APPLICATION OF LASER SURFACE POLISHING ON ADDITIVE MANUFACTURED PARTS OF INCONEL 718 NICKEL-BASED SUPERALLOY

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DOI: 10.17973/MMSJ.2020_03_2019141

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This article deals with the influence of laser polishing parameters on the final surface quality of nickel-based superalloy Inconel 718 produced by metal additive manufacturing. The aim is to optimize the laser polishing process parameters to reduce the surface roughness of the sample. The investigated parameters of the laser are scanning speed, frequency, focal length, and pulsed and continuous wave regimes are considered. The samples of Inconel 718 are produced by direct metal laser sintering technology. Depending on the printing orientation, the roughness after AM is Ra 5 – 12 µm. The samples were machined to ensure uniformity of the monitored and tested surface. An IFM – G4 3D optical microscope is used for the surface evaluation. The initial roughness of the samples before applying laser polishing was Ra 1 - 2 µm. The roughness after laser polishing is significantly reduced to Ra 0.369 µm.

KEYWORDS

Laser polishing; Additive Manufacturing; Pulsed regime; Continuous wave regime; Inconel 718; Surface roughness

1 INTRODUCTION

Additive manufacturing technology brings new research challenges. Nowadays, many research centers around the world are focusing on metal additive manufacturing. These teams are developing new methods, creating information and processes which improve the material/mechanical properties of additively manufactured parts. A much-discussed topic is Hot Isostatic Pressing (HIP). Jiang et al., 2019 dealt with the influence of this method on final material properties and structure. They found that HIP at 1120 °C for 1.5 h fully dissolves the inter-dendritic micro-segregation into the matrix. When the longer time is used the microstructure is changed from columnar to equiaxed grains and it influences the Young's modulus. It means that the mechanical properties can be influenced. This finding is confirmed in another article [Bean et al., 2019], which describes the influence of the print orientation of tensile samples on the final mechanical properties and surface quality. They identify the influence of the anisotropy of the Inconel 718 and confirm that in the Z printing direction, samples had approximately 35 MPa lower yield and tensile stress. Similar results are presented by another team [Golinveaux et al., 2019]. They studied in detail the character of the cracks and they identified general problems of the PBF process. They found pores and lack of fusion inside the part which initiates cracks. They concluded that the internal material structure and surface layer without defects is important for the mechanical stability of the additive manufactured parts. It is known that the surface quality influences the results of fatigue tests. This dependency is investigated by [Scurria et al., 2019]. They compare mechanical and electrochemical polishing. As they describe in the article, the differences between these methods very significantly influence the fatigue test results. Another team of authors [Witkin et al., 2016] try to use the same laser which is used for the sintering process for surface modification. They optimized the laser energy to smoothen the part during the build with a pulse profile to induce re-melting without spallation or ablation. The results show that surface features such as partially sintered powder particles and surface connected porosity can be reduced. Finally, the surface quality of the additive manufactured parts is a very important issue and it is dependent on a few main inputs, but generally on the quality of the metal powder. The quality of the metal powder changes during the process and the time of use. It influences the amount of porosity and the final mechanical properties as the authors described in this article [Sukal et al., 2018].

2 EXPERIMENTAL EQUIPMENT

In this experiment a nanosecond fibre laser was used with a wavelength of 1060 nm and maximum pulse energy of 1 mJ. This laser is characterized by tuneable waveform technology which allows it to deliver pulses with different pulse durations which have different influences on the machined parts. The area affected by the laser was measured at the focal point. The measured diameter of the affected area was 45 µm. The laser is moved by a scanning head with galvanometric mirrors. The maximum speed of the laser spot was 0.6 m/s. Laser polishing was applied to additively manufactured parts of Inconel 718 nickel-based superalloy. The samples were then machined to ensure uniformity of the monitored and tested surfaces. The surface roughness of samples processed by conventional machining was Ra 1.3 µm. The topology of the surface before laser polishing can be seen in Fig. 1. The surface topology was evaluated on an Alicona IFM - G4 3D optical microscope.

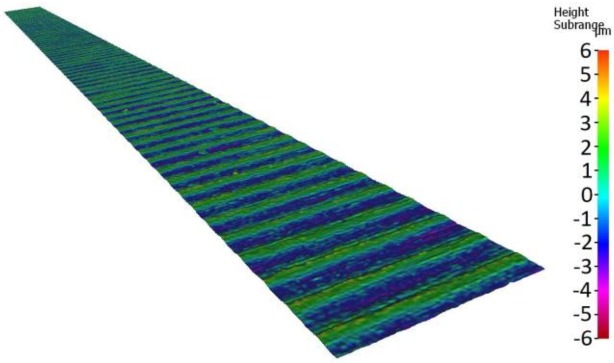


Figure 1. The initial surface of the sample

3 EXPERIMENT

In this experiment two laser regimes were investigated. The first was the pulsed regime which can generate pulses with durations from 6-500 ns and peak power of tens of kW. The second was the continuous wave regime. To investigate the parameter dependency on the resulting surface roughness a matrix of parameters was created. But in order to acquire valid results appropriate parameters need to be chosen. For example, [Bartolo et al. 2006], dealt with the influence of laser parameters on surface roughness. When choosing the appropriate frequency values for this experiment, lower values were chosen, because frequency influences spot overlap and pulse energy. When higher values of frequency are applied on the surface, cracks appear, as can be seen in Fig.2, and the reason seems to be the high spot overlap. With speed the limiting factors are higher values, where the time of interaction between the laser and the surface is inadequate and the surface is not structured enough. There are no appropriate ways to define the right process parameters for laser polishing, because the process parameters are dependent on other parameters, for example on the type of material, the initial surface roughness and so on.

When the first parameters were applied on the sample, the laser intensity was too high, causing evaporation of the material and melt ejection, as can be seen in Fig.3. The laser intensity is dependent on the power and on the area of the laser spot. The spot diameter was increased to reduce the laser intensity according to the following equation:

$$I = \frac{P_{peak}}{S} = [W/m^2] \qquad (1)$$

Where:

I… laser intensity W/m^2

P_{peak}… peak power W

S…area of laser spot m^2

The spot diameter was increased by changing the focal length and the resulting width of the influenced area was 80-90 µm. The main reason for decreasing the laser intensity is to prevent material evaporation. Material evaporation is undesirable in laser surface polishing, because according to [Temmler et al. 2012], laser polishing is accomplished by re-melting the surface and the surface tension moves the molten material from the peaks into the valleys on the surface and the surface becomes even. But it needs to be taken into consideration that only an uneven surface in the micro scale can be polished in this way, because the amount of the molten material is dependent on spot size. In Fig. 3 and Fig. 4 can be seen how changing the focal length influences the surface roughness, resulting in better in better surface quality with a displacement of 2 mm above the surface, therefore this displacement was used in the experiment for both regimes.

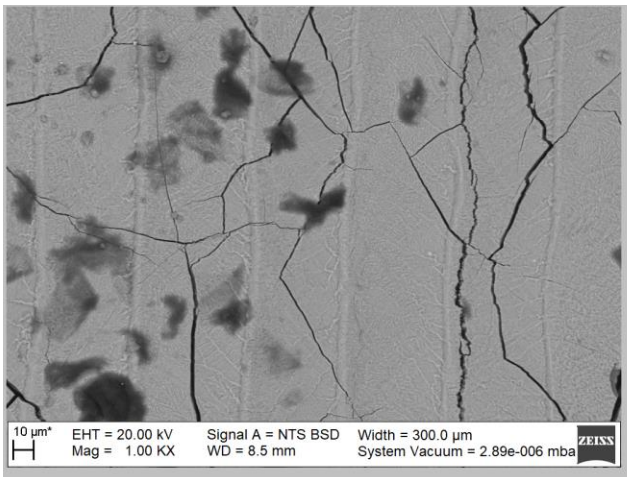


Figure 2. Cracks on the surface with high frequency and high spot overlap

Figure 3. The result of laser polishing at focal length

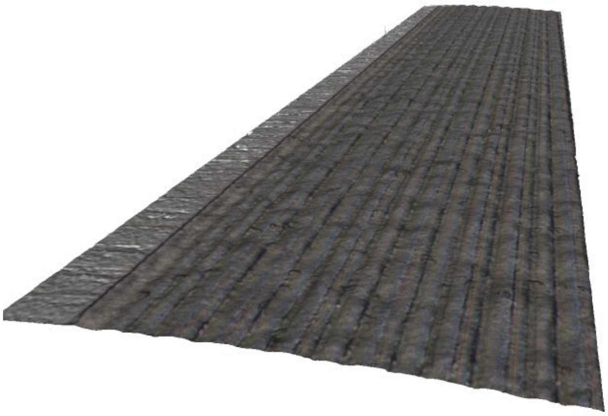


Figure 4. The result of laser marking at distance 2mm above surface

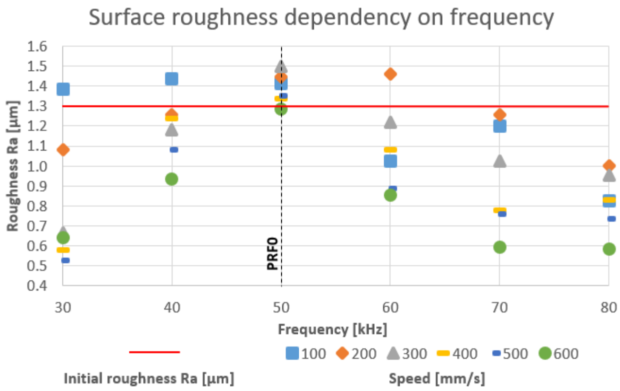
4 RESULTS AND DISCUSSION

4.1 PULSED REGIME

Tab. 1 shows the measured roughness Ra, acquired from the polished surfaces after applying different process parameters. From Tab. 1 can be clearly seen that the surface roughness improved with increasing speed. With the frequency the roughness dependency is not so clear. Graph 2 shows that with increasing frequency up to 50 kHz the roughness decreases and with further increases in the frequency, the roughness decreases. The reason behind this is that with a 35 ns pulse the maximum energy per pulse is achieved at 50 kHz. This frequency is called PRF0. Frequency at PRF0 has the highest energy value of 1 mJ. With a decrease of frequency below PRF0 the energy would naturally rise, but since 1 mJ is the maximum possible value, the lower frequency is compensated by a decrease of power. The surface polished at 50 kHz can be seen in Fig. 6. The surface shows signs of high intensity laser polishing: material evaporation and melt ejection. The best surface roughness can be seen in Fig 5. It was achieved with process parameters of 30 kHz and 500 mm/s. The surface was improved by 56% to Ra 0.5257 µm.

Table 1. Resulting surface roughness due to the change of parameters

Roughness Ra [µm]		Speed [mm/s]					
		100	200	300	400	500	600
Frequency [kHz]	30	1.384	1.083	0.666	0.581	0.526	0.640
	40	1.438	1.257	1.180	1.248	1.080	0.935
	50	1.411	1.446	1.496	1.339	1.352	1.286
	60	1.027	1.462	1.216	1.084	0.887	0.855
	70	1.201	1.254	1.025	0.780	0.759	0.596
	80	0.826	0.999	0.955	0.830	0.734	0.583



Graph 1. Dependency of roughness on frequency after applying laser polishing with pulsed regime

As can be seen on Fig.5, even though the laser spot diameter was increased and laser intensity reduced, the material was partially molten and partially evaporated. The indicators are the grooves with the shape of gauss laser propagation. Even though the material was partially molten we cannot call this process laser polishing by re-melting the surface, because the surface was partially evaporated.

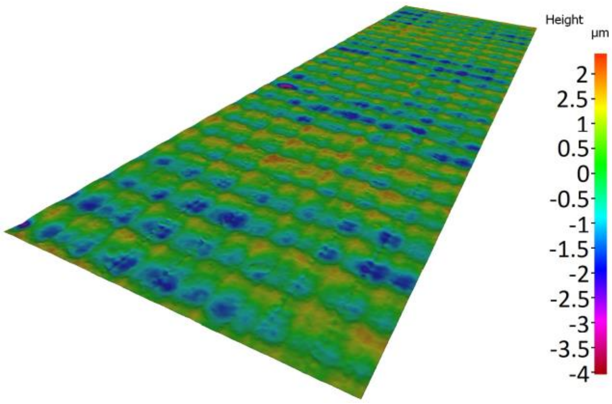


Figure 5. Surface topology after laser polishing

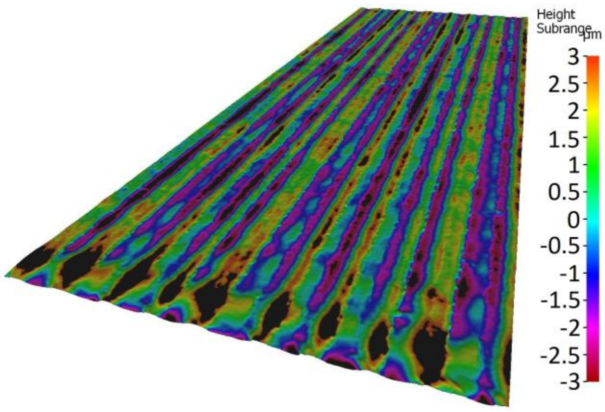


Figure 6. The worst surface topology obtained after applying laser polishing

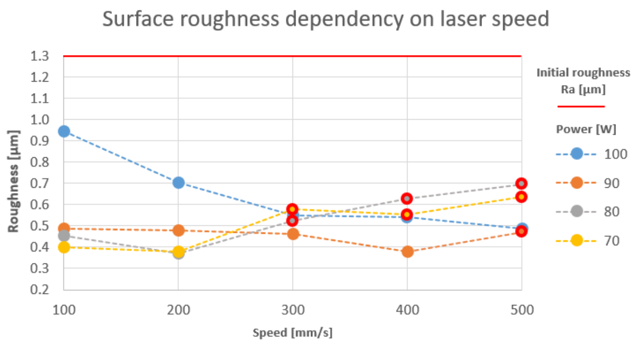
4.2 *CONTINUOUS WAVE REGIME*

With the continuous wave regime, the maximum power was chosen, because unlike the pulse regime, the continuous wave regime cannot reach a peak power of tens of kW. However, the advantage of continuous wave is that the melted depth is much greater and therefore is more suitable to use in laser polishing by re-melting the layer for higher surface roughness.

With the continuous wave regime, the best surface roughness of 0.3690 µm was achieved by applying parameters of 40 W and a speed of 200 mm/s. From Graph 2 we can see that roughness has improved with higher speed and also with lower power. The laser wasn't able to structurize the surface completely due to a change of the focal length in combination with the higher laser speed and the lower laser power. This resulted in a decrease of affected areas and adjacent laser crossing paths did not overlap each other, as can be seen in Fig. 12. Therefore, the hatching distance was changed so the adjacent crossing lines would overlap and the results can be seen in Tab. 2 with the red values. However, even though the hatching distance was changed and the adjacent lines overlapped, the roughness increased with higher speed and lower power because of the shallower melt depth.

Table 2. Resulting surface roughness due to the change of parameters

Roughness Ra [µm]		Speed [mm/s]				
		100	200	300	400	500
Power [W]	50	0.9428	0.7016	0.5509	0.5393	0.4888
	45	0.4852	0.4779	0.4605	0.3799	0.4708
	40	0.4520	0.3690	0.5241	0.6270	0.6948
	35	0.3981	0.3771	0.5771	0.5528	0.6358



Graph 2. Dependency of roughness on frequency after applying laser polishing with CW regime

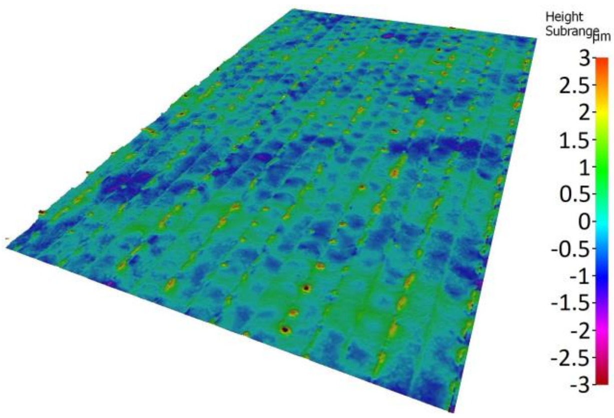


Figure 7. The best surface topology acquired after applying CW

The photographs below show how the affected area changes with the different parameters. With the increased power, the energy also rises, resulting in heat increase and a larger heat affected zone. This is supported by Fig. 8 and Fig. 9, where the width of the crossing lines changed from 101 µm to 91 µm when the power was reduced from 50W to 45W. Speed was also a factor in heat propagation. With the increase of the speed the interaction time of the laser and the surface decreases, resulting in smaller widths of the crossing lines as can be seen in Fig. 10 and Fig. 11.

The photographs also show black droplets which affect the surface roughness. The origin of these droplets is unknown and further investigations will have to be performed. However, the number of droplets is significantly reduced by changing the parameters. The higher speed of the laser and lower power had a positive effect on reducing the number and size of the droplets.

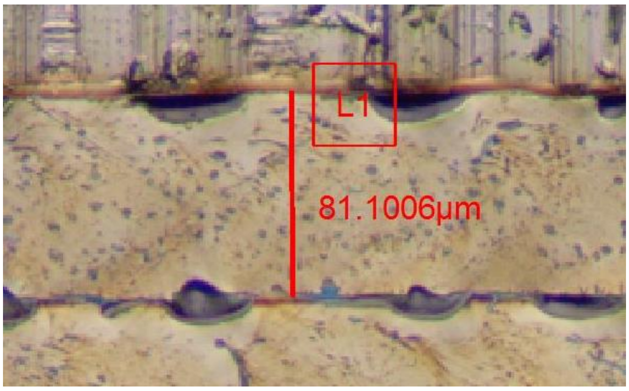


Figure 8. Microscopy picture of CW polishing with parameters of 35W and 200 mm/s

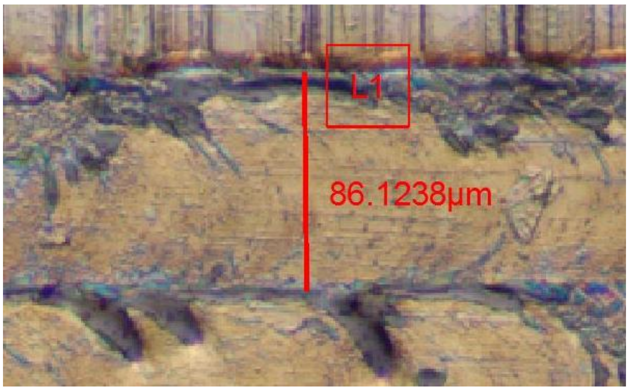


Figure 9. Microscopy picture of CW polishing with parameters of 40W and 200 mm/s

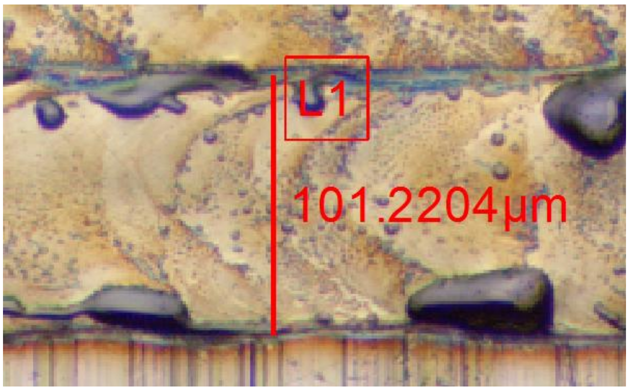


Figure 10. Microscopy picture of CW polishing with parameters of 50W and 300 mm/s

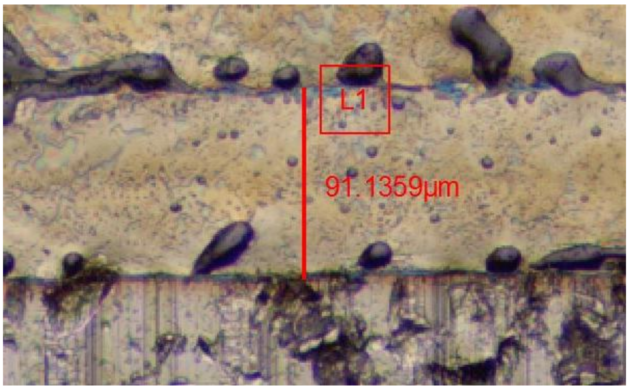


Figure 11. Microscopy picture of CW polishing with parameters of 50W and 500 mm/s

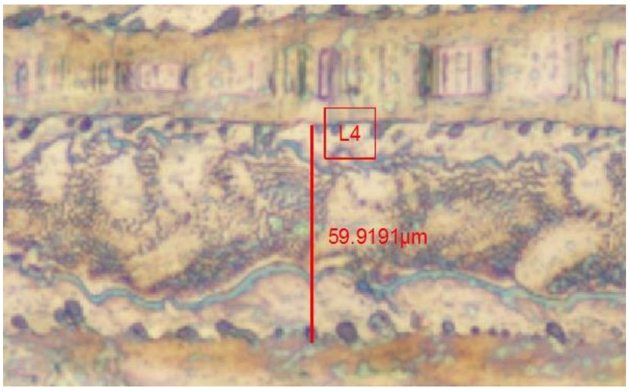


Figure 12. Microscopy picture of CW polishing with parameters of 45W and 500 mm/s

5 CONCLUSION AND RECOMMENDATIONS

Two regimes were investigated and both regimes exhibited different behaviours when applied on a surface. The best results were obtained by applying the continuous wave regime giving a roughness Ra of 0.3690 µm, an improvement of the surface roughness by 72%. Even though the pulsed regime also showed good results, it was possibly because the initial surface roughness was only between Ra 1 - 2 µm. For surfaces with higher roughness a pulsed laser would not be sufficient because of the shallower melted depth and material evaporation. These properties of the pulsed laser with a pulse duration of nanoseconds are beneficial for different applications than laser polishing, for example laser marking. The continuous wave regime showed good results because of the greater melt depth, however the problem is that with a continuous wave the energy is constantly supplied into the melt pool and whirls appear in the melt pool resulting in an uneven surface, meaning that smaller values of roughness could be difficult to produce. This could be solved with the pulsed laser, but with long pulse durations of milliseconds or microseconds. Therefore, the pulses would not have enough peak power to evaporate the material and the time between pulses would allow the molten surface to solidify. Another way to improve surface roughness would be to further increase the spot diameter, so the intensity of the laser is not concentrated in the centre of the laser spot but is more evenly distributed across the diameter. However, the laser needs to have enough power to compensate for the increase of the diameter. Unfortunately, the laser used in this experiment had a maximum average power of 50W. These recommendations are only speculations and would have to be confirmed by experiment.

This article deals only with the influence of the parameters on surface roughness. But laser polishing influences other surface properties, for example hardness, tribological properties, residual stress and so on. This will be the main focus for further research.

ACKNOWLEDGMENTS

This contribution was based on the solution of grant TG02010303 in the program for the support of applied research and experimental development of EPSILON agency TAČR.

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