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Laser based post processing of additive manufactured metal parts

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Abstract

Additive manufacturing (AM) techniques, like powder-bed based Selective Laser Melting (SLM), are gaining in importance which leads to a continuously increasing market. The SLM process offers the opportunity to generate highly complex solid metal parts, with low porosity and good mechanical properties. However, the layer-wise production process has also certain disadvantages, like a relatively high surface roughness with fluctuations depending on component shape, position and orientation during the fabrication process. Therefore, there is a demand for post processing methods offering similar design flexibility as the SLM process itself. Laser based post processes of additive manufactured parts like laser cleaning and laser polishing provides the possibility of a contact-free and full-automatable surface treatment of metal alloys with short processing times.

This paper deals with the investigation in laser cleaning and the development of laser polishing of SLM parts made of steel or aluminum. Laser cleaning with an ns-pulsed fibre laser leads to effective ablation of residual metal powder on the rough topography of the SLM surfaces and a significant reduction of the oxide layer. Laser polishing revealed a reduction of the surface roughness of greater than 95%, i.e. from a Ra-value of 8.7 µm on AlSi10Mg (initial state) to a Ra-value of 0.2 µm or lower (final state) and on X2CrNiMo17-12-2 steel (1.4404) from a Ra value of 12.5 µm down to 0.35 µm at a process rate of up to 35 cm^2/min. Polishing strategies with one and multiple crossings are investigated. Several test series with pulsed wave (pw) and continuous wave (cw), with variation of laser parameters like laser spot diameter, beam intensity or the feed rate have been investigated.

Keywords: Additive manufacturing, Selective Laser Melting (SLM), stainless steel 1.4404, Aluminum AlSi10Mg, Surface cleanliness, Laser Cleaning, Laser Polishing, Surface Quality

1. Introduction

Due to ongoing investigation and development, the powder-bed based selective laser melting (SLM) process is in production. The main advantages of this technology are a broad range of useable metals with

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the possibility to build individual complex parts and good mechanical properties (Kempen et al., 2012, Mower and Long, 2016). Based on the ability of fabricating parts directly from CAD models, an increased geometrical freedom results, which leading to complex part geometries and shapes. However, the layer-wise process and complex geometries also cause a relatively high surface roughness and contaminated surfaces (Van Hooreweder et al., 2017). The emerging roughness depends on the shape of the individual part orientation and positioning during the manufacturing process (Yasa and Kruth, 2011a, Hitzler et al., 2017). Possibilities to reduce the roughness of selective laser melting were investigated, i.e. hatch strategies (Gebhardt et al., 2014), laser parameters (Calignano et al., 2013) and laser remelting of each layer (Yasa and Kruth, 2011b). Based on these the opportunities to reduce the roughness were found to be limited. Hence, additional options were studied, i.e. cutting, chemical polishing (Łyczkowska et al., 2014), abrasive blasting (Manfredi et al., 2014), mechanical polishing (Li et al., 2014) or laser ablation (Campanelli et al., 2013). They all have several disadvantages in common: loss of accuracy due to geometrical restrictions, governed by the post processing technique, non-contact free and non-selective processing, wastage of material and environmental issues. Additionally, the rough contaminated SLM part are not suitable for usage in cleanrooms, food industry or medical implementation.

An environmental friendly and fast way to remove inherent particle on the surface is Laser Cleaning. Laser cleaning, as shown in Figure 1 (a), is typically done by pulsed laser systems with pulse durations in the µs and ns-Range. A short pulsed beam with high pulse peak intensity is guided over the surface of the part. Deposits, oxide layers or in this case the residual inherent powder of the SLM-material are getting evaporated or ablated without interaction with the lower reflective bulk. The ablated particles are removed by an integrated suction system of the Cleaning Laser.

A productive way to reduce the surface roughness and structure SLM manufacturing process is laser polishing. Laser polishing is a contact-free post processing technique with a comparable degree of geometrical freedom like the selective laser melting process itself (Ross, 2014). During polishing, material of the sample´s surface is molten by the laser beam, (Figure 1 (b)).
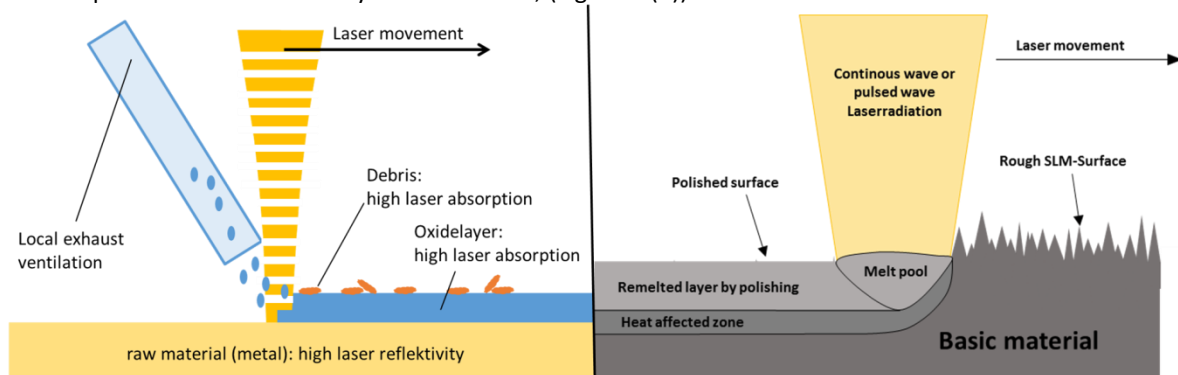

Fig. 1. (a) Schematic illustration of the laser cleaning process and (b) of the laser polishing process

The surface tension of the liquid material smoothens the roughness by a material flow (Willenborg, 2006). The irradiation, introduced by laser polishing, results in a flattened remelted layer and a heat affected zone underneath.

Investigations have shown the possibilities of laser polishing of selective laser melted metal parts, such as aluminum (Schanz et al., 2016), steel (Ukar et al., 2010) and titanium (Marimuthu et al., 2015). The metallurgical influence of laser polishing of aluminium was investigated (Schanz et al., 2017). Thereby, the

impact of laser intensity and laser operation mode (continuous and pulsed wave) on roughness, surface appearance, melt depth, porosity and hardness were investigated.

For industrial usage, the area rate of polishing is significant. A common option is to increase the laser power and, respectively, adjust the other polishing parameters, i.e. scan velocity, track overlap, laser beam intensity and repetition rate (Schmidt et al., 2015). In addition to the laser parameters, the chosen laser source and its intensity distribution have an impact on the polishing process as well (Hafiz, 2012).

In this paper, the influence of laser cleaning on surface contamination were reviewed. The relatively rough surface was smoothened by laser polishing. Parameters on achievable surface roughness were investigated i.e. laser mode, laser power, defocus position. For industrial use, feed rate and number of crossings on surface characteristic were reviewed.

2. Experimental Setup

2.1. Used laser systems for laser cleaning and laser polishing

The investigations are divided into two partial examinations, laser cleaning and laser polishing. For laser cleaning a short pulse laser in the nanosecond range of the type Trumpf TruMark 5020 with an average power of 20 W was used. Figure 2 shows the setup for the investigations on laser cleaning. The beam is guided two dimensionally by means of a scanner optic and an f-theta lens with a maximum operation field of 180 * 180 mm². The beam caustics has a focus diameter d_f of approximately 100 μm and a focal length of 254 mm. He is implemented in the 4-axis laser cell TruMark Station 5000.
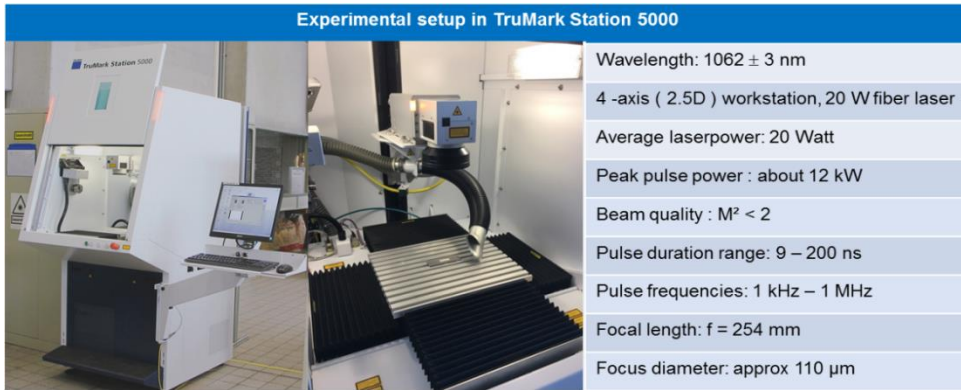

Fig. 2. Experimental setup for the laser cleaning process, TruMark Station 5000

The laser polishing of the additive manufactured parts is carried out by means of a disk laser of the type Trumpf TruDisk 4002 with a maximum power of 4000 W. The examinations occurred by using continuous wave (cw) mode as well as pulsed wave (pw) mode. For processing by means of pulsed wave mode, the laser operated with a maximum pulse frequency of 1000 Hz and a pulse duration of 0.3 ms. The laser beam is guided with a 200 μm gradient index fiber to a modified 5-axis Trumpf laser cell TLC40. Figure 3(a) shows the setup for the investigations. The beam deflection is carried out by means of a scanner optics of type SAO 1.06/1D, which enables a one dimensional oscillation of the laser beam with a maximum frequency of 300 Hz. Figure 3 (b) shows a schematic representation of the pendulum movement over the surface using the scanner optics in conjunction with the machine axis.
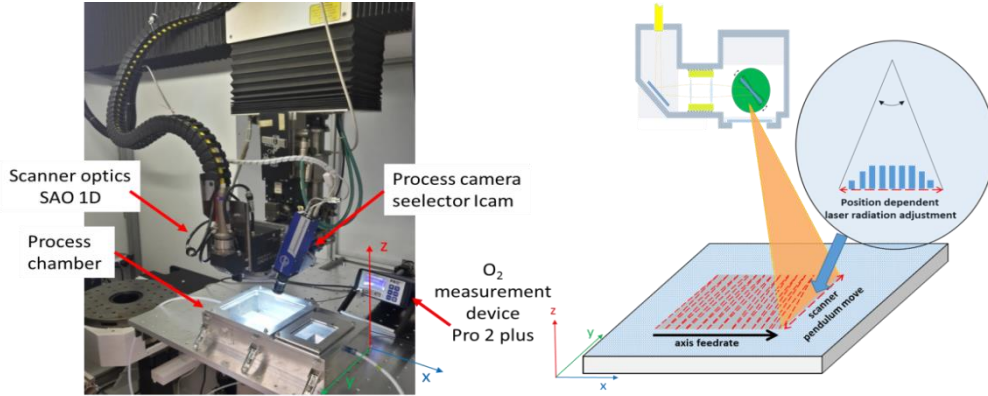
Fig. 3. (a) Experimental setup, TRUMPF Laser Cell TLC 40, 1D Scanner, process chamber; (b) Schematically illustration of laser polishing process

The Scanner-guided laser beam has a focus diameter d_f of 430 µm, a Rayleigh length Z_R of 5.4 mm and a divergence angle $\Theta = 4.4°$ (Fig. 4 (a)). The polished area has a dimension of $10 * 10 \ mm^2$. The pendulum movement in y-direction is superimposed by the axis federate of the scanner head in x- direction. Due to zero pendulum velocity at the turning points (dead points) the melting depth in the border areas of the polished areas is increasing, which results in an inhomogeneous polishing quality. This effect is caused by an inhomogeneous energy input on the pendulum track with constant laser output. In order to prevent this inhomogeneous energy input an adaption of the laser power in the border areas is made. Figure 4 (b) shows the adjusted laser power in relation to the pendulum position. As can be seen, the pendulum axis is sectioned into 15 segments and the corresponding laser power is progressively reduced by 200 W at two segments of each of the right and left border area. The value of the reduction corresponds to 5% of the maximum laser power of 4000 W.
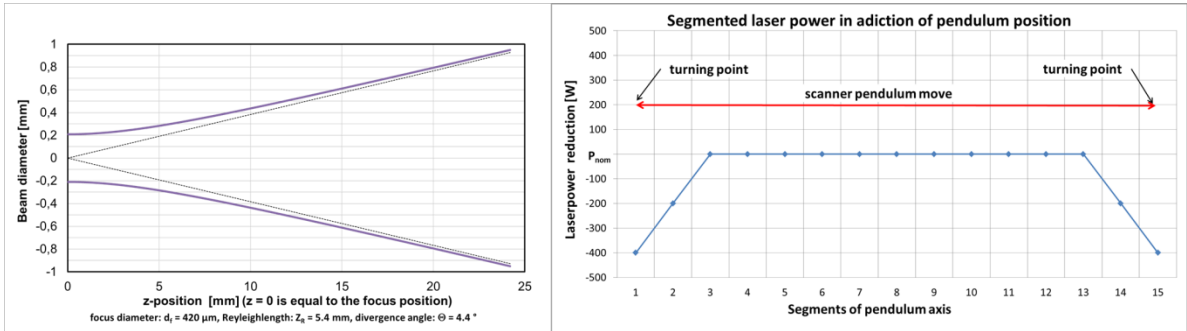

Fig. 4. (a) Laser beam caustic of 1D Scanner, Laser power segmentation over pendulum position

As the samples need to be protected from oxygen, the processing of the work pieces takes places under a purified inert gas atmosphere in a process chamber. A residual oxygen measuring instrument of type PRO2 plus controls the residual oxygen concentration for the laser polishing process, which needs to be less than 40 ppm O^2. With a camera of type selector Icam HD-1 the polishing process is recorded (Fig. 3 (a)).

2.2. Measurement devices

The polished and initial surfaces are investigated quantitatively and qualitatively. The quantitative analysis of the surfaces roughness, i.e.Ra and Rz, according to EN ISO 4288, is done tactilely by means of a perthometer of type MarSurf M400. According to standard for the initial surface with Ra > 2 µm a cutoff wavelength of 2500 µm is used, whereas for the polished surfaces with Ra < 2 µm a cutoff wavelength of 800 µm is used. The listed results in this paper are based on five measurements on different positions on the analyzed surface, which are averaged to a mean value. A digital microscope of type Zeiss Smartzoom 5 is used for the qualitative surface characterization. The surface composition was analyzed with energy dispersive X-ray analysis of type Ametek EDAX Trident. A topographical examination of the surface is carried out by means of a white light interferometer of type Zygo ZeGage, which can capture an area of 800 * 800 μm^2.

2.3. Material and samples

The experimental investigations, addressed in this paper, are implemented on the aluminum alloy AlSi10Mg and the austenitic corrosion proof X2CrNiMo17-12-2 steel (1.4404). For both materials rectangular plates with the dimension of 100 * 30 mm^2 and a material thickness of 2 mm (AlSi10Mg) resp. 3 mm (1.4404) are build by selective laser melting on a SL280[HL] SLM-machine (SLM Solutions GmbH). The machine has a building chamber size of 280 * 280 * 280 mm^3 and is working with a 400 W Yb-fibre-laser. The samples are orientated in different angles form horizontally to vertically in order to investigate the influence of the orientation angle to the initial surface roughness caused by the layer wise fabrication process. The average powder grain diameter is 37 µm on both materials. The slicing thickness amounts at AlSi10Mg 50 µm and 30 µm for 1.4404 steel. The building process was done in nitrogen gas atmosphere.
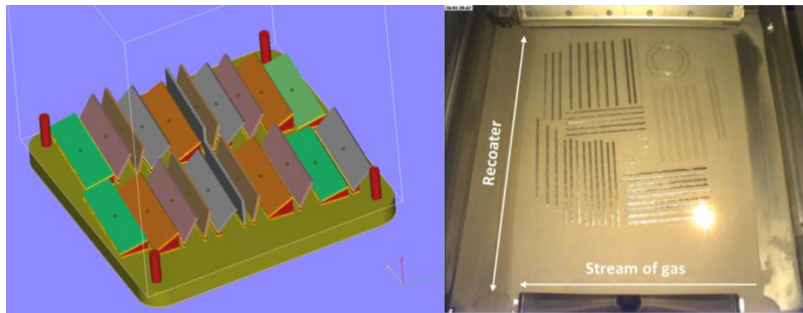

Fig. 5. (a) Aluminum samples on SLM-building platform; (b) SLM-chamber with 1.4404 samples in progress

The applied parameters of the SLM process for AlSi10Mg and 1.4404 are given in Tab.1.

Table 1. Chosen parameters of the SLM-building process

	Scan speed [mm/s]	Laser power [W]	Hatch distance [mm]	Scan vector [mm]	Rotation angle increment [°]
Material	AlSi10/1.4404	AlSi10/1.4404	AlSi10/1.4404	AlSi10/1.4404	AlSi10/1.4404
Contour	600/350	350/100	-	-	-
Core	930/800	350/200	0.17/0.12	10/7.5	90/90
Final layer	850/400	350/320	0.15/0.18	-	-
Contour offset	600/550	350/150	-	-	-
Support	900/650	350/100	-	-	-

After cutting of the samples from the building platform, the SLM surfaces roughness was analyzed. Figure 6 (a) shows the dependency of the sample roughness on the sample orientation in the building process. The aluminum samples roughness varies between a Ra value of 7.6 µm on top surface samples to a Ra value of 10.0 µm on 75° degree orientated samples. Moreover it can be seen that the orientation parallel to the Recoater or vertical has an influence to the surface topography. The current surface topography on vertical orientated parts is shown in is shown in Figure 6 (b).
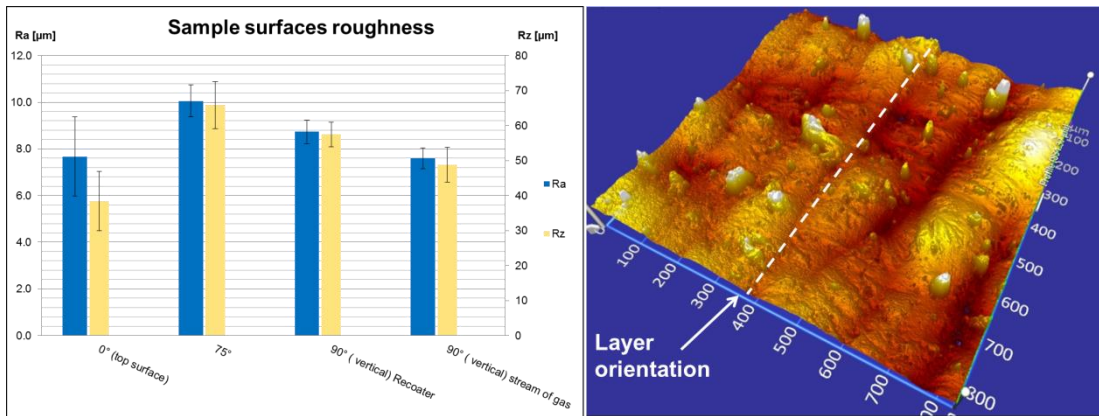

Fig. 6. (a) Aluminium sample surfaces roughness with max-min deviation, (b) SLM surface topography 90°

The 1.4404 parts were analyzed equally. In relation to the aluminum samples, the steel parts have a exceed roughness. The Ra value of vertical parts depending on the orientation to the recoater ranges in between 11.8 µm and 12.5 µm.

3. Results

3.1. Laser cleaning

Optimum parameters are identified by a parameter study. With pulse frequency of 65.5 kHz and 70 ns pulse duration in combination with a feed rate of 3 m/s and a hatch distance of 0.1 mm the best results are revealed. In Figure 7 a microscopic image of the laser cleaned surface is illustrated.
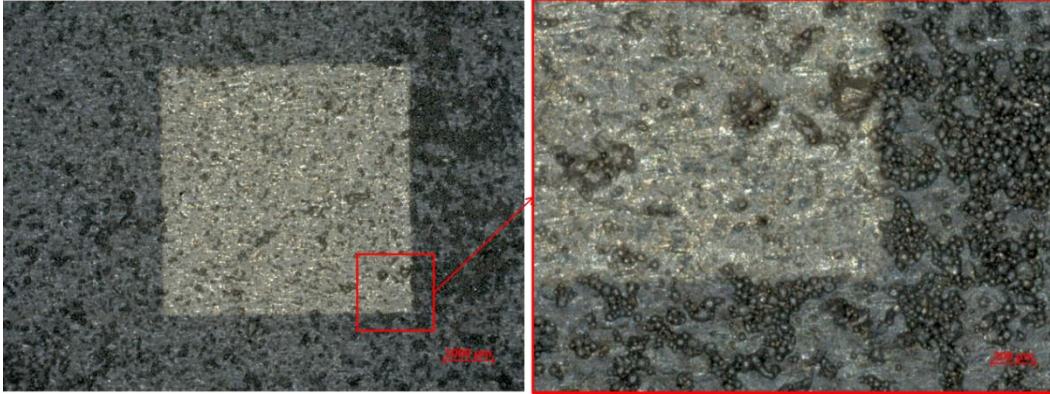

Fig. 7. Microscopic image from the border of a laser cleaned field

The structure of the initial surface after the building process is filled with residual powder (right and upper part), especially in the surface hollows. Within the practiced process the most of it can be ablated. The remaining particular particles are now only concentrated in the hollows of the structure, where they have a stronger connection to the basic material. The dark surface layers can be removed too. By chemical energy dispersive X-ray analysis a smaller amount of oxygen compounds on the surface could be detected.

3.2. Laser polishing

A reduction of roughness is achieved by remelting the surface structure. In this investigation a test field matrix with field dimensions of 10 * 10 mm² and a distance between two fields of 2 mm was put up on the samples. Basic process parameter limits and strategy were taken from previous studies. The investigation is divided in two studies. In the first study, the laser source is operating in pulsed mode with the laser specific maximum repetition rate of 1000 Hz and the shortest possible pulse duration of 0.3 ms (duty cycle 30%) for a maximum area rate. For smooth surfaces the laser polishing process requests large pulse overlaps. So the minimum pendulum frequency of 10 Hz was chosen. In the second investigations, laser polishing with continuous laser emission is performed. Tab. 2 gives an overview about the fixed process parameter of this present study.

Table 2. Fixed process parameters

General parameters	Unit	Value
Pendulum width	mm	10
Process gas flow rate	l/min	15
Residual Oxygen	ppm	40
Pulsed wave (pw)	**Unit**	**Value**
Pulse frequency	Hz	1000
Pulse duration	ms	0.3
Scanner pendulum frequency	Hz	10
Continuous wave (cw)	**Unit**	**Value**
Scanner pendulum frequency	Hz	50
Focal position	mm	12

3.2.1. Pulsed wave: Optimum focus position and laser beam intensity

First, the pulse overlap as a significant process parameter was studied by changing the laser spot diameter on the polishing surfaces. This was done by shifting the focus position in Z-direction relating to the surfaces of the samples. All further process parameters are taken from previous studies and are shown in the table of Figure 8 (a). In Figure 8 (a) the achieved surfaces roughness in Ra in relation to the focus position is plotted. The largest surfaces roughness reduction to a Ra value of 0.18 µm was reached at a focus position of 12 mm above the sample surfaces. Lower or higher focal positions led to an increasing roughness. At 12 mm the laser spot diameter amounts to 1.06 mm with an average pulse overlap of 81%. Further the influence of the laser beam intensity on the laser polishing process was investigated (Figure 8 (b)). By changing the laser pulse power between 1200 W and 2000 W at a focus position of 12 mm the laser beam intensity varies between 1.4 kW/mm² and 2.2 kW/mm². The largest roughness reduction of 98% to a Ra value of 0.18 µm was achieved with the laser beam intensity of 1.74 kW/mm². The area rate at the velocity of 50 mm/min and double crossing is 25 mm²/min.

Lower intensities led to an insufficient melting bath for a complete removing of surface structures with bigger structure wavelength. An excessive laser intensity generates a deeper melting bath which leads to melting bath turbulences and evaporation in the laser process area.
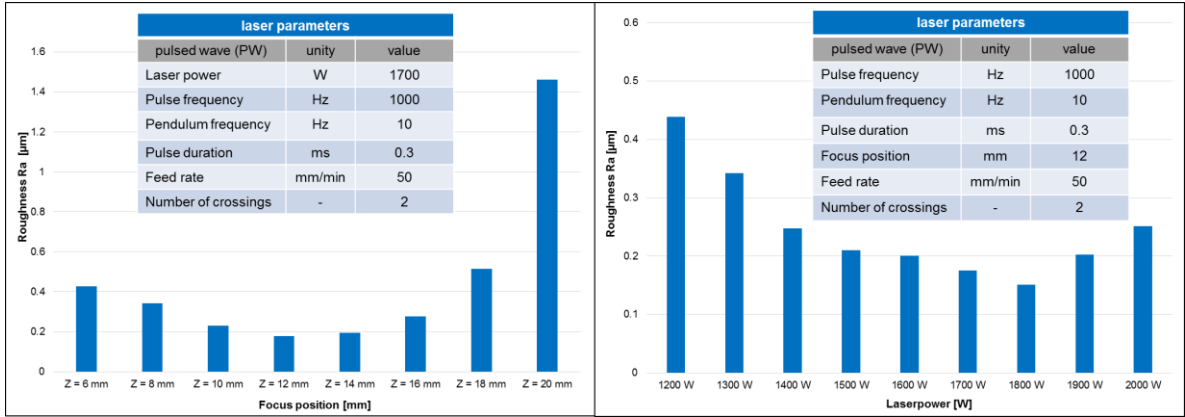
Fig. 8. (a) Surfaces roughness in order to the focus position, (b) Surfaces roughness in order to pulse power and laser beam intensity

3.2.2. Expedient feed rate and number of crossings

Besides the optimum pulse overlap and the laser beam intensity the track overlap is a significant parameter for the achievable roughness and the area rate of the process. In the following investigation the axis velocity of the laser head was changed from 40 mm/min to 70 mm/min. Thereby the track overlap varies between 89.0% and 93.4%. The same parameter combination was done by one and two crossings. Following diagram (Fig. 9 (a)) shows that the achievable roughness is decreasing with decreasing velocity and is going to halve with a second crossing from the same direction (2x0). The lowest Ra value is reached with 40 mm/min scan head velocity and two crossings. If laser polishing is done with the same laser process parameters but in crossed laser process direction the achievable polishing quality is increasing at identical area rate. With 70 mm/min and once crossing from each direction (1x1) a Ra value of 0 21 μm is reached (Fig. 9 (b)).
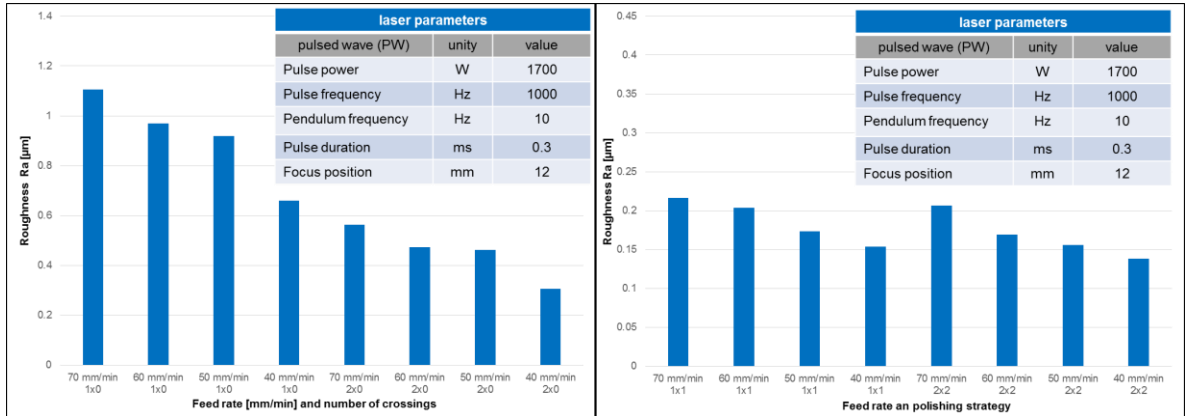

Fig. 9. (a) Feed rate and number of crossings, (b) Polishing with crossed process directions

In comparison, double crossings from the same direction (2x0) lead to Ra = 0.56 μm. If laser polishing is done with twice crossings from each direction (2x2) the lowest Ra value in this investigation of 0.14 μm could

be realized. Further investigations showed that with polishing from different directions lead to an orientation independent constant surface quality.

3.2.3. Continuous wave: Process window

At polishing with continuous laser radiation pulse frequency is no longer a limiting factor. So it is possible to work with higher pendulum frequencies and feed rates. This offers the opportunity to work at higher average laser power. On the basis of pre investigations a five times larger pendulum frequency and a focus position of 12 mm were chosen. In these studies the laser power was varied between 800 W and 1400 W and the feed rate was changed between 100 and 400 mm/min. The evaluation on Figure 10 shows, that 800 W laser power leads to an insufficient surfaces smoothing. The microscopic image shows that the energy per unit length was too low for a complete remelting of the SLM surface structure. With increasing laser power the influence of the feed rate to the achievable roughness is getting lower. At 1400 W laser power in a wide process window between the feed rates of 200 mm/min to 350 mm/min the Ra value is below 0,25 µm. This investigation was done with one crossing, so within the process window, area rates up to 35 cm²/min are possible.
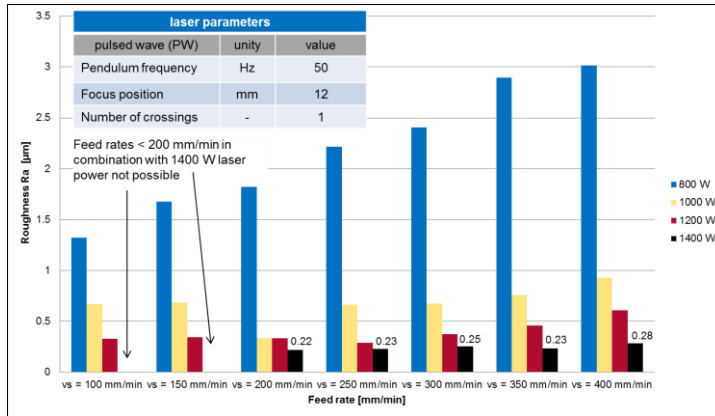

Fig. 10. Laser polishing with continuous laser radiation (cw)

The same investigations are done for the X2CrNiMo17-12-2 steel (1.4404). There the achieved minimum Ra value with multiple crossing is 0.34 µm with pulsed mode. Following table 3 gives a summary of the achieved laser polishing results on both materials.

Table 3. Overview about the achieved roughness reduction by laser polishing

Laser polishing of SLM surfaces				
Material	AlSi10Mg		1.4404	
Ra SLM surface	7.5 µm – 10.5 µm		11.8 µm – 12.5 µm	
Laser mode	Pulsed (pw)	Continuous (cw)	Pulsed (pw)	Continuous (cw)
Ra min single crossing	0.66 µm	0.23 µm	0.91 µm	0.61 µm
Max. area rate	4 cm²/min	35 cm²/min	4 cm²	20 cm²/min
Ra min multiple crossings	0.14 µm	Not investigated	0.34 µm	0.63 µm
Max. area rate	1 cm²/min	Not investigated	1 cm²/min	5 cm²/min

4. Conclusion

It could be shown, that with laser polishing, mostly all of the residual particles in the rough SLM surfaces can be removed and oxide layers are reduced without structuring the raw material. With the achieved results, done by laser polishing, surface qualities at high area rates up to 35 cm²/min for a wide industrial field could be reached. So the shown laser based processes could be a highly automatable and economic solution for post processing of additive manufactured SLM-parts.

Acknowledgements

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