Balling’ of material caused by long thin melt pools degrade surface roughness [8-10]. Other process phenomena degrading the surface quality of AM parts are discussed in [11-13]. One of these phenomena is ‘staircase effect’, which is the result of layer-wise approximation of part geometry. Partially fused powder particles are also a common cause of surface roughness [14].

Usually, Conventional machining is used for improving the part’s surface finish and bringing it within GD&T. Spierings et al. [15] used CNC turning to finish AM parts built in AISI 316 and 15-5 HP steels. Taminger et al. [16] used high-speed milling (HSM) to finish aluminum AM parts. Löber et al. [17] were able to reduce the as-built

surface roughness of AISI 316L steel parts using grinding. Beauchamp et al. [18] used shape-adaptive grinding to finish Ti6Al4V AM parts. A hybrid of additive and subtractive machine tools is also used to mitigate surface roughness as described by Flynn et al. [19].

To minimize or eliminate the need for post processing, some researchers are deploying variants of laser polishing as a method to improve the surface finish of metal AM parts. Willenborg [20], Perry et al. [21], and Wang et al. [22] are some of the researchers who gave some valid theories for how to use the process parameters effectively to achieve a highly smoothen surface after laser polishing. By utilizing the same laser used to build the metal AM part towards improving its surface finish, it is possible to improve part finish during its manufacturing process in the same chamber.

In laser polishing, the top surface of an AM part is re-melted, and material is redistributed from peaks of the surface roughness to the valleys because of surface tension and gravity [23,24]. Laser polishing offers many obvious advantages over conventional methods, such as, high processing rate, minimum heat-affected zone (HAZ), and easily adjustable process parameters [25]. However, laser polishing cannot get rid of certain surface features with high wavelengths also known as waviness. Poor energy density choices during laser polishing will yield material defects that mimic bulge like structures on the surface [26], which eventually increases the surface roughness and waviness. High wavelength surface features (waviness) are especially high in AM processes like Directed Energy Deposition (DED), where in the beam size is higher compared to other AM processes and because of it, track overlap leads to a wavy surface pattern.

Wavy surface features left after laser polishing can be attributed to 1) initial waviness of the part before polishing. Track overlap is one of the factors contributing towards waviness in AM parts. And 2) high energy density used for polishing processes can cause wavy features because of the mass transport of the fluid flow in the melting pool [26]. This study proposes a novel three-step process, which can get rid of initial waviness. This process can yield a surface with significantly low roughness. The three sequential steps of this process are 1) Pulsed Laser Machining/Ablation (PLM), 2) Laser Macro-Polishing (LMP), and 3) Pulsed Laser Micro-Polishing (PLµP). PLM is used to ablate some material off the top surface to get rid of the high wavelength surface features (waviness). This step also removes any partially melted or sintered powder particles attached to the surface. LMP and PLµP are then used to bring down the surface roughness. The sequence of these processes was chosen based on results obtained from arbitatry tests. Visiably wavy surfaces were obtained for samples where PLM was not performed. Waviness was eliminated in the samples on which PLM was performed. Figure 1.1 shows the surface profile of the samples with and without PLM. It is clear from Figure 1.1 that PLM removes waviness.

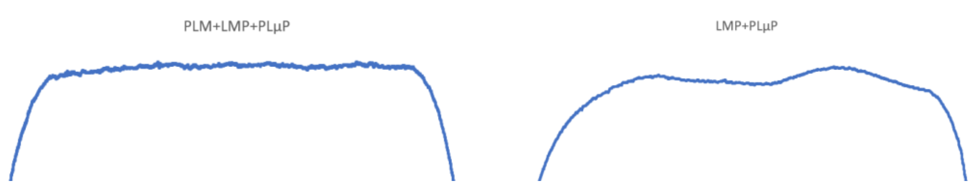


Figure 1.1. Surface profiles of samples

PAPER

I. COMBINING LASER AIDED ABLATION AND POLISHING TO MINIMIZE SURFACE ROUGHNESS OF ADDITIVELY MANUFACTURED ALUMINIUM COMPONENTS

ABSTRACT

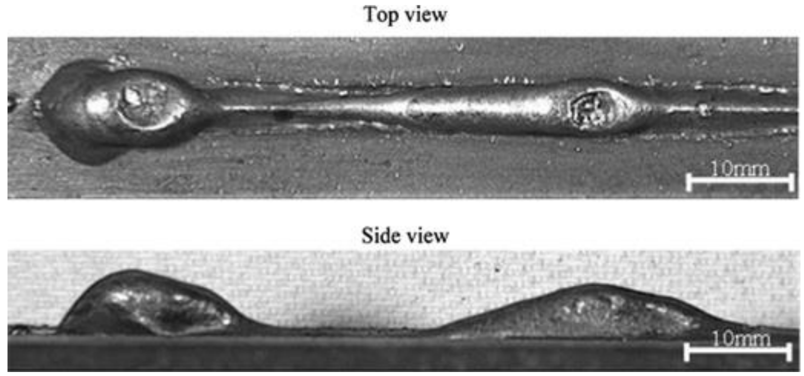
This Additively manufactured (AM) parts need post-processing due to surface roughness of the final part being much higher than the acceptable range for most applications. Laser polishing can be used to bring the surface roughness in an admissible range, but if the initial roughness is very high then the energy density for the polishing process needs to be very high to achieve a significant reduction in roughness. This high energy density can produce many process defects. Also, laser polishing alone cannot get rid of high wavelength asperities (aka. waviness). Any waviness in the part after the polishing process can be linked with 1) initial waviness in the as-built part (which is significantly high in Directed Energy Deposition (DED) parts) and 2) high energy density used during polishing which can escalate the phenomenon. This waviness makes it harder to achieve dimensional accuracy. This paper proposes a solution, to extensively reduce surface roughness while mitigating surface waviness, using a combination of laser ablation, laser macro-polishing and laser micro-polishing. Laser ablation reduces the initial waviness. Low energy density prevents the generation of any new waviness during laser polishing. Surface roughness (Ra value) of 1.11 µm in one direction and 1.60 µm in another was achieved, which was more than 93% reduction in Ra compared to the as-

built part. At the end, a process to achieve dimensional accuracy using laser ablation is illustrated.

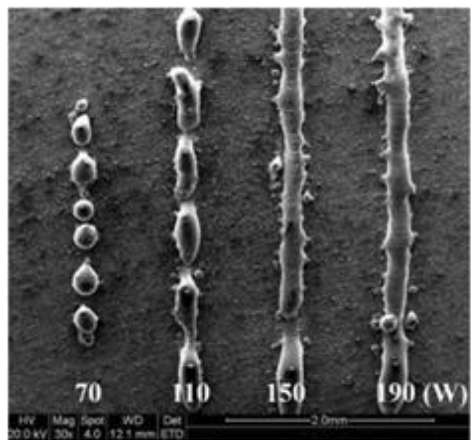
1. INTRODUCTION

The Additive manufacturing (AM) is emerging as a successful manufacturing process for the production of parts with complex geometries that are otherwise difficult to produce using conventional manufacturing processes [1,2]. In industries such as aerospace, automobile, medical implants, etc., complex, light-weight and/or customizable parts can significantly improve the competence and so AM is increasingly being used in these fields. However, parts produced using most metal AM processes exhibit poor surface roughness and geometric accuracy in their as-built state [3-5]. So post-processing is obligatory to qualify the part for the final application.

Many factors account for dimensional inaccuracy, and poor surface quality of metal additive manufactured parts. Surface tension associated with temperature gradients of the melt pool can cause rapid hydrodynamic motions known as Marangoni flow, resulting in the ‘dishing’ or ‘humping’ as explained in [6,7] and illustrated in Figure 1(a). As shown in Figure 1(b), ‘Balling’ of material caused by long thin melt pools degrade surface roughness [8-10]. Other process phenomena degrading the surface quality of AM parts are discussed in [11-13]. One of these phenomena is ‘staircase effect’, which is the result of layer-wise approximation of part geometry. Partially fused powder particles are also a common cause of surface roughness [14].



(a)



(b)

Figure 1. Process defects that increase surface roughness. (a) Top and side view of humped bead-on-plate welds [7]. (b) SEM image showing the ‘balling’ phenomenon for different laser power [9]

Usually, Conventional machining is used for improving the part’s surface finish and bringing it within GD&T. Spierings et al. [15] used CNC turning to finish AM parts built in AISI 316 and 15-5 HP steels. Taminger et al. [16] used high-speed milling (HSM) to finish aluminum AM parts. Löber et al. [17] were able to reduce the as-built surface roughness of AISI 316L steel parts using grinding. Beauchamp et al. [18] used shape-adaptive grinding to finish Ti6Al4V AM parts. A hybrid of additive and

subtractive machine tools is also used to mitigate surface roughness as described by Flynn et al. [19].

To minimize or eliminate the need for post processing, some researchers are deploying variants of laser polishing as a method to improve the surface finish of metal AM parts. Willenborg [20], Perry et al. [21], and Wang et al. [22] are some of the researchers who gave some valid theories for how to use the process parameters effectively to achieve a highly smoothen surface after laser polishing. By utilizing the same laser used to build the metal AM part towards improving its surface finish, it is possible to improve part finish during its manufacturing process in the same chamber/machine.

In laser polishing, the top surface of an AM part is re-melted, and material is redistributed from peaks of the surface roughness to the valleys because of surface tension and gravity [23,24] as shown in Figure 2. Laser polishing offers many obvious advantages over conventional methods, such as, high processing rate, minimum heat affected zone (HAZ), and easily adjustable process parameters [25]. However, laser polishing cannot get rid of certain surface features with high wavelengths, also known as waviness. Figure 3 illustrates the difference between surface roughness (low wavelength features) and surface waviness (high wavelength surface features) as defined by ASME B46.1 [26]. Poor energy density choices during laser polishing will yield material defects that mimic bulge like structures on the surface [27], which eventually increases the surface roughness and waviness. High wavelength surface features (waviness) are especially high in AM processes like Directed Energy Deposition (DED), where in the

beam size is higher compared to other AM processes, and because of it, track overlap leads to a wavy surface pattern.

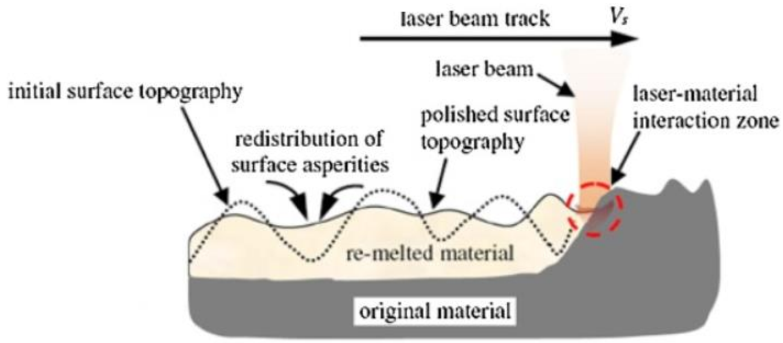


Figure 2. Schematic view of laser polishing [24]

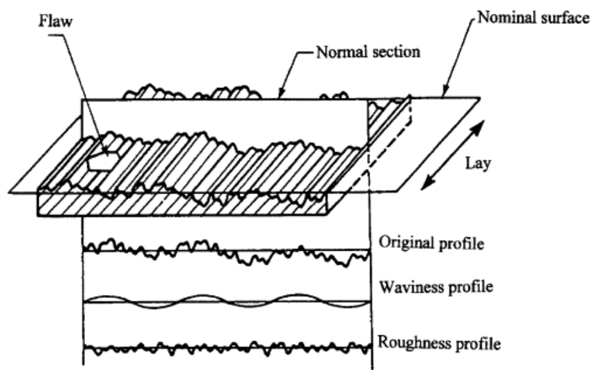


Figure 3. Difference between surface roughness and surface waviness [26]

Depending on the amount of laser energy delivered to the surface and the material properties, the melting depth could vary anywhere between 0.5 and 200 µm. Laser polishing through material redistribution tends to be generally classified into two main categories, termed as macro-polishing and micro-polishing. The difference between the two categories can be primarily defined by the depth of the molten layer, which could be either “deep” or “shallow” with respect to the height of the asperities. Table 1

summarizes the differences of both polishing processes as defined by Mohajerani et al. [25]. The macro polishing process can be compared to a rough machining process and the micro polishing process can be compared to a fine finishing process.

Table 1. Macro- and micro- polishing [25]

Parameter	Macro-polishing	Micro-polishing
Laser type	High-power CW laser	Pulsed laser
Melting depth	20 to 200 µm	0.5 to 5 µm
Initial surface roughness	>2 µm	<2 µm

Wavy surface features left after laser polishing can be attributed to 1) initial waviness of the part before polishing. Track overlap is one of the factors contributing towards waviness in AM parts. And 2) high energy density used for polishing processes can cause wavy features because of the mass transport of the fluid flow in the melting pool [27]. This study proposes a novel three-step process, which can get rid of initial waviness. This process can yield a surface with significantly low roughness. The three sequential steps of this process are 1) Pulsed Laser Machining/Ablation (PLM), 2) Laser Macro-Polishing (LMP), and 3) Pulsed Laser Micro-Polishing (PLµP). PLM is used to ablate some material off the top surface to get rid of the high wavelength surface features (waviness). This step also removes any partially melted or sintered powder particles attached to the surface. LMP and PLµP are then used to bring down the surface roughness. All three steps are explained in more detail in the following sections. A

method to increase dimensional accuracy using laser ablation is also demonstrated at the end.

2. MATERIAL AND METHOD

The proposed 3-step process involves the use of different laser operations. Laser Macro Polishing (LMP) is usually done using a high-power Continuous Wave (CW) laser. While the ablation and micro polishing is carried out using a lower power pulsed laser. 949-1001nm Teradiode laser, a 2 kW CW laser was used to carry out LMP. This is the same laser used to deposit the samples. 1064 nm IPG laser YLP-V2, a 100 W pulsed laser was used for PLM and PLµP processes. The CW laser was focused using a 200 mm focal length focusing optics in a 1.25 mm diameter spot. The beam diameter for the pulsed laser was 65 µm. Thorlabs supplied GVS312, 2-Axis Scanning Galvo System combined with FTH254 F-Theta scanning lens was used to scan the pulsed laser on the workpiece. Effective focal length of the F-Theta lens is 254mm. Powder is supplied using a powder feeder provided by Powder motion labs and focused using a in house designed nozzle. Argon was used as shield and carrier gas. Figure 4 shows the experimental setup.

5052 aluminum annealed substrates were used to deposit on. The powder used was Scalmalloy aluminum alloy. The powder was sieved to a particle size of 105 µm. Table 2 shows the chemical composition of the powder.

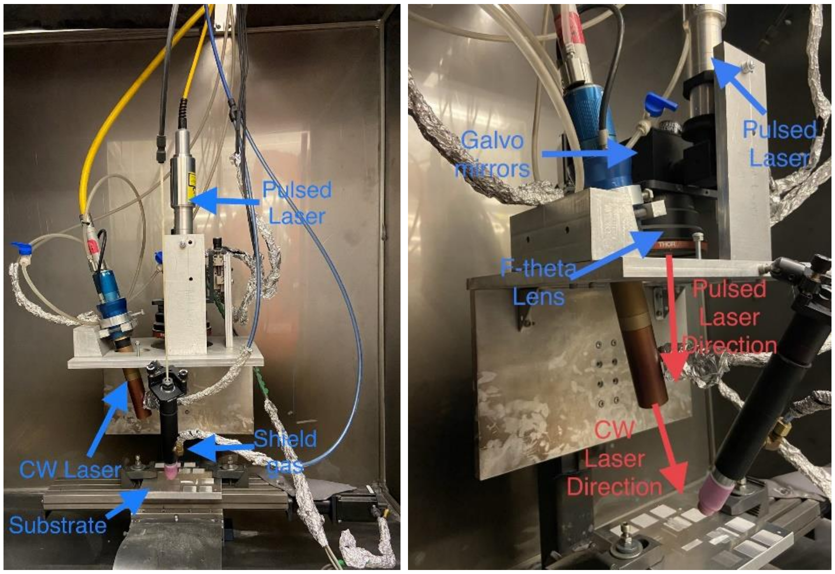


Figure 4. Expremental set-up

Table 2. Chemical composition of scalmalloy powder (Al Bal.)

Element	Mg	Sc	Zr	Mn	Si	Fe	Zn	Cu	Ti	O	V
wt% (min)	4.00	0.60	0.20	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
wt% (max)	4.90	0.80	0.50	0.80	0.40	0.40	0.25	0.10	0.15	0.05	0.05

Using the CW laser at parameters described in Table 3, forty-four 0.84in x 0.84in samples were deposited, as shown in Figure 5(a). These patch samples were used to perform the following tests. Samples are clearly numbered from 1 to 44. Samples 1-12 were used for Test 1, 13-28 for Test 2, and 29-44 for Test 3. A laser displacement sensor was used to capture the surface profiles after each test. These surface profiles were used to calculate the surface roughness (Ra) value, according to the ASME B46.1 standard, of the as-built samples and samples after Test 1. Mitutoyo surface roughness tester (surface

profilometer) Suftest - 212 was used to measure the roughness of the samples after Test 2 and Test 3.

Three tests were performed to optimize the parameters for all three process steps:

(Test-1) To optimize the parameters of the PLM process; using the pulsed laser at different parameters described in Table 4, the material is ablated from top of the sample patches 1-12. Ablation is performed using the pulsed laser at the focus. Removed material was calculated for each test. The parameters yielding the best surface were chosen for the final test. Figure 5(b) shows the part after Test 1. A pattern created using a combination of galvo mirrors and CNC table was used to achieve maximum material removal. Galvo mirrors were used to scan a 3mm solid circle and CNC table was used to create a raster pattern with 70% overlap of this solid circle.

(Test-2) To optimize the parameters of the LMP process, patches 13-28 were used. The material was ablated using a PLM process done using parameters optimized in the previous test. After that using different parameters described in Table 5, the LMP process was performed on these patches. Laser Macro Polishing (LMP) is performed using CW laser. Two cycles, one in the parallel direction and second in the perpendicular direction to the deposition tarck, of LMP were performed. Melt depth and Ra values were calculated. Optimal parameters were selected based on this data (explained in detail in the Results section). Figure 5(c) & 5(d) shows the part after Test 2. For this test a raster pattern with 30% overlap of CW laser beam was used. Shield gas was used to minimize oxidation, at a flow rate of 4 L/min for this process.

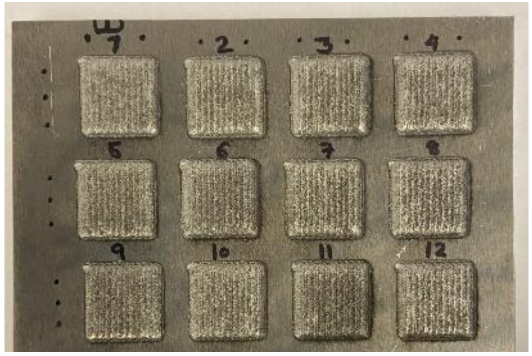
(Test-3) To optimize the parameters of the PLμP process, PLM and LMP were performed on samples 29-44 using parameters obtained from the previous two tests.

Using different parameters described in Table 6, PLµP process was performed on these patches. PLµP is performed using the pulsed laser with focal offset of 1 inch. Two cycles, one in the parallel direction and second in the perpendicular direction to the deposition tarck, of PLµP were performed. It is important to avoid ablation during this step, so final parameters were selected based on whether the parameters yield melting or ablation and Ra value. Figure 5(e) & 5(f) shows the part after Test 3. For this test pattern same as Test 1 was used.

Using parameters gained from these three tests, the final patches was created. A separate test was performed to illustrate the capability of the PLM process to improve the dimensional accuracy of an AM part.

Table 3. Parameters used to deposit the samples

Parameters	Value
Power (W)	1600
Feed Rate (in./min.)	20
Overlap between tracks (%)	30
Powder mass flow rate (g/min.)	6
Shield gas flow rate (L/min.)	4



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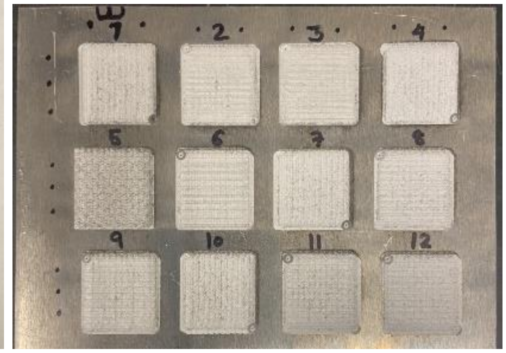

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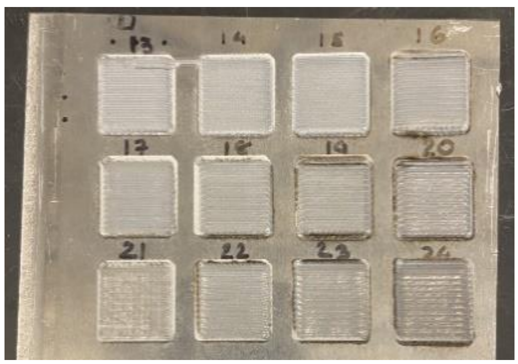

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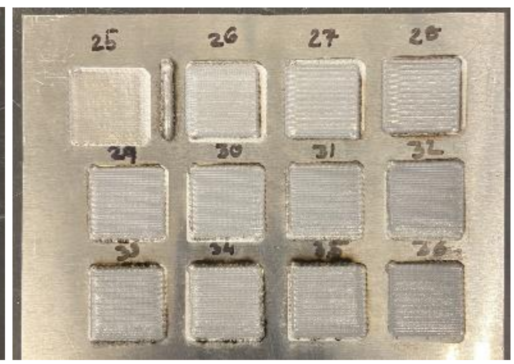

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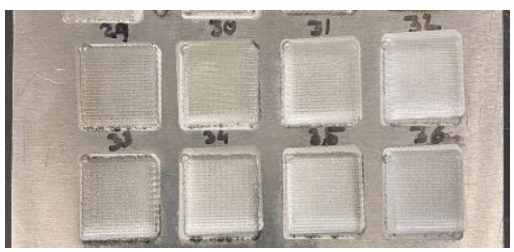

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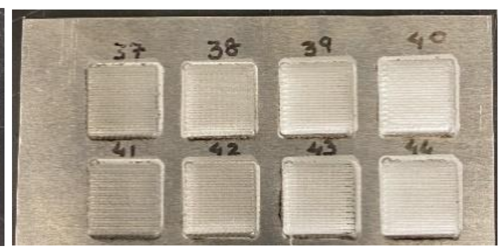


(f)

Figure 5. Samples (a) As-built samples (1-12), (b) Sample after PLM (1-12), (c)&(d) Samples after PLM+LMP (13-28), (e)&(f) Samples after PLM+LMP+PLμP

3. RESULTS AND DISCUSSION

The roughness of the as-built sample, shown in Figure 5(a), was more than 30 microns. Data from the surface profile captured using the displacement sensor was used to get this roughness value. It was not possible to measure the roughness of the as-built part and samples after Test 1 using the surface profilometer without damaging the touch probe. The results from all three tests were as follows:

(Test 1): Parameters used for Test 1 are shown in Table 4. Feed rate and the number of cycles were the variable parameters. The purpose of Test 1 was to achieve maximum material ablation, so all these tests were performed using a pulsed laser at focus, and power was kept constant at 100W. The material removal rate was calculated using surface profile data. Figure 6 shows the material removal calculation for Sample 1, approximately 0.1mm of material is removed from the top of Sample 1 after the PLM process. The roughness of the samples after Pulsed Laser Machining (PLM) is still high but the high wavelength features are eliminated. The purpose of this process is to eliminate the waviness of the deposited sample. Figure 7 illustrates the working principle of the PLM process.

It is clear from the table that the material removal rate increases with an increase in the number of cycles. Also, increasing the feed rate reduces the material removal rate. As it can be seen in Figure 6, PLM helps reduce high wavelength surface features. The optimum set of parameters for this test would be the one resulting in minimum high wavelength surface features while removing the least amount of material. Sample no. 8 seems to fit this criterion the best. Sample 8 also has the least roughness.

Table 4. Results of Test 1 (PLM)

Sample No.	Feed rate (in./min.)	No. of cycles	Material ablated (mm)	Roughness (Ra) after PLM (µm)
1	6	1 (y)	0.1	28.46
2	6	2 (y,x)	0.2	26.92
3	6	4 (y,x,y,x)	0.45	32.38
4	9	1 (y)	0.05	30.02
5	9	2 (y,x)	0.1	31.82
6	9	4 (y,x,y,x)	0.25	28.31
7	12	1 (y)	0.05	39.61
8	12	2 (y,x)	0.1	21.24
9	12	4 (y,x,y,x)	0.2	29.89
10	15	1 (y)	0.025	36.54
11	15	2 (y,x)	0.05	27.55
12	15	4 (y,x,y,x)	0.2	24.22

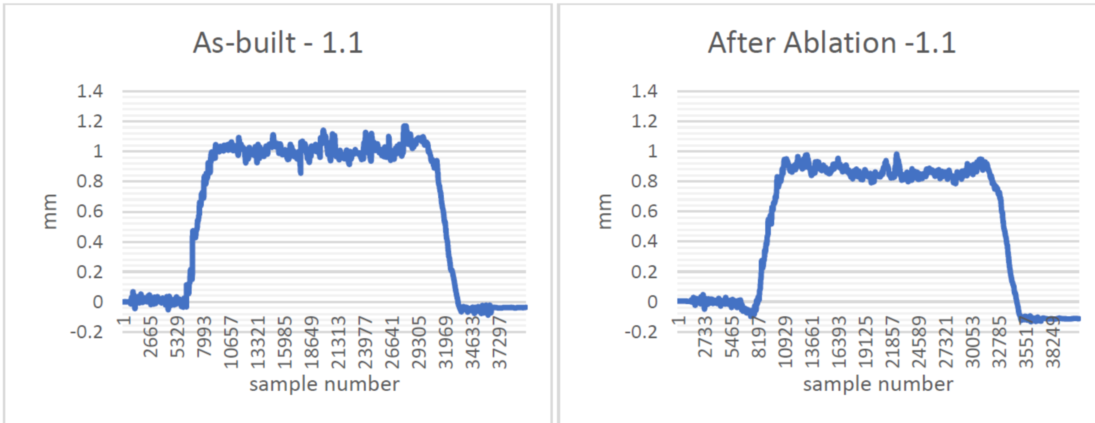


Figure 6. Surface profile of Sample 1 as-built and after PLM (ablation) process

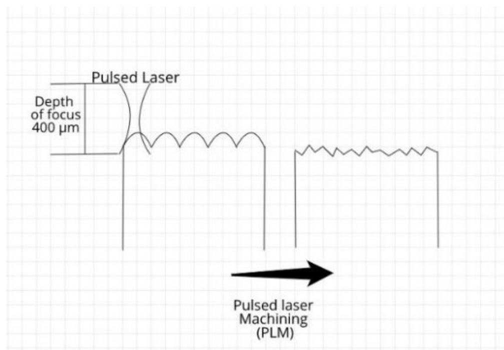


Figure 7. Working principle of PLM process

(Test 2): PLM was performed on Samples 13-28 using the parameters optimised in the previous test (i.e., the parameters of Sample 8 in Table 4). After that Laser Macro Polishing (LMP) was performed on this sample using parameters defined in Table 5. Shield gas was used to minimize oxidation, at a flow rate of 4 L/min for this process. Average roughness value (Ra) was measured using a surface profilometer. Laser Macro Polishing (LMP) process melts material from the peaks, and that molten material fills the valleys. Figure 8 illustrates the surface profile of Sample 16 after PLM, and after LMP, it

is clear from this figure that molten metal from the peaks fills the valleys and thus reduces the surface roughness. LMP reduces roughness significantly.

Optimum parameters for this test were the one which gave minimum surface roughness (Ra) value. Sample number 18 produced the least roughness (see Table 5), so the laser power of 1200W and feed rate of 18in./min are the optimum process parameters for the LMP process.

Figure 8. Surface profile after PLM and after LMP (Sample 16)

(Test 3): PLM and LMP were performed on Samples 29-44 using the parameters optimized in the previous two tests (Sample 8 in Table 4 for PLM and Sample 18 in Table 5 for LMP). After that PLμP was performed on these samples. Figure 5(e) & 5(f) shows samples after PLμP. Parameters used for this process are shown in Table 6.

The laser power of 40W and Feed rate of 12in./min yields the best result. For Sample number 29, Ra value was 1.11 μm in the x-direction (normal to deposition tracks) and 1.6μm in the y-direction (parallel to deposition tracks).

Table 5. Results of Test 2 (PLM+LMP)

Sample No.	Laser Power (W)	Feed Rate (in./min.)	Ra in x direction (microns)	Ra in y direction (microns)
13	1000	12	2.92	2.08
14	1200	12	7.18	4.63
15	1400	12	5.66	4.95
16	1600	12	1.28	3.20
17	1000	18	2.07	1.86
18	1200	18	1.89	1.13
19	1400	18	2.26	3.28
20	1600	18	1.83	3.34
21	1000	24	6.99	4.23
22	1200	24	1.94	2.33
23	1400	24	2.55	1.68
24	1600	24	2.33	3.37
25	1000	30	2.57	4.55
26	1200	30	1.32	2.50
27	1400	30	2.82	4.64
28	1600	30	4.09	6.98

Table 6. Results of Test 3 (PLM+LMP+PLµP)

Sample No.	Laser Power (W)	Feed Rate (in./min.)	Ra in x direction (microns)	Ra in y direction (microns)
29	40	12	1.11	1.60
30	60	12	1.89	1.94
31	80	12	1.98	3.98
32	100	12	1.97	5.30
33	40	18	1.58	4.71
34	60	18	2.28	5.24
35	80	18	2.59	4.34
36	100	18	2.03	4.36
37	40	24	1.74	2.66
38	60	24	1.64	3.71
39	80	24	2.23	5.33
40	100	24	3.64	5.24
41	40	30	2.40	6.15
42	60	30	2.33	5.17
43	80	30	2.55	5.37
44	100	30	1.84	4.40

Using the optimized parameters, all three processes (PLM+LMP+PLµP) were repeated 3 times, the achieved roughness in both directions was in the range of 1-2 µm.

A separate test was performed to illustrate the potential of PLM process to improve dimensional accuracy. Figure 9 (a) shows the as-deposited block. This block was poorly deposited to represent the worst-case scenario. Figure 9 (b) shows the block after PLM. Only the pulsed laser was used during this test. Table 7 shows the dimension of the block before and after PLM.

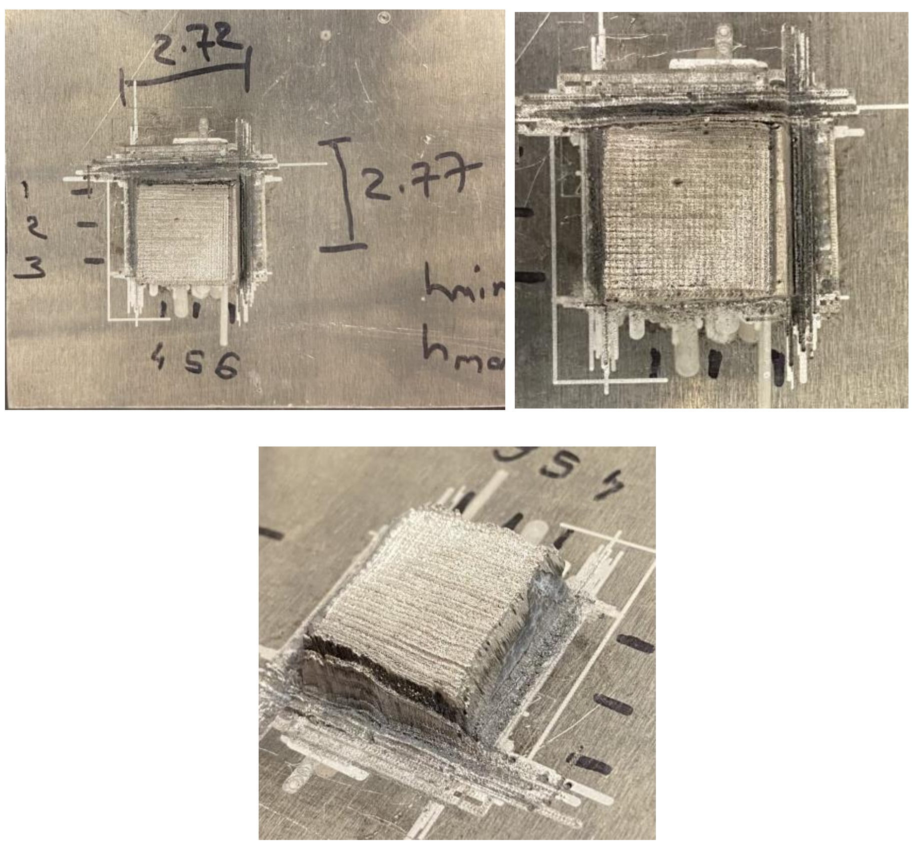
The pulsed laser was scanned onto the work piece in a solid square shape using the galvo mirrors. This gave the ability to remove material, while maintaining the shape of edges.

The purpose of this test was to illustrate the ability of PLM process to achieve dimensional accuracy. Pulsed laser can be used to remove desired amount of material, by changing the distance between the workpiece and the laser. Depth of focus for the pulsed laser used in this study is 400µm. Figure 10 shows the correct placement of the laser beam to remove 150µm material from the top of the substrate.

Table 7. Dimensions of the block before and after PLM

Dimensions	Before	After
Area	2.72cm x 2.77cm	2.35cm x 2.37cm
Height	1.02cm to 1.26cm	0.96cm

(a)



(b)

Figure 9. PLM to improve dimensional accuracy: (a) before (b) after

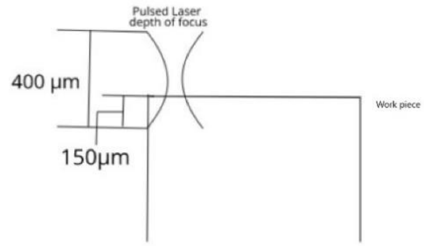


Figure 10. Depth of focus of pulsed laser

4. CONCLUSION AND FUTURE WORK

This work proposes a laser-based manufacturing process to produce parts with roughness value Ra in the range of 1-2 μm. The roughness of the as-built part was more than 30 μm, which means this combination of processes yields a 93% improvement in surface roughness. The waviness generated during the deposition is also eliminated after the PLM process. The surface roughness after PLM is high, but the LMP and PLμP brings it down significantly. PLM can be used to improve dimensional accuracy. In case of AM processes, such as SLM, where waviness is not an issue, PLM step can be eliminated and just LMP+PLμP can be used to improve surface roughness.

In the future, an investigation will be performed to determine the influence of these processes on the mechanical properties of the sample. Also, use of these processes to improve the dimensional accuracy will be further investigated. Different patterns for PLμP process will be studied to make surface finish even better and to reduce the time for this process.

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SECTION

2. CONCLUSIONS

A three-step process is used to reduce the surface roughness of AM parts. A roughness improvement of 93% was achieved at the end of this process. The roughness of the final part was in the range of 1-2 µm. The waviness generated during the deposition is also eliminated after the PLM process. The surface roughness after PLM is high, but the LMP and PLµP brings it down significantly. This process can produce AM parts that are ready to use and requires no post-processing.

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