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Influence of pulse duration and scanning direction on the deformation of edges during laser micro polishing

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Abstract

Laser micro polishing with pulsed laser radiation has been investigated regarding the smoothing of surfaces. It is often described that this process influences the geometry of the surface less than conventional polishing techniques, which are often based on abrasive smoothing. But it is currently unknown how much the geometry of parts is influenced during laser micro polishing. The edges are of particular interest since they often determine the function of surfaces and it is known that they are significantly rounded during laser macro polishing with continuous wave laser radiation.
Therefore, in this paper the influence of the pulse duration and the scanning direction on the deformation of edges during laser micro polishing is investigated. Milled test samples made of TiAl6V4 are used for the examinations. Three different pulse duration regimes ($t_P \approx 200$ ns, $t_P = 285\text{-}660$ ns, $t_P = 1.22\text{-}1.60$ µs) as well as three scanning directions are investigated. The analysis is performed with laser scanning microscopy for the geometry of the edges and white-light interferometry for the roughness of the surfaces. The results show that the pulse duration has minor influence and that the deformation of edges presumably depends more on the beam dimensions. Additionally, scanning of the surface in a meandering pattern perpendicular to the edge leads to less deformation than scanning parallel to the edge.

Keywords: Laser Micro Polishing, Laser Polishing, Edge Deformation, Edge Rounding, Surface Functionalization

1. Introduction

Laser micro polishing with pulsed laser radiation is a surface finishing technology for smoothing and functionalizing surfaces. The laser radiation is used to heat a small part of the surface so that the material liquefies. The surface of the resulting melt pool is smoothed due to capillary forces (surface tension). After

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cooling, the surface solidifies in the smoothed state. Polishing of parts is performed by moving the laser beam over the surface, often in a meandering pattern. The single remelted zones overlap to a certain extent so that each part of the surface is remelted several times (Vadali, 2013).

Until now, the main focus of investigations has lain on decreasing the surface roughness, i.e. smoothing of surfaces. But for correct function of parts, often not only the surface roughness, but also the shape of the edges is important. However, almost no literature is available concerning the influence of laser micro polishing on the geometry of edges.

Morrow et al., 2017 investigated if a surface topography prediction model for laser micro polishing can also be used to predict the shape of blunt, square and sharp edges after laser micro polishing. The simulations and the experimental results matched well for the blunt and the square edges for lower fluences (up to 4.5 J/cm² in their case). For higher fluence (7.5 J/cm²), material accumulation was observed on the laser micro polished side of the square edge. The amount of reallocated material increased with increasing fluence. A comparison of the simulated and experimental results for the sharp edges was not possible since the laser micro polished edge could not be measured.

In the present paper, further investigations concerning the influence of the laser micro polishing process on the deformation of edges are performed. The main focus lies on the examination of the influence of the pulse duration and the scanning direction, i.e. the orientation of the meandering pattern.

2. Experimental setup, analysis and procedure

2.1. Experimental setup

Three different, fiber-coupled laser beam sources are used for the investigations enabling the use of different pulse durations: an SPI “redENERGY G3” fiber laser, a Fraunhofer ILT “HPQL” rod laser and a TRUMPF “TruMicro 7050” disk laser (Table 1). For the redENERGY G3, the pulses are generated by modulation in such a way that the shape of the pulses is similar to pulses generated with a Q-switch (including peak power in the kW range). This laser beam source additionally supports different pulse durations by choosing different so-called “waveforms”. Waveform “0” is used for the investigations, the pulse duration t_P is therefore $t_P \approx 200$ ns.

Table 1. Properties of the laser beam sources

Laser beam source	redENERGY G3	HPQL	TruMicro 7050
Generation of pulses	Modulation	Q-switch	Q-switch
Laser wavelength	1064 nm	1064 nm	1030 nm
Pulse duration	~200 ns (@ waveform 0)	100 - 500 ns	1.3 - 2.1 µs
Intensity distribution in focal plane	Gaussian	Top-hat	Top-hat
Maximum pulse energy (@ 20 kHz)	1.33 mJ	20 mJ	25 mJ

Each laser beam source is connected to a different experimental setup. All setups comprise a laser scanning system “hurrySCAN 30” from Scanlab (Germany) with F-Theta lens, a process chamber and an oxygen meter from ZIROX (Germany). Laser micro polishing is performed in Argon atmosphere in the process chamber to prevent oxidation and (particularly in this special case of processing TiAl6V4) nitration. The oxygen meter is used to measure the quality of the process atmosphere. More information about the experimental setups can be found in Temmler et al., 2014 (redENERGY G3), Temmler et al., 2012 (HPQL) and Nüsser et al., 2011 (TruMicro 7050).

Table 2. Process parameters

Laser beam source	redENERGY G3	HPQL	TruMicro 7050
Pulse frequency	20 kHz	20 kHz	20 kHz
Pulse duration	~200 ns	285-660 ns	1.22-1.60 µs
Beam dimensions (in focal plane)	Ø80 µm	Ø250 µm	☐200 µm
Fluence	varied	varied	varied
Scanning velocity	320 mm/s	1000 mm/s	800 mm/s
Track distance	10 µm	30 µm	24 µm
Shielding gas	Argon	Argon	Argon

Table 2 gives an overview about the process parameters used for the experiments. There are some restrictions concerning the choice of the beam dimensions:

The maximum pulse energy for the redENERGY G3 is quite small (1.33 mJ, cf. Table 1). The largest beam diameter that leads to a fluence high enough for polishing is about 80 µm. Therefore, this beam diameter is used for the investigations.

The pulse-to-pulse stability of the HPQL is quite low if the output power is low. Hence, the beam diameter must exceed a critical minimum size so that (for a given fluence) the laser beam source can be used at an operating point with acceptable pulse-to-pulse stability. The critical beam diameter is in the range of 250 µm for titanium materials (the fluence needed for polishing strongly depends on the physical properties of the material, particularly on the absorption). This beam diameter is therefore chosen for the experiments.

The experimental setup used for the investigations with the TruMicro 7050 comprises a laser power attenuator. This allows running the laser beam source with high power and, therefore, high pule-to-pulse stability and adjusting the pulse energy via the power attenuator. As a consequence, there are no restrictions for the beam dimensions, which can only be varied in discrete steps at this setup by choosing specific combinations of collimation and F-Theta lenses. A beam dimension of ☐200 µm is used since this is the dimension which is as close to the dimensions used for the HPQL as possible. The beam geometry in the focal plane is rectangular since an optical fiber with a rectangular shape is used for guiding the laser radiation from the laser beam source to the experimental setup.

In the experiments with the TruMicro 7050, it turned out that the power attenuator was not able to reduce the pulse energy to the necessary level for lower fluence (cf. Fig. 7). Hence, for lower fluence the laser output power of the laser beam source was reduced, which resulted in small changes in pulse duration.

Former investigations with the HPQL described in Nüsser et al, 2011 showed that the use of a scanning velocity of 1,000 mm/s and a track distance of 30 µm leads to effective smoothing of the surface. Thus, these process parameters are used for this laser beam source. The scanning velocity and the track distance are scaled down and up according to the beam dimensions for the redENERGY G3 and the TruMicro 7050, respectively.

2.2. Analysis

Two parameters are analyzed: The roughness of the laser polished surfaces and the edge geometry.

For the roughness, the 3D surface topography of the laser micro polished samples is measured with a NewView 7300 white-light interferometer from Zygo (USA). Three measurements are performed per test field. This data is then used for calculating the roughness in dependence on the spatial wavelength with the help of a phase-correct profile filter. More information about the calculation can be found in Willenborg, 2006.

The edges of the samples are measured with a laser scanning microscope VK9710-K from KEYENCE (Japan) with a vertical resolution ("z pitch") of 500 nm. The analysis is performed with the software supplied by the manufacturer. For each measured field, one average profile is calculated out of three single profiles evenly distributed over the surface. The averaged profile is then analyzed. This has the advantage that the influence of the roughness on the profile decreases, which simplifies the measurement of specific distances and radii for the analysis. Three measurements are performed per laser polished test field, so in the whole each result is based on nine single profiles.

There are different properties of the laser polished edges which are investigated. Fig. 1 shows a profile of a laser micro polished edge and gives an overview about the measured distances and radii.

The unpolished side on the left is named side "1", the laser micro polished side is side "2". The distances and radii have corresponding indices. Two lines, l_1 and l_2, are created representing the ideal surface profile without any roughness or material accumulation. Both lines intersect in the reference point R. The point of intersection PI is the intersection point of the edge profile and the angle bisector.

The points A_1 and A_2 are the highest points that the edge profile has in common with the lines l_1 and l_2. B_2 is the point at the maximum of the material accumulation, i.e. the point with the longest distance between the surface profile at side 2 and l_2. C_2 represents the end of the material accumulation (seen from R). a_1, a_2, b_2 and c_2 are the distances from R to the specific points.

The radii r_{1A} and r_{2B} are constructed with the points A_1 and PI and B_2 and PI, respectively. Several analyses of different edges have shown that these two radii represent a good approximation of the edge profile.

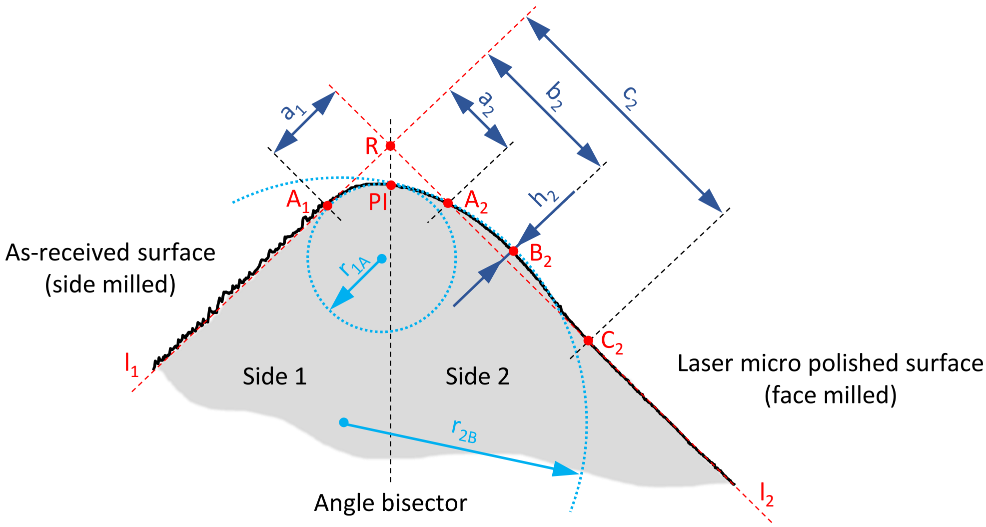

Fig. 1. Profile of laser micro polished edge with measured distances and radii

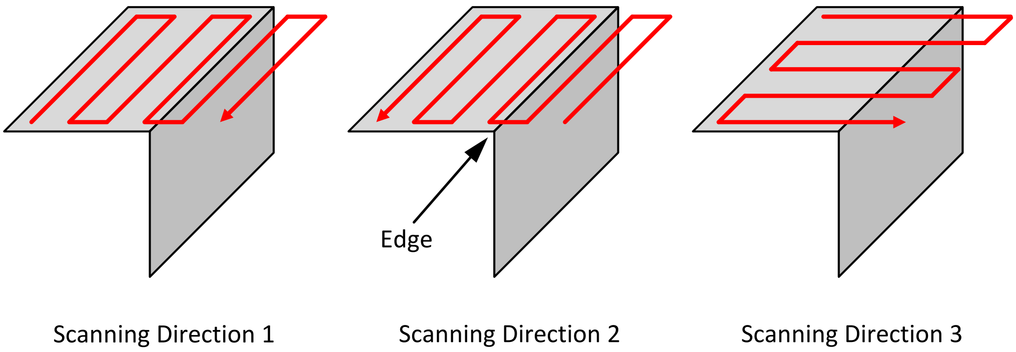

Fig. 2. Scanning directions

2.3. Procedure

The specimens are finely milled TiAl6V4 samples. The surface to be polished is created by face milling, the side which is left untreated by side milling. The edges of the as-received specimens are measured prior to laser micro polishing to ensure that these are sharp or close to sharp (e.g. very small burr of a few micrometers). If possible, all test fields are applied on the same specimen to ensure deviations in edge geometry of the as-received specimens are as small as possible. The specimens are cleaned with ethanol in an ultrasonic bath for 10 min and are subsequently rinsed with highly pure isopropanol.

Laser micro polishing is performed from the top in all cases, i.e. the laser beam is perpendicular to the surface. The size of the meandering scanning pattern is 20x8 mm, with 20 mm along the main tracks and 8 mm along the step-over direction. Different scanning directions (SDs), i.e. orientations of the meandering pattern, are used in the experiments (Fig. 2). When SD 1 is used, polishing starts on the surface and ends after the edge. For SD 2, polishing starts outside and ends on the surface. When SD 3 is used, the meandering pattern is orientated in such a way that polishing is along the edge, i.e. the main tracks are perpendicular to the edge. For SD 1 and SD 2, scanning ends and starts several millimeters outside the surface. This ensures complete processing of the edge. For SD 3, half of the pattern is on and half of it is outside the surface.

While for the investigation of the influence of the pulse duration scanning direction 1 is used, all three scanning directions are used for the investigation of the influence of the scanning direction.

3. Results

3.1. Pulse duration

Fig. 3a shows the roughness spectra of the surfaces laser micro polished with the laser beam source redENERGY G3 and a pulse duration of $t_P \approx 200$ ns. The micro roughness (spatial wavelength $\lambda \leq 10$ µm) decreases with increasing fluence down to a minimum roughness that is achieved with fluences of $F = 1.72$ J/cm² and $F = 2.25$ J/cm². A further increase in fluence leads to an increase in roughness in comparison to the minimum roughness.

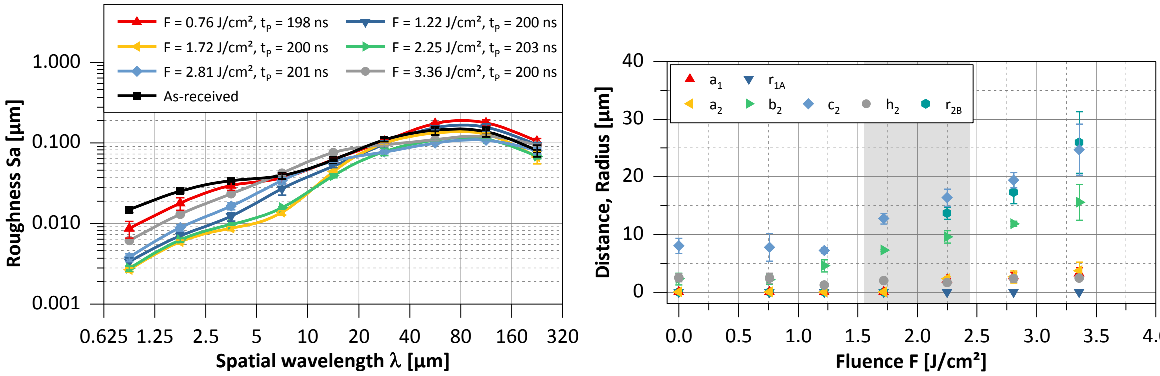

Fig. 3. (a) Roughness spectra of the surfaces laser micro polished with the laser beam source redENERGY G3 and different fluence; (b) Distances and radii of the corresponding edges in dependence on the fluence

Fig. 3b shows the distances and radii of the as-received (F = 0 J/cm²) and the laser micro polished edges in dependence on the fluence of the corresponding surfaces. The grey are represents the fluences that lead to the lowest micro roughness. The as-received edge contains small burr with a height of h_2 = 2.5 µm and a length of c_2 = 8.0 µm. Its maximum is b_2 = 2.3 µm away from the edge.

The smallest fluence investigated (F = 0.76 J/cm²) does not lead to a change in burr geometry. Since there is additionally only a small change in surface roughness (Fig. 3a), it can be concluded that there is only very little melting of the surface.

A fluence of F = 1.22 J/cm² leads to melting of the burr, this is why its height is reduced to h_2 = 1.2 µm. Further increase in fluence leads to an increase in distances and radii. This means that the deformation of the edge increases with increasing fluence. Particularly the radius r_{2B} and the distances b_2 and c_2 are affected. This means that especially the deformation of the edge on the laser polished side increases. Additionally, the height of the material accumulation increases, at the same time it moves away from the edge (a_2, b_2, c_2) so that a larger area close to the edge is affected by laser micro polishing.

The lowest roughness is achieved with fluences of F = 1.72 J/cm² and F = 2.25 J/cm². However, the deformation of the edge is lower when a fluence of F = 1.72 J/cm² is used. Therefore, it can be concluded that, when the use of different fluences leads to almost the same surface roughness, it is beneficial for the edge geometry to use a fluence as low as possible.

If sufficient melting is achieved (F ≥ 1.22 J/cm²), the distance and radii linearly increase with increasing fluence. This effect is also observed when the other two pulse duration regimes are used (cf. Fig. 6+7 in Appendix A).

For the investigation of the influence of the pulse duration on the edge deformation, the edges of the surfaces with the lowest roughness from each pulse duration regime are compared. Fig. 4a shows the distances and radii of the surfaces with the lowest roughness achieved for the three different pulse duration regimes.

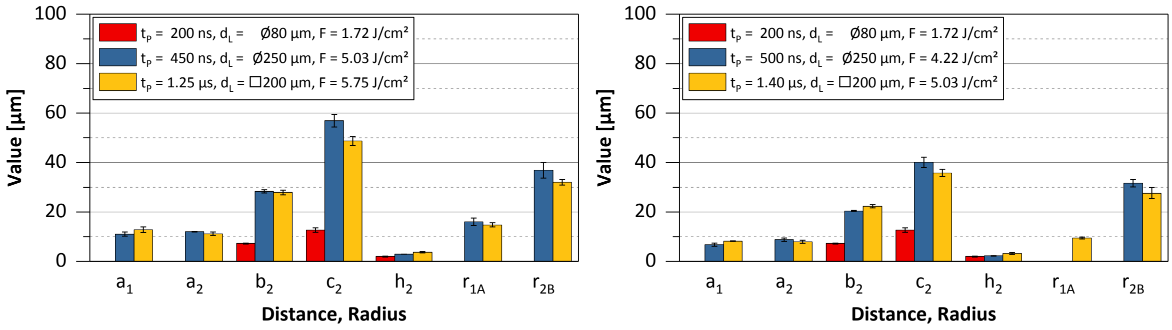

Fig. 4. (a) Distances and radii of the edges of the surfaces with the lowest roughness achieved for the three different pulse duration regimes
(b) Distances and radii of the edges of the surfaces with same micro roughness, but higher meso/macro roughness than in (a)

The distances a_1 and a_2 and the radii r_{1A} and r_{2B} are not present for the pulse duration t_P = 200 ns since the edge deformation is almost not present for the surface with the lowest roughness. The deformation of the edges laser micro polished with longer pulse duration is significantly higher. The deformation is similar for these two pulse duration regimes, but in most cases the edge polished with a pulse duration of t_P = 450 ns has a slightly higher deformation than that polished with a pulse duration of t_P = 1.25 µs.

The pulse duration of the HPQL is 2.25 times longer than that of the redENERGY G3. The pulse duration of the TruMicro 7050 is 2.78 times longer than that of the HPQL. Although the difference in pulse duration is (slightly) higher between the HPQL and the TruMicro 7050, the difference in deformation of the edge is much lower in comparison to the difference in pulse duration between the HPQL and the redENERGY G3. Hence, probably a different reason is responsible for the deformation of the edge.

Due to the technical limitations described in section 2.1, the beam dimensions and intensity distribution is (beside the pulse duration) different for the three laser beam sources. The beam diameter used for polishing with the redENERGY G3 is much smaller than that used for polishing with the other two laser beam sources. This corresponds to the level of edge deformation and implies that not only the pulse duration, but also the beam dimensions and, possibly, the intensity distribution play a significant role in the deformation of the edge during laser micro polishing.

For the HPQL and the TruMicro 7050, there are surfaces that have the same micro, but a slightly higher meso (λ = 10-80 µm) and macro (λ = 80-320 µm) roughness than the surfaces with the lowest overall roughness. When these surfaces are compared with the surface polished with the redENERGY G3, the result is similar (Fig. 4b). The deformation is much higher for the HPQL and the TruMicro 7050 than for the redENERGY G3. Again, the deformation of the edge is slightly higher when the HPQL is used in comparison to the TruMicro 7050. The only exception is the radius r_{1A}, this radius is not present for the HPQL.

To summarize, the deformation of the edge during laser micro polishing presumably depends more on the beam dimensions than on the pulse duration. Further investigations are necessary to quantitatively assess the strength of the influence of the pulse duration.

3.2. Scanning direction

When surfaces are laser micro polished, the laser beam is usually guided over the surface in a meandering pattern. It is possible that the orientation of this pattern influences the deformation of edges. Therefore, the influence of the scanning strategy on the deformation of edges is investigated.

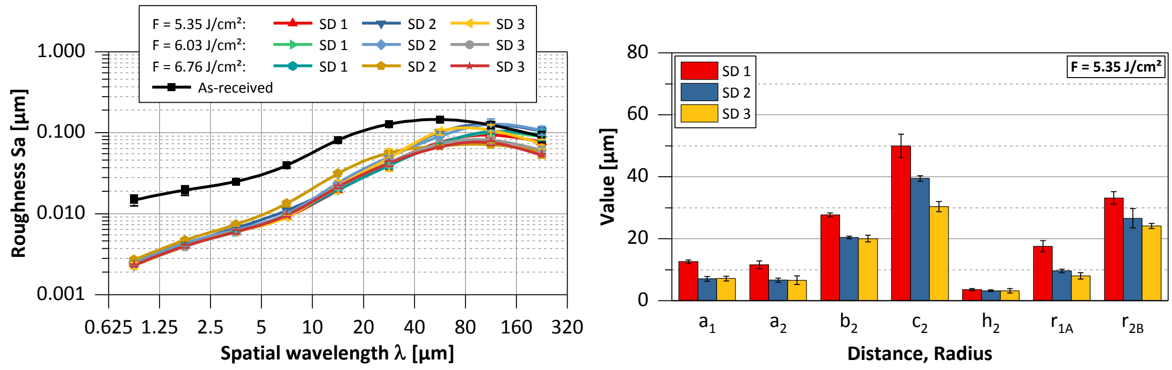

Fig. 5. (a) Roughness spectra of the surfaces laser micro polished with different scanning direction and fluence (TruMicro 7050); (b) Distances and radii of the edges polished with a fluence of F = 5.35 J/cm² and different scanning directions

The examinations are performed with the laser beam source TruMicro 7050. Three different fluences are investigated which are in the range of fluences that lead to the lowest roughness (cf. Fig. 7). The pulse duration is t_P = 1.30 µs. The process parameters are the same as for the investigation of the influence of the pulse duration (Table 2).

The roughness after polishing is independent from the scanning direction (Fig. 5a). Almost the same micro and meso roughness is achieved with each of the three fluences and scanning directions, except with a fluence of F = 6.36 J/cm² and SD 2. It may be possible that the as-received surface had a higher roughness in this case.

The deformation of the edges depends on the scanning direction, it decreases from SD 1 to SD 3 (Fig. 5b). This is also the case when the other two fluences are used (cf. Fig. 8a+b). The reason for this effect is presumably heat accumulation at the area close to the edge.

When SD 1 is used, there is high heat accumulation since the edge is polished at last, so the material has already been heated up before. Additionally, there is less cooling than for bulk material since cooling is mainly influenced by thermal conduction, not by convection or thermal radiation. For SD 2, the heat accumulation is lower since the edge is remelted at first. But it is not as low as for SD 3 since the whole edge is remelted in a very short period of time due to the scanning tracks which are close and parallel to or even directly on the edge. When SD 3 is used, there is more time for the area close to the edge to cool down between the different laser tracks since the laser beam moves away from the edge for some time (cf. Fig. 2).

With increasing heat accumulation, the depth of the remelted zone presumably increases. If the depth of the melt pool increases during polishing, more material can be moved away from the edge due to surface tension effects. Therefore, the deformation of the edge increases from SD 1 to SD 3.

To summarize, the use of scanning tracks perpendicular to the edge leads to the same smoothing of the surface as scanning tracks parallel to the edge, but the deformation of the edge is lower in the first case.

4. Summary & Conclusion

The influence of the pulse duration and the scanning direction on the deformation of edges during laser micro polishing was investigated. Three different pulse duration regimes ($t_P \approx$ 200 ns, t_P = 285-660 ns, t_P = 1.22-1.60 µs) and three different scanning directions, i.e. orientations of the meandering scanning pattern, were used.

The influence of the pulse duration is presumably superimposed by an influence of the beam dimensions. The beam dimensions appear to influence the deformation of edges much stronger than the pulse duration. Therefore, no reliable conclusion can be made at the moment concerning the influence of the pulse duration, further investigations concerning the influence of the beam dimensions are necessary.

Nonetheless, there is a linear correlation between the fluence and the distances and radii investigated. This correlation was observed for all three pulse duration regimes. Therefore, it was concluded that a fluence as low as possible should be used for laser micro polishing, for example if the same level of smoothing is reached with different fluences. In this case, the use of a low fluence leads to less deformation of the edge without decreasing the smoothing effect.

The scanning direction of the meandering pattern influences the level of deformation. A scanning direction with scanning tracks perpendicular to the edge leads to a lower deformation than scanning tracks parallel to the edge due to lower heat accumulation in the latter case. The roughness is independent from the scanning direction.

Future work should particularly concentrate on investigating the influence of the beam dimensions to better assess the influence of the pulse duration. Furthermore, additional scanning strategies should be examined with main focus on minimizing heat accumulation at the edge to minimize deformation.

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Appendix A.

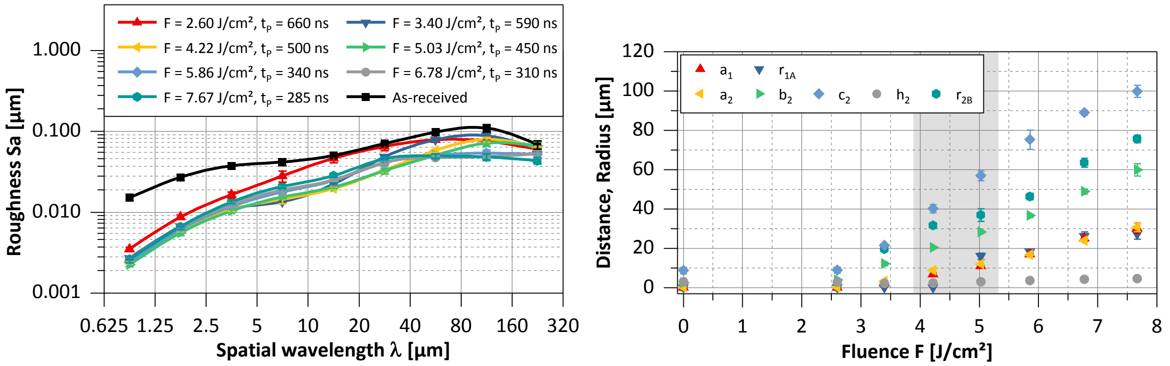

Fig. 6. (a) Roughness spectra of the surfaces laser micro polished with the laser beam source HPQL and different fluence;
(b) Distances and radii of the corresponding edges in dependence on the fluence

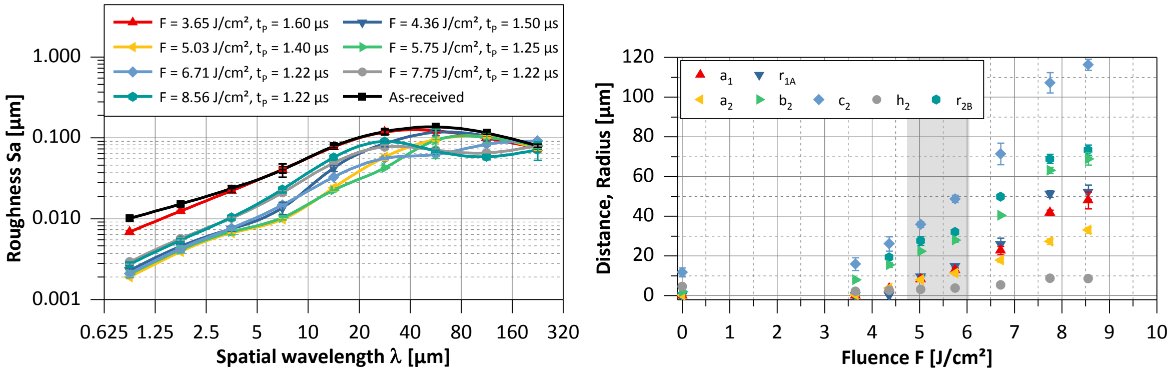

Fig. 7. (a) Roughness spectra of the surfaces laser micro polished with the laser beam source TruMicro 7050 and different fluence;
(b) Distances and radii of the corresponding edges in dependence on the fluence

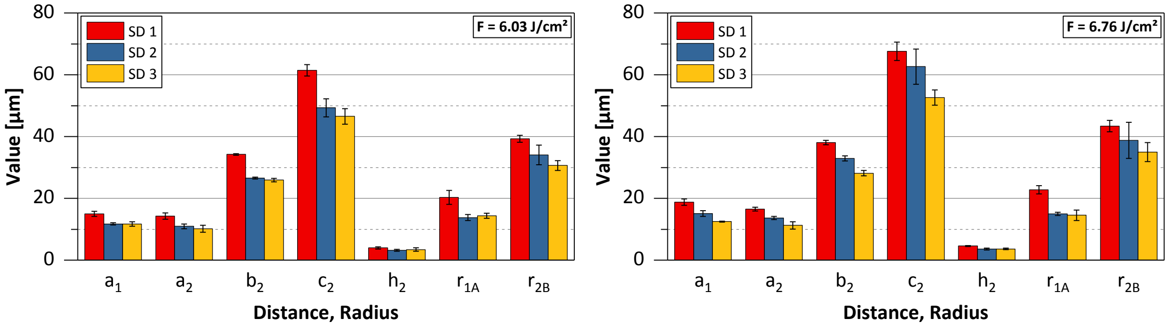

Fig. 8. Distances and radii of the edges polished with the laser beam source TruMicro 7050, a fluence of (a) F = 6.03 J/cm²,
(b) F = 6.76 J/cm² and different scanning directions