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Laser polishing of PBF-LB manufactured stainless steel surfaces

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Abstract. Laser powder bed fusion (PBF-LB) is additive manufacturing where material is added layer by layer. This technology has revolutionized the manufacturing during last few recent years by enabling more efficient material usage and more functions to each component. However, for many industrial cases, the PBF-LB surfaces need an additional finishing operation like the machining or polishing operation. Laser polishing process was studied to solve the problems of traditional technologies to improve the surface quality and to enable automation of it. In this study parts were manufactured by PBF-LB of austenitic stainless steel (AISI 316L) into shapes of mechanical property testing samples in different orientations and locations in building platform. The surface roughness was measured prior and after polishing. The experiments showed that considerable surface smoothening even up to 85% (Sa from 48 μm to 11 μm) was reached in two treatments.

1. Introduction

Laser powder bed fusion is additive manufacturing where material is added layer by layer. The metal powder is fused according to 3d-model sliced to thin layers on powder layers. This technology has revolutionized the manufacturing during last few recent years by enabling more efficient material usage and more functions to each component. Even though this technology is growing in use gradually there is some major drawbacks slowing down the development. (ISO/ASTM 52900:2021)

However, as commonly known by engineering practices and studies there are a lot of applications where the surface quality, e.g. due to fatigue, aesthetic or tribological functions; accuracy or low roughness requirements, requirements are such that the L-PBF manufactured surfaces need an additional finishing operation like machining or polishing operation. Traditional polishing processes usually are based on abrasive or chemical techniques. These technologies have several drawbacks like dimensional constraints in case of complex shape or variations in material thickness, high environmental impact, long processing time and high cost. Typically, these also involve issues with awkward work phase with health risks for operators, which cannot be solved due to difficulties in automation of the process.

The research on laser polishing has started in early 2000 and has been growing on volume during last few years by Scopus. Typically, it is used for smoothening the surface of metals, polymers, ceramics and glasses, so the technology is pretty versatile. Naturally different materials require different



technologies and the process itself can be carried out with some different techniques e.g. via melting or via ablation. The process can be carried out with various different lasers reaching from CO₂ and Nd:YAG lasers to currently more common fiber and disk lasers.

Even though the process is not brand new the research on topic has increased considerably during laser years. A Scopus search in May 15th 2023 with search text: “laser polishing” AND “metals” and “laser polishing” AND “stainless steel”, see Figure 1, found totally 117 and 47 publications, since 1994 when first publications were published.

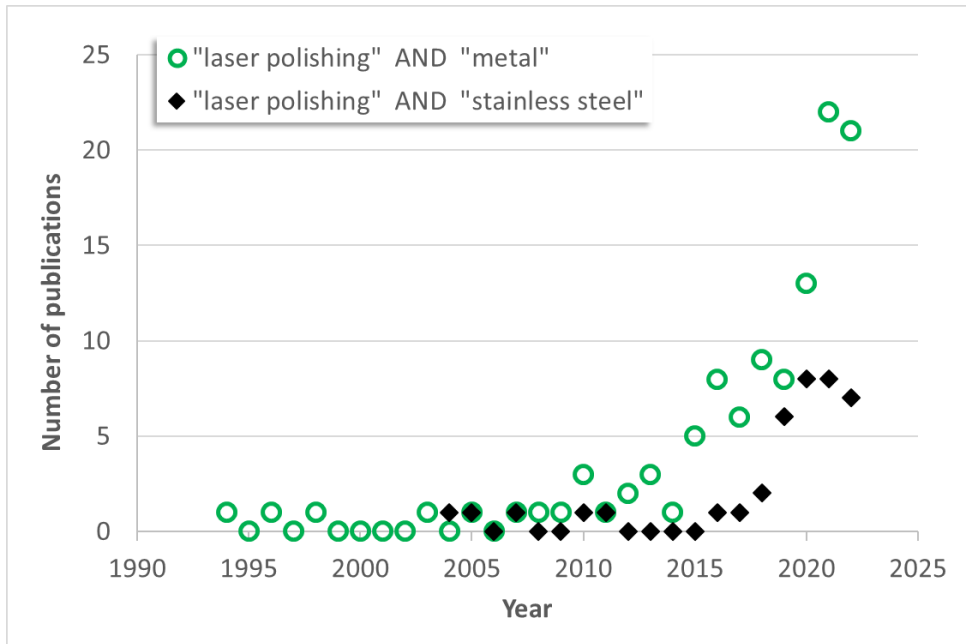


Figure 1. Number of publications per annum by Scopus for searches “laser polishing” AND “metals” and “laser polishing” AND “stainless steel”.

The process can be done both with continuous wave or pulsed laser beam. Laser polishing for metals is typically based on melting a thin surface layer of the workpiece followed with the surface smoothing by interfacial tension. In this case beam is using the existing material of “hills” to fill the “valleys” in the surface texture. Figure 2 shows the principle of laser polishing in practice, whereas figure 3 shows typical result of laser polishing.

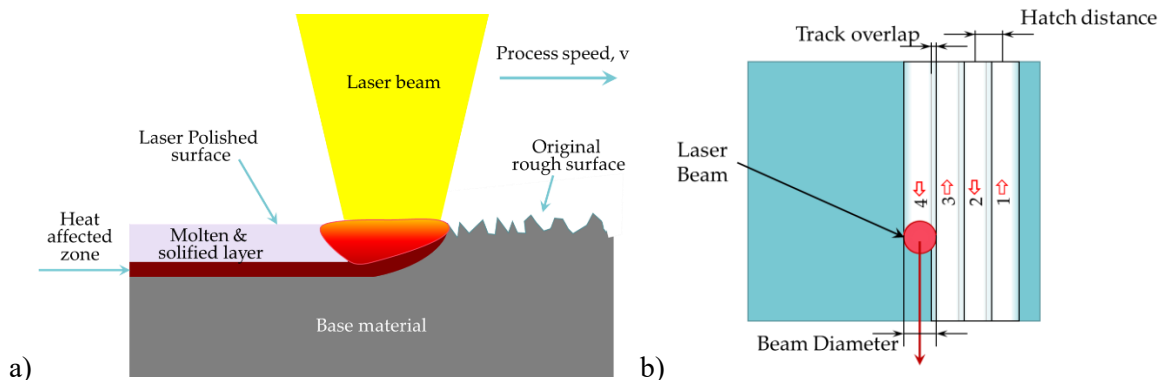


Figure 2. Laser polishing principle a) side view and b) top view.

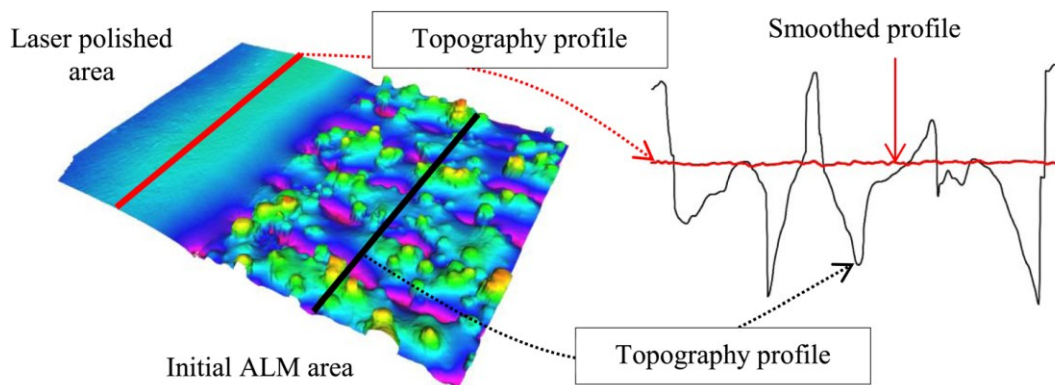


Figure 3. Laser polishing is melting the material which is then smoothed by surface tension and leaves a totally different surface roughness. [1]

The technology has actually been used also for deburring of parts after machining operations and rounding and deburring of sheet metal parts [2]. In these cases, naturally there is usually not need to do more than one track. There are some results reported of polishing of austenitic stainless steel of AISI 316L standard. Table 1 has collection some of them. As from table 1 shows one problem in comparison is formed by the type of roughness informed. Ra is conventional line roughness measurement procedure, but it will bring out different results as Sa which is roughness of an area. In any case typically the polishing is done with solid state laser fiber or Nd:YAG, which will result typically to roughness decrease of 84.6 – 96.2%. The only results with CO₂ laser show the lowest improvement which still is of quite high value.

Table 1. Results from literatures of polishing experiments for AISI 316L type stainless steel manufactured with PBF-LB process. Unfortunately, the references did not follow rules of accuracy.

Ref.	Material	Laser type		Ra	Ra	Sa	Sa	St	St	Roughness decrease
				μm	μm	μm	μm	μm	μm	
1	316 L	Fiber	CW			21.0	0.79			96.2 %
1	316 L	Fiber	CW			18.0	2.34			87.0 %
3	316 L	Fiber	pulsed					9.77	1.5	84.6 %
6	316 L	Fiber	CW	10.0	1.4					86.0 %
7	316 L	Nd:YAG	pulsed	12.0	1.5					87.5 %
8	316 L	Fiber	pulsed	4.75	0.4					91.6 %
9	316 L	CO ₂	CW	10.4	2.7					74.0 %

A pulsed laser can be used also for surface polishing. This makes process a bit more complicated since together with track overlap the pulse overlap must also be considered. However, the process seems to work pretty well e.g. according to Bhaduri et al., 2017[3] who used MOPA-based Yb-doped nanosecond (ns) fiber laser source, maximum average power 50 W and wavelength of 1064 nm. They polished austenitic stainless steel SS316L parts made with binder jetting process called Digital Metal®(DM). In this study it was found that the energy density and pulse overlap along are together with the beam scanning direction the most important factors in laser polishing. A maximum reduction in areal surface roughness of over 94% was achieved at the optimized LP settings. [3]

Ability of laser polishing to treat selected locations of part is presented e.g. by Bhaduri et al., who presented results of polishing specific locations of a machine component [3]. They improved the surface roughness from 2.41 μm to 0.24 μm. The energy input plays an important role in polishing process such that lower energy input result in insufficient melting while that beyond the optimized value the higher energy input led to ablation and surface over-melting of material in case of pulsed laser. [3]

The aim of this study is to find out whether can laser polishing is suitable for post-processing to improve surface quality to level required by engineering applications. The second aim was to study can normal high-power multimode laser be used for polishing. Laser polishing process has potential to solve the problems of mechanical tools in improvement of surface quality and finally to enable automation of it. Automation would be the final goal and laser beam as non-wearing tool, no force process and flexibility in shape and form can be much more flexible tool and set less restrictions to product design than e.g. machining of grinding.

2. Experimental procedure

In this study the test samples were manufactured by PBF-LB/M/ of austenitic stainless steel (AISI 316L) as a sheet in 45-degree angle to the building platform. The sheet was the cut with laser beam into samples of suitable size for testing. The surface roughness of the samples was measured prior an after the laser polishing experiment with optical measuring system. Polishing was carried out with fiber laser with different process parameters. There were three sub goals for the experimental procedure:

- A. study the effect of laser power (B1 vs B2 vs B4)
- B. study the effect of energy input at various speed and various laser power (B1 vs B2 vs B3 vs B4)
- C. study the effect of number of treatments on the polishing result (A5 vs B1)

The material used was EOS StainlessSteel 316L (according to UNS S31673 standard) material, with general powder particle size distribution of 20 – 65 μm [9]. The nominal analysis of material is presented in table 2. The printing was carried out with EOS290M powder bed fusion printer with EOS standard parameter values for this material (316L_040_FlexM291_1.).

Table 2. Powder chemical nominal composition (wt.-%)

Cr	Ni	Mo	C	N	Fe
17.00 - 19.00	13.00 - 15.00	2.25 - 3.00	- 0.03	- 0.10	bal.

2.1. The polishing procedure

The polishing experiments were performed with high power laser system typically used for e.g. welding and hybrid welding experiments. This was intentionally selected laser, since the availability of such a laser is good and the beam intensity profile, top hat, would provide quite even heat input to whole process zone. The laser used can be tuned to use only 1-2 modules thus the low laser power used was attainable.

- Laser: IPG YLS 10000 CW fiber laser
- Wavelength: 1070 nm
- Processing fiber core diameter: 400 μm
- Optical processing head: Precitec YW52
- Collimation length: 200 mm
- Focal length of focusing: 300 mm
- Beam intensity profile: top hat
- Beam diameter at focal point: 0.8 mm.
- Focal point position: on the sample surface.

The experiments were performed with Yaskava / Motoman UP50N Industrial robot. With this movement systems the constant processing speed for polishing experiments reached by starting process on top of the masking plate such that in beginning while system was accelerating the beam did not reach the test sample.

The laser power used was varied between 50 – 200W (to avoid too high heat input on lower speeds, only low power levels were used). The processing speeds used were between 20 – 130 mm/s (defined by previous experience to be suitable for robot use). Most of experiments were carried out with two

round treatment rounds. Table 3 summarizes the used parameter value combinations in different experiments.

Table 3. The used parameter value combinations in experiments.

Experiment	laser power, W	Process speed, mm/s	Treatment rounds
A	50, 100, 160	20 - 70; interval 10	2
B	50, 100, 160	20 - 70; interval 10	2
	200	80 – 130; interval 10	2
C	100	20 - 70; interval 10	1/2

2.2. The surface roughness measurement procedure

The measurements have been made with a Bruker Alicona Infinite Focus G6 optical 3D surface quality measuring device, the software of which is MetMaX 2.1 and its LaboratoryMeasurementModule 9.2 software. When measuring the surface roughness of the printed, unpolished plates, a 5x magnification was used, because a reproducible result was not obtained from the image at a higher magnification. In the measurements of the polished surfaces, 10x magnification was used, which was the highest possible accuracy for the surface quality in question. The measurement processes were carried out according to the device manufacturer's instructions.

Surface roughness measurements were made on metal printed (PBF-LB/M/) pieces before polishing and after laser polishing. Since no established method has been defined for the implementation of the measurements, the profile (2D) and area (3D) surface roughness of all samples were measured. In 2D measurements of surface roughness, the measuring device complies with standards ISO 4287 and ISO 4288. In 3D surface roughness measurements of the area, the instructions of the ISO 25178 standard series were followed.

The optical measurement used is well suited for measuring the surface quality of metal products printed with the PBF-LB/M/ method. The surface of the printout is so rough that a traditional tactile measuring probe may stick. In addition, the printed surface has sharp valleys that the touching measuring probe cannot reach.

The measurement parameters are defined according to the device manufacturer's instructions. First, a sample of one image has been taken from the surface to be measured, from which a rough estimate of the Ra and Rz values of the surface has been obtained, and the structure of the surface structure has been determined from the profile of the surface. With these values, the vertical resolution (Vr) and lateral resolution (Lr) could be calculated for the measurement, the lens suitable for the measurement was confirmed, and the length of the measurement area (Lc). The factors resulting from the properties of the surface of the object to be measured affect the resolutions used in this study as follows:

$$Vr = \frac{Rz}{(15...30)}$$

where:

Vr = Vertical resolution

Rz = Average height difference between the highest peaks and the lowest valleys of the surface

The definition provides a range of Vr values suitable for the shape of the surface, from which a certain value is assigned to the measuring device.

$$Lr = \frac{\text{Structural length}}{10...40}$$

where:

Lr = lateral resolution

Structural length = defined from the profile measured from the sample

The definition provides a range of L_r values suitable for the shape of the surface, from which a certain value is assigned to the measuring device.

The definition of surface roughness according to the 2D standard is based on five measurement areas, and the length of individual measurement areas is defined in five categories according to surface roughness. In this study, the R_a values of the surface roughness were in the categories 2 – 10 μm and 10 – 80 μm , in which case the length of the measuring profile should be 12.5 mm ($L_c=2500 \mu\text{m}$) or 40.0 mm ($L_c=8000 \mu\text{m}$).

In these measurements, it was not possible to describe the measurement profile length (L_c) according to the standard, so the measurement profile was made as a continuous back and forth line on the surface described. Using this method, all measurements were made with standard L_c values.

3. Results and discussion

3.1. The effect of laser power on the polishing result

The effect of laser power on polishing was tested with three power levels (parameter values B) 50, 100 and 160 W. The processing speed with each power was varied from 20 to 70 mm/s at intervals of 10 mm/s. All samples were treated twice with same parameter set. After each polishing, the change in surface roughness was determined, in which the obtained surface roughness parameters after treatment were compared to the untreated surface. The graphs in figure 4 contain samples B1, B2 and B4 parameters ΔR_a , ΔR_z , ΔS_a and ΔS_z as functions of process speed. As the figure 4 shows typically, the decrease of roughness is decreased with the increase in speed with all power levels. Also, the decrease of roughness was also decreased with decrease in power. This leads to the conclusion that the selected power levels were quite good for first experiments since the optimum power range is probably in between the currently used power levels with this beam set-up.

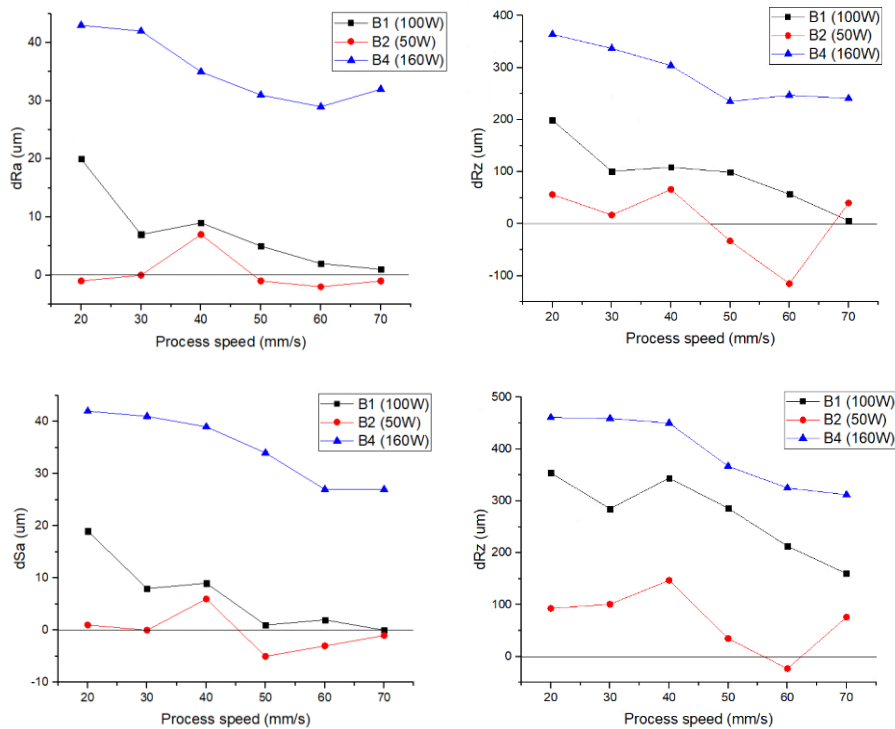


Figure 4. The effect of process speed and laser power for surface roughness values. Different surface roughness change values in function of the process speed with different laser polishing powers.

Based on the results, at a power of 50 W, the average surface roughness (Ra, Sa) does not significantly change at the speeds used. In contrast, at a power of 50 W, the average peak-to-valley roughness profile (Rz, Sz) has changed somewhat. It can be assumed that at this power and at these speeds, the highest peaks of the surface to be polished will be lowered without significant polishing taking place.

At higher powers, the changes in surface roughness are already significant. As the power increases and the process speed slows down, the polishing process improves as expected. It can also be seen that the Rz and Sz values change more strongly than the average surface roughness values Ra and Sa. Even in these cases the highest peaks melt and descend more easily.

3.2. The effect of energy input on polishing result

The heat input is calculated by dividing the laser power with process speed. Typically, this is suitable way to analyse the effect of parameter values on the process. In addition to the results of the previous experiment (50W, 100W and 160W), the evaluation of the effect of the energy input was performed with the parameter 200 W with each line varied speed from 80 to 130 mm/s at intervals of 10 mm/s. Each sample was measured prior and after the treatment. All samples had two treatment rounds on top of each other. The average of each prior roughness parameter was calculated to measure the difference between the prior and after values to represent the amount that the treatment affected the roughness. The graphs contain all the samples parameters ΔRa , ΔRz , ΔSa and ΔSz as functions of energy input. Naturally the values of Rz and Sz are always higher than the more common value in mechanical engineering the Ra and Sa. Typically for conventionally manufactured surfaces the Ra and Sa are suitable since the surface roughness is often quite even e.g. in after machining. See figure 5.

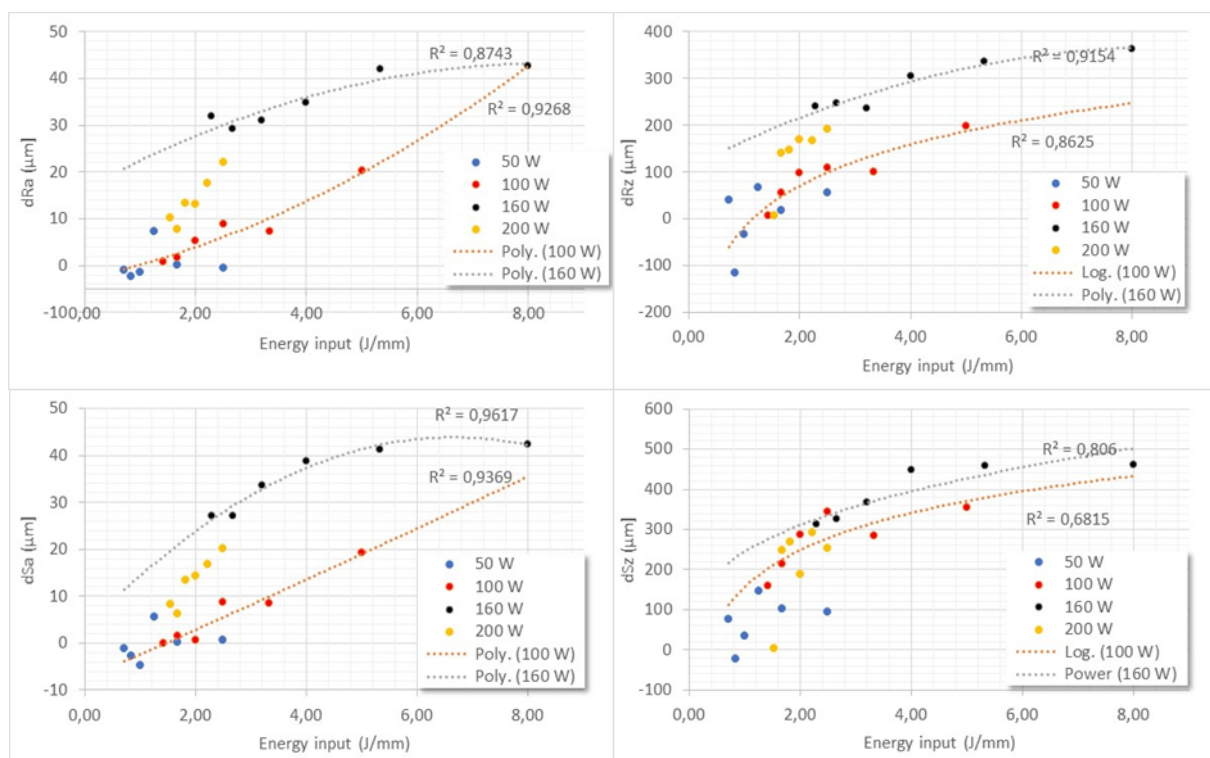


Figure 5. Different surface roughness change values in function of the energy input with different laser polishing powers and speed.

Based on the obtained results, it can be observed that at the lowest energy inputs used in the experiments, polishing did not occur regardless of the used laser power. With the energy inputs of the experiment 5 - 8 J/mm at 160 W laser power, the surface roughness changes were almost the same, i.e. increasing the energy input did not improve the obtained results. In contrast, with 100 W laser power, changes occurred in that range. Even with 200W laser power, changes in surface roughness were obtained with a lower energy input, but the results do not yet show an optimal energy input, whereby increasing the energy input no longer improves the change in surface roughness. The risk of increasing the energy input is the possible unwanted changes to the shape and properties of the piece. With a higher power of 200 W, the surface melts, even if the speed is increased. Based on the results, by increasing the laser power, polishing takes place with a lower energy input.

3.3. Effect of repeated treatment

To study the effect of carrying out several polishing rounds by second polishing treatment on top of first treatment two sample lines were selected for secondary treatment study. A5 and B1 sample lines were made with using the single laser power (100W). The processing speed with each line varied from 20 to 70 mm/s at intervals of 10 mm/s. The surface roughness of each sample was measured prior and after the treatment. Sample A5 was treated once and sample B1 was treated twice. The average of each prior roughness parameter was calculated to measure the difference between the prior and after values to represent how did the treatment affect to the roughness of the surface. The graphs in fig 6. contain both samples A5 and B1 parameters ΔRa , ΔRz , ΔSa and ΔSz as functions of process speed.

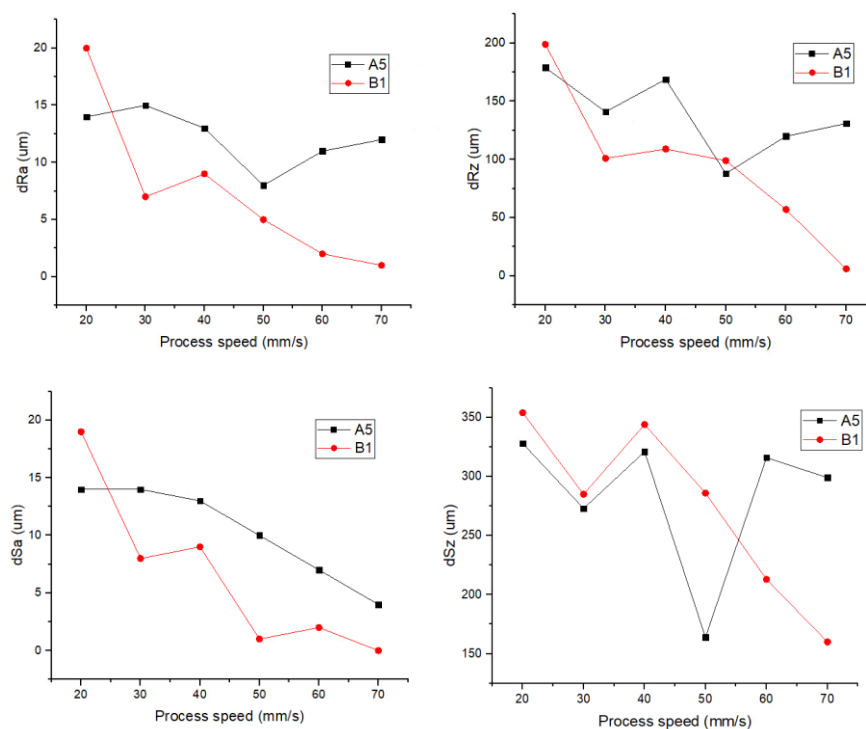


Figure 6. Different surface roughness change values in function of the process speed with different laser polishing powers after two polishing.

Based on the results, the changes in surface roughness measured at all values for both polishing cycles are significant at lower process speeds. As the process speed increases, the effect of the second polishing time ends. From the results, it can be concluded that during the first polishing, the highest peaks are smoothed out and at higher process speeds, the energy is not enough to melt larger surfaces.

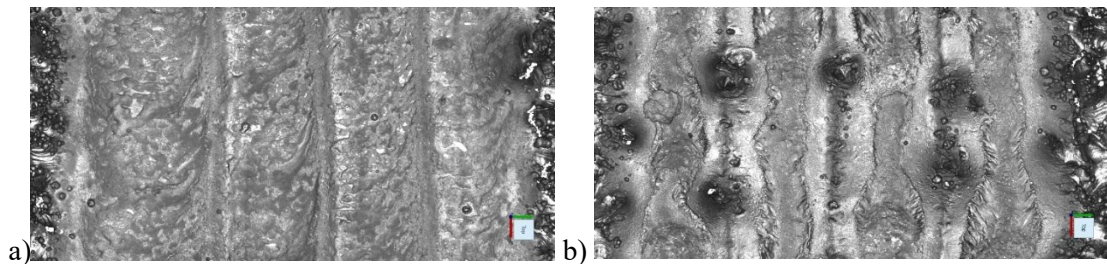


Figure 7. An example of LPF-LB/M manufactured surface after a) one polishing treatment (A5) and b) two polishing treatments (B2).

The results of two polishing rounds were interesting. The second polishing treatment made the surface rougher in some cases from the surface of first polishing treatment. From the images in Figure 7 a), the first polishing time created a smooth surface, but after the second polishing time, the surface has deep valleys (Figure 7 b). This is visible more clearly in Sz and Rz values, which are measuring the maximum difference in surface roughness and only with high, over 60 mm/s speed, the second round was smoothening the surface more. Also, in case of Sz which measures the area this phenomenon is more obvious. It can be assumed that the first polishing session has left pores under the layer, which will open with the second polishing session.

4. Conclusions

The experiments showed that considerable surface smoothening was reached in all part surface orientations and location. It was also found that this technology can provide a considerable improvement to surface finish of PBF-LB/M/ manufactured parts and that the technology is potential for automation.

The results clearly show that laser polishing improves surface quality when the power and speed of the process are suitable for polishing. There is a lot of scatters in the results, but the trend clearly shows the effect. The number of tests is too small to determine more precise polishing power, speed and other values.

Based on the obtained measurement results, measurements of the surface quality of PBF-LB metal prints should be made using optical measurement methods. The quality of the surface of the prints is so rough that you cannot get a reliable result with a touch measuring device, or you don't get a result at all.

In terms of evaluating the efficiency of the polishing process, it does not matter if the parameters of surface roughness Ra, Rz, Sa or Sz are used. All values or their changes can be used to describe the effect of the process on the surface quality. When a measuring device is available to measure the regional surface roughness parameters (Sa, Sz), then their use we recommended.

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