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Influence of the build angle dependent surface quality on the ultra-short pulsed laser ablation of additive manufactured AlSi10Mg samples

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Abstract

Additive Manufacturing (AM) been proved as a method to offer new possibilities for the production of highly complex parts. One new interesting but yet small field of application is the 3D printing of complex optical elements, e.g. complex reflective mirror optics with integrated lightweight structures.
However, to achieve surfaces with an optical quality on additive manufactured metal parts, mostly mechanical machining processes such as diamond turning or pad polishing are used. The studying of laser material processing, e.g. ultra-short pulsed laser ablation as a post-processing method for additive manufactured optical components is of great importance. In this study, we investigate the influence of the initial surface quality on the ultra-short pulsed laser ablation process. Therefore, we varied the build angles of our samples and used different laser parameter setups to determine e.g. the material removal rate, process efficiency and achievable surface quality.

Keywords: laser ablation; post-processing; additive manufacturing; ultra-short pulsed laser

1. Introduction

Today, Additive Manufacturing (AM) and ultra-short pulsed (USP) laser technology are two cutting-edge technologies. Both offer a broad band of applications. One interesting but jet not well investigated application is the 3D printing of reflective metal mirrors. Here, example use-cases are lightweight optics for space

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technology (Heidler et al. 2017) or freeform optics for optical measurements (Sigel et al. 2017). However, for the printing of metal optical mostly powder bed technologies are used. They offer the opportunity to use a lot of different materials and alloy. Nevertheless, the big disadvantage of this layer wise powder bed manufacturing process is a very rough surface concerning the optical demands to these products. For that reason, the development of flexible post processing technologies is of big interest. Ultra-short pulsed laser ablation offers a great opportunity in this field. One reason for this is the so-called cold ablation, in which there is almost no heat-affected zone. However, beside the process results regarding achievable surface qualities, also the process efficiency is of great importance if USP laser ablation should be used as an industrial post-processing technology for AM metal parts. While the correlation of the absorption, respectively the process efficiency, of continuous or short-pulsed laser radiation and a varying surface roughness is well known, there are is a lack of knowledge for ultra-short pulsed laser ablation. Especially for 3D printed parts this is necessary. The surface roughness here varies with the build angle. To achieve a homogeneous process result and an as high as possible ablation rate, a correlation between the build angle roughness and the adjusted laser parameters should be available. In 2018 Wu et al. (Wu et al. 2018) presented a first study according the ablation rates for ultra-short pulsed laser processing on mold steel and stainless steel samples with different roughness. They found high ablation rates, respectively ablation efficiencies, even for low surface roughness. This contradicts conventional laser material processing methods, where a higher roughness also leads to an increased efficiency, commonly due to multi reflections absorption processes. Because of this known influence of the roughness on the energy absorption and thus of the material removal rate, investigations for AM materials are done in this work to find dominating material and process characteristics.

2. Experimental set-up

We performed our experiments in this work using a Satsuma HP² (AMPLITUDE, France) ultra-short pulsed laser sytsem, with a tunable pulse duration range 0,36 ps – 10 ps at center wavelength of 1030 nm and a repetition rate from single pules up to 40 MHz. For our experiments, the laser system is optimized to work with 20 W average laser power at pulse repetition rate of 400 kHz. The Satsuma is integrated in a high precision 5-Axis

Fig. 1. Microcut UKP high precision machine with integrated ultra-short puled laser

machine, microcutUKP (LLT GmbH, Ilmenau Germany) to enable 3D laser micro machining. Therefore, the laser beam is guided by an optical rail system into the machine. With the help an exelliSCAN 14 (SCANlab, Puchheim Germany) galvo scanner system and F-a tele centric F-theta lens the laser beam focused and moved over the work piece surface.

The test samples were fabricated using a SL M280 (SLM Solutions, Lübeck, Germany) metal 3D printing system and AlSi10Mg powder provided by Kymera International. The sample plates have a size of 80 50 mm and a thickness of 3 mm. To achieve a different surface roughness for each sample, the samples were orientated in four different build angles, 45°, 60°, 75° and 90°. The variation of the build angle resulted in different initial surface roughness due to the known stair case effect for layer wise manufacturing processes.

We measured the roughness and ablation depth using a Keyence VR3100 profilometer. To quantify the roughness we used the arithmetic surface roughness Sa and the root mean square height Sq, respectively RMS. After the characterization of the initial surfaces, we performed the ultra-short pulsed laser ablation experiments. Table 1 lists the parameters for the ablation study. For all experiments, we chose a constant pulse overlap PO of 80% to avoid the influence of incubation effects on the ablation results (Neuenschwander et al. 2012). Therefore, we increased the scan velocity v_{scan} for higher pulse repetition rates f_{rep} and kept the focal diameter of d_f = 46 µm constant, which resulted in the same number of pulses per dot N constant. Further, we set the track overlap TO to 80% equal to the pulse overlap to achieve a homogenous surface.

Table 1. Varied parameters during the experiments

parameter	unit	value
f_{rep}	kHz	100; 200
v_{scan}	m/s	0.9; 1,8; 3,6
E_p	µJ	2.5 - 50

Before we investigated the influence of the repetition rate and the pulse energy E_p, we determined the minimum number of crossings and hatch angle to get the best roughness. As know from (Brenner et al. 2019) the ablation depth for surface smoothing should be at least as high as the maximum initial roughness Sz, which in our case is max. 146 µm.

3. Results and discussion

3.1. Initial surface roughness, number of crossings and hatching

We see in Fig. 2. a) and b) the highest initial surface roughness values for a build angle of 45° and a decreasing roughness for higher build angles due to a decreasing stair case effect. However, the Sz value depends not as

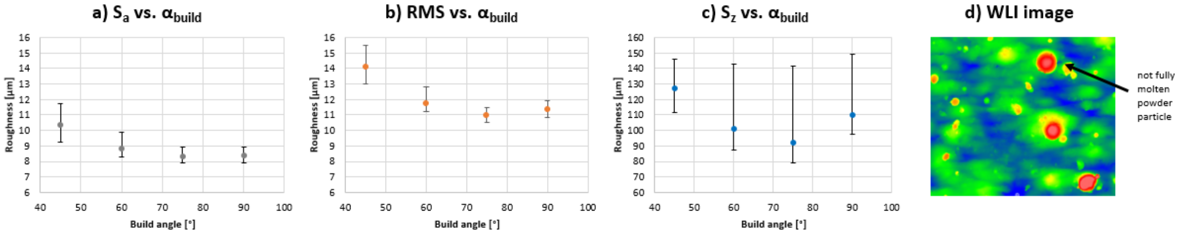

Fig. 2. Initial surface roughness of the additive manufactured samples

much as Sa and RMS from the build angle. Although, the mean value of three measurements for Sz hints to an angle dependent behavior, the min. and max. error bars overlap for all samples, see Fig. 2 c). This might be of partially located and not completely molten powder particles remaining of the surface, d).
For the preliminary study according the number of crossings and the achieved ablation depth we see a strict linear behavior. If the number of crossings doubles also the ablation depth doubles. The average ablation depth per crossing is approx. 3.7 µm and varies slightly. This already hints to a different absorption behavior for different build angles. With 200 kHz, t_H = 0.8 ps and 20 µJ we achieved an ablation depth of 150 µm for 40 crossings on a 90° build sample part. There, we reached the best roughness reduction with an incremental hatch angle of 36° between each crossing, which we took for the ablation study.

3.2. Material removal rate

One important process parameter is the Material Removal Rate (MRR), also known as ablation rate $\dot{V}$. In this work, we calculated the material removal rate by dividing the measured ablation volume V by the process time t_{proc}. Fig 3 displays the results depending on the used pulse energy and build angle. For low fluences a measurement of the ablation depth was not always possible because of an ablation depth in the range of the surface roughness.

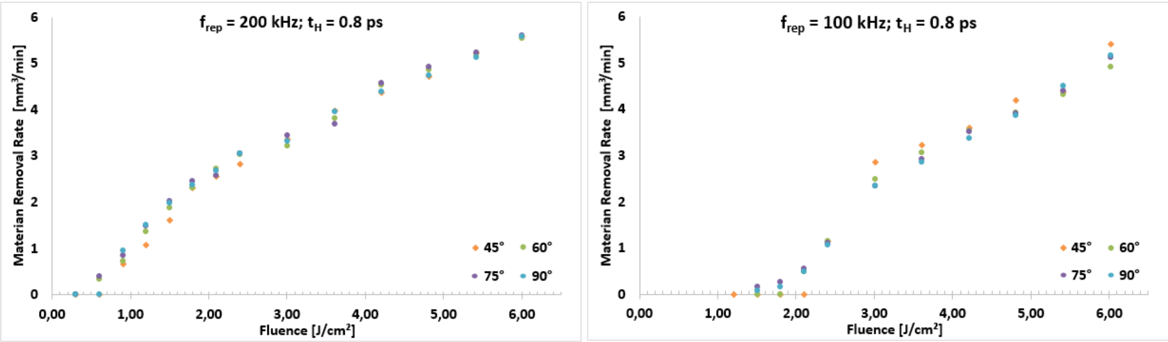

Fig. 3. Material removal rate for different build angles

We observe for both used pulse repetition rates almost the same maximum MRR values for higher fluences. However, in the regime below 3 J/cm² the slopes of the two graphs differ. This might be due to heat accumulation effects for higher pulse repetition rates.

3.3. Ablation efficiency

In addition to the reached ablation rates, we compared the ablation efficiency of the experimental results by dividing the achieved material removal rate in the process by the used average power, see Fig. 4. For all samples we observe a maximum ablation efficiency at 1,81 J/cm². If this optimal fluence F_{opt} equals e^2*F_{th} given by (Finger 2017), then the ablation threshold F_{th} is approx. 0,245 J/cm².
If we compare the ablation efficiencies for a pulse prepetition rates of 200 kHz and 100 kHz we see a different behavior between the build angle and the ablation efficiency. For f_{rep} = 100 kHz there seems to be an increased efficiency around the optimal fluence point for higher initial surface roughness and build angle, respectively. In contrast, we observed a slightly higher ablation efficiency in these regions for a lower surface roughness.

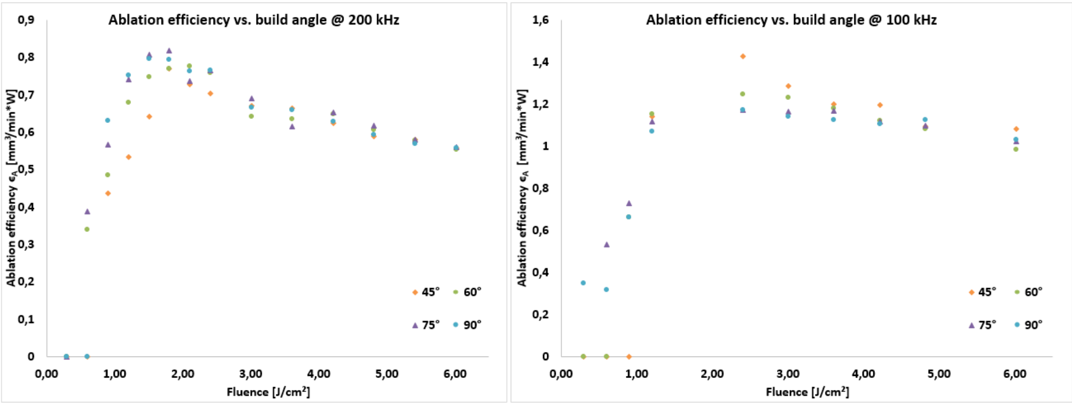

Fig. 4 Ablation efficiency for t_H= 0.8 ps and f_{rep} = 200 kHz (left) and f_{rep} = 100 kHz (right)

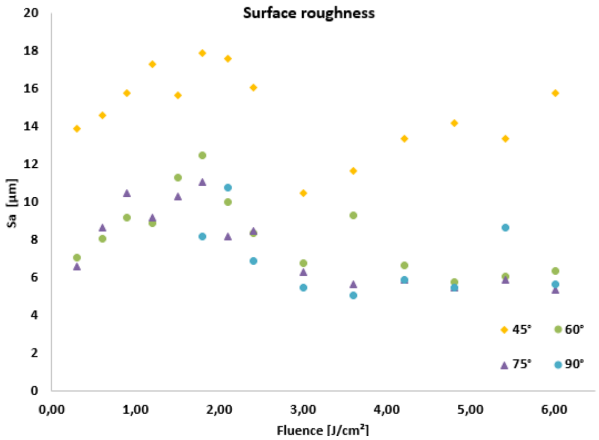

Fig. 5: Final surface roughness S_a depending on the build angle for f_{rep}= 200 kHz

3.4. Achieved surface roughness

We observed, that the achievable surface quality strictly depends on the initial surface roughness, see Fig 5. Further, we can observe a significant drop for a fluence around 2-3 J/cm² depending on the build angle. We will investigate this phenomenon in further experiments and analysis. The reached surface qualities are in the range of the initial sample roughness.

4. Conclusion

In our experiments we investigated the influence of the initial surface roughness of additive manufactured AlSo10Mg on the ablation results according the achievable material removal rate, ablation efficiency and surface quality. We observed in our experiments:

- An increasing ablation rate for higher fluences, which is not significantly depends on the build angle and initial surface roughness of the sample part.

- According the ablation efficiency an optimal fluence of 1,81 J/cm² for all samples. Since the ablation rate is almost the same for both used repetition rates the maximum ablation efficiency for 100 kHz is almost twice as high as the maximum ablation efficiency for 200 kHz.
- The derived threshold fluence for AlSi10Mg in this experiments was 0,244 J/cm²
- The achieved final surface quality strongly depends on the initial surface roughness. The development of the roughness depending on the applied fluence is not fully understood yet and need further investigations.

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