Hydroabrasive machining of internal channels of parts obtained by SLM

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Abstract. The paper discusses the effect of hydro abrasive treatment on the inner surface of products obtained by selective laser melting (SLM). The hydro abrasive treatment effect on the faceting of these products has been investigated, the process simulated in ANSYS, and an area defined in which cavitation bubbles have occurred. The abrasive grain of black silicon carbide has been used as a filler; cylindrical samples printed of VT6 titanium alloy (an analog of Ti6Al4V) have been processed.

1. Introduction
Additive technologies are increasingly being used in various spheres of our life in almost four decades after their emergence. They are more distributed in industries where a prototype or a high-precision product should promptly be obtained. Additive processes allow obtaining surfaces that are impossible or extremely difficult to receive using conventional techniques based on cutting. Among additive-based manufacturing techniques, the fast-growing one is selective laser melting (SLM) involving layer-by-layer deposition of metal powder and melting layers by laser radiation. This technique allows obtaining products with properties close to the desired ones, but due to certain problems, their use immediately after printing is most often impossible. Many authors have studied various parameters affecting the SLM process and according to their recommendations, the phase composition [1–6], porosity, and rough surface defect (including cracking and gas capture from the construction chamber) [1, 2, 7-13] issues can be avoided, and the strength/ductility relationship adapted to a specific product application [1, 5, 10]. Despite the above mentioned, some issues cannot be resolved: high surface waviness and roughness, and some major defects, i.e., stuck-on particles and other surface layer faults prevent the product from using immediately after printing. That is why products obtained by SLM require post-processing. In the case of complex internal geometry, conventional processing is not suitable, so non-standard processing techniques should be developed and used. This paper discusses the hydro abrasive treatment of inner surfaces (channels and cavities).

2. The Waterjet processing description
The hydro abrasive treatment (HAT) technique applied in this work is similar to the hydro abrasive jet treatment; the difference is the lack of accelerating abrasives by air, and consequently, their velocity is lower, and processing takes place inside a workpiece on all inner surfaces at once. For HAT, three microrelief formation patterns are possible depending on the initial surface roughness height and the size of the holes and furrows left by abrasive particles on the workpiece [13] the surface roughness
after processing exceeds the initial one, the workpiece roughness does not change, the roughness obtained is less than the initial one.

As a result of the experiment, the expediency of applying HAT to reduce the surface roughness of products obtained by SLM becomes obvious. In this work, VT6 titanium alloy (the most commonly world-used titanium alloy [14]) has been used, and since the material cut using this treatment technique is approximately the same for all titanium alloys [15], similar results will be obtained when processing other ones. Along with the surface roughness, the HAT effect on the faceting of cylindrical products obtained by SLM should be clarified since due to the technological heredity peculiarities, faceting occurs both during the conversion of the CAD model into the STL one and due to the limitations of the printing machine itself.

3. Samples used
For the experiment, cylindrical samples with the dimensions shown in figure 1 have been printed using the SLM technique. The printing mode has been as follows: laser radiation power \( P = 275 \text{ W} \), scanning velocity \( S = 805 \text{ mm/s} \). To ensure better heat exchange excluding the sample sagging when removing it from the printing platform, an allowance - the so-called sacrificial layer has been added to the sample. After printing, the samples have been heat-treated together with the printing platform in an oven to remove residual stresses in the following mode: heating at 600 °C for 6 hours, holding for 2 hours, and cooling with an oven for 8 hours. Then, the samples have been removed from the printing platform and processed on a lathe to cut the sacrificial layer, i.e., crosscut to a size of 40.0,1 mm.

![Figure 1. Initial dimensions of the samples printed.](image)

After removing from the printing platform and crosscutting, the samples have been weighed on a laboratory balance SARTOGOSM LV 210-A. The inner surface roughness of the samples has been measured perpendicular to the printing tracks using an automated profilometer-profile recorder BV-7669. To measure roundness, an RA-1600 Mitutoyo Roundtest roundness gage has been used. Roundness has been measured at 3 points on the inner surface of each sample - on the upper and lower sides, and in the middle.

4. The experiment description
For the experiment, a laboratory hydro abrasive treatment unit shown in figure 2 has been assembled. Deionized water and abrasive grains of black silicon carbide (54C) with F46 grain size have been used as a process carrier and an abrasive filler, respectively. The concentration of abrasives in the unit was 10, 15, 20, and 25 % as the mass ratio of abrasive material to deionized water. The reference sample has been tested by pumping water without abrasives. Every 15 minutes, treatment was stopped to measure the weight and roughness of the samples. After the experiment, the samples’ roundness has been measured.
During the experiment, according to the pressure gauges, it has become obvious that cavitation occurred in the sample processing area. To determine the exact location of cavitation, we have simulated the process in ANSYS.

5. Simulating experiment in ANSYS
To perform a numerical study of the hydro abrasive treatment process, the workpiece contour should be built. To simplify the calculation, only the sample processing area has been considered. The contour consists of simple geometric shapes, so it can be built directly in ANSYS. To perform the simulation, two sets of identical particles should be created. The first set is fully constrained to allow particles to effect on the flow field and predict this effect. The second set is unilaterally constrained, but contains a much larger number of particles to provide a more accurate calculation of the volume fraction of particles and the local wall forces without affecting the flow field. To increase the simulation accuracy, the input velocity profile is set, simulating a fully developed boundary layer. To more accurately simulate the inlet, the input velocity profile has been determined with the boundary layer already fully developed there. The calculation has been performed using the formula (1):

$$U = W_{\text{max}} \left(1 - \frac{r}{R_{\text{max}}} \right)^\frac{1}{7}$$

(1)

$W_{\text{max}}$ is the maximum velocity at the simulation area input, $R_{\text{max}}$ is the maximum pipe radius, $r$ is the distance from the axis line. Figure 3 shows the pressure distribution.
It can be seen from the pressure diagram, a sharp pressure drop occurs at the processed sample input due to cavitation at this point. Cavitation has been detected in field experiments using two pressure gauges installed upstream and downstream of the area processed. The pressure gauge installed downstream of the sample has shown 0 indicating the occurrence of cavitation. Thus, simulation proves occurrence of this phenomenon and for more accurate calculation, cavitation should be set with an additional pair of substances - water and water steam with the indication of the saturated water steam pressure at a given temperature.

6. The Experiment results
To assess the amount of material cut and the change in the surface roughness, the samples have been weighed before and every 15 minutes of the processing; the weighing results are shown in table 1. The roughness change results are shown in table 2. As can be seen from the table, the largest material cut has taken place during the first 15 minutes of the processing, which is explained by the intensive removal of powder grains formed due to the baling effect from the sample surface. These particles may be cut by water jet without abrasives due to the cavitation effect, but in this case, surface will wear much slower (sample 5). Sample No. 3 processed at an abrasive concentration of 20 % in the system has shown the greatest weight loss.

| Sample No. | Before Processing | Weight, mg | Total Difference |
|------------|-------------------|------------|-----------------|
|            | in 15 minutes     | in 30 minutes | in 45 minutes |
| 1          | 12,615.0±0.4      | 12,577.6±0.4 | -               | 37.3  |
| 2          | 12,653.8±0.4      | 12,597.9±0.4 | -               | 55.9  |
| 3          | 12,622.5±0.4      | 12,615.9±0.4 | -               | 6.6   |

| Sample No. and Abrasive Concentration | Processing Time |
|---------------------------------------|-----------------|
|                                       | Untreated       | 15 minutes     | 30 minutes     | 45 minutes     |
|                                       | Ra, μm          | Ra, μm         | Rz, μm         | Rz, μm         | Rz, μm         |
| Sample 1, 10 %                        | 5.60            | 3.62           | 29.38          | 3.29           | 26.20          |
| Sample 2, 15 %                        | 5.29            | 4.24           | 33.30          | 2.64           | 20.68          |
| Sample 3, 20 %                        | 5.25            | 2.37           | 19.40          | 1.03           | 10.29          |
| Sample 4, 25 %                        | 4.99            | 2.46           | 18.72          | 1.90           | 16.42          |
| Sample 5, 0 %                         | 4.78            | 4.26           | 31.50          | 4.12           | 29.98          |

The data in table 2 have been obtained by averaging all the roughness measurements throughout the entire sample, and the values in table 3 have been averaged for each sample side. Each sample has been measured at three different points on each side. As can be seen from table 2, the least surface roughness has been obtained at an abrasive concentration of 20 % on sample No. 3. Further increase in the abrasive concentration negatively affects the pump parameters. Table 3 shows that the least roughness is on the nozzle side. This may happen for two factors: due to cavitation or the angle of attack at the sample input. Reference sample 5 shows that the effect of cavitation is not so large as to cause such a difference in roughness on different sample sides; therefore, it can be concluded that both factors affect the sample roughness, and cavitation may probably be enhanced due to the presence of abrasive in the processing area.
Table 3. Change in the average roughness value on each side.

| Sample No. and Abrasive Concentration | Processing Time |
|--------------------------------------|-----------------|
|                                      | 15 minutes      | 30 minutes      |
|                                      | 1 side | 2 side | 1 side | 2 side |
| Ra, Rz                              | Ra     | Rz     | Ra     | Rz     |
| Sample 1, 10 %                      | 3.01   | 23.50  | 4.24   | 35.25  |
| Sample 2, 15 %                      | 4.07   | 31.20  | 4.41   | 35.40  |
| Sample 3, 20 %                      | 1.92   | 17.50  | 2.81   | 21.30  |
| Sample 4, 25 %                      | 2.12   | 15.63  | 2.80   | 21.80  |
| Sample 5, 0 %                       | 4.06   | 30.70  | 4.47   | 32.30  |

To measure roundness, an RA-1600 Mitutoyo Roundtest roundness gage has been used. Roundness has been measured at 3 points on the inner surface of each sample - on the upper and lower sides, and in the middle. The measurement data are given in table 4. Z is the height from zero-level in millimeters, at which the samples have been measured.

Table 4. The samples roundness data, μm

| z, mm | Sample No. |
|-------|------------|
|       | 1 | 2 | 3 | 4 | 5 |
| 34-37 | 55.088 | 35.112 | 29.833 | 36.415 | 43.259 |
| 50-52 | 42.433 | 43.899 | 32.113 | 33.86 | 51.62 |
| 70-72 | 42.739 | 46.084 | 28.161 | 25.733 | 63.224 |

When printing these samples, linear interpolation turned out to be 0.03, and most likely, this is a limitation of the SLM machine itself. After printing, this figure changes due to the baling effect, sharp corners become stuck with powder grains, and peaks grow on flat surfaces, which makes out-of-roundness higher than that of the model. After hydro abrasive pumping, on sample 3, which showed the least surface roughness, the out-of-roundness is on average 0.03 mm close to that of the original model (the model out-of-roundness is 0.03 mm). This means that the faceting remains after hydro abrasive treatment, and it will decrease with increasing processing time that should be verified in further experiments.

7. Conclusions
In this work, a hydro abrasive unit has been built for internal pumping of products, in the course of operation of which the optimal concentration of abrasives has been determined for this unit. The roughness and weight of the product obtained by SLM have maximally reduced for the first 15 minutes of processing due to the cut of non-fused particles. Thus, hydro abrasive treatment can be used to improve the surface layer of products obtained by SLM.

Faceting caused by the scanning peculiarities has remained in the final product. The printing machines have a limitation on linear interpolation, which means that further improvement in the original STL model quality will not make sense due to the scanning limitations. Hydro abrasive treatment may reduce faceting during post-processing of products, but this requires longer processing time.

Cavitation occurring in the course of processing should be considered. Cavitation increases the cut of material in a certain area, which can both help and interfere in processing since the roughness is not uniform in different processing areas. The effect of the abrasive grain size and clarification of the optimal concentration will be considered in further works. The reasons for the increase in the product roughness and waviness at the last processing stages are also considered and studied. More
sophisticated simulation can help to more accurately find out the cavitation area and to simulate wear due to both cavitation and abrasives.

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