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Enhancement of the area rate for laser macro polishing

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Abstract

Look at the state of the art for polishing of metals in industry most of the parts are polished manually, because current automated polishing techniques often cannot be used on parts with freeform surfaces and function relevant edges.
One possible solution to automate the polishing of metallic freeform surfaces is the 3D laser polishing with continuous wave laser radiation. The achievable roughness is limited to Ra values between 0.05 and 0.5 µm depending on the material and its homogeneity. Depending on the used circular shaped intensity distribution with beam diameters up to 600 µm the area rate for laser polishing is limited to 1 cm²/min. Take into account the machine costs and the running costs the costs for laser polishing are approx. 70 €/hour.
Based on the limited roughness and/or on the costs currently only few industrial implementations exist for laser polishing. To bring laser polishing in industry there are two possibilities: on the one hand the achievable roughness has to be decreased and on the other hand the laser polishing process has to be speeded up to reduce the costs.
This paper will focus on the increase of the area rate and will present two approaches for the increase.

Keywords: laser polishing; intensity distribution; area rate

1. Introduction and state of the art

Laser polishing is based on using laser radiation to remelt a thin surface layer. A circular laser beam with a defined beam diameter d_L is moved with the scan velocity v_S and track offset dy on contour-aligned tracks in a meandering pattern over the surface (Figure 1). Due to the surface tension material flows from the peaks to the valleys, thus causing the surface to resolidify smoother than in its previous state [Willenborg]. The process parameters (e.g. laser power, scan velocity, beam diameter and track offset) have to be adapted to the initial roughness, the treated material and the desired roughness.

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Typical laser beam diameters for laser polishing are in the range of 150-600 µm. The diameters of the melt pool and the laser beam are similar. Therefore, roughness with spatial wavelength larger than 600 µm is not removed.

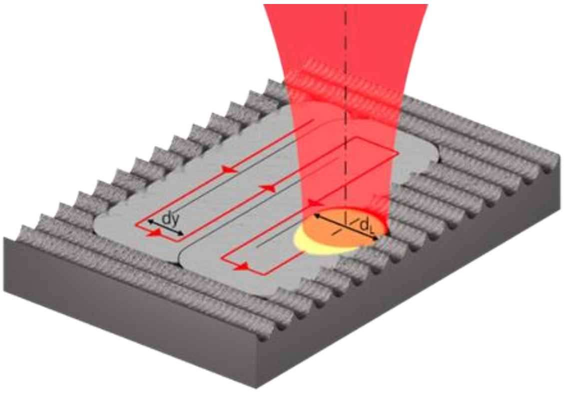


Fig. 1. Schematic of the process principle of the laser polishing process

On milled initial steel surfaces typically fiber or disk lasers with continuous wave laser radiation and circular Tophat or Gaussian intensity distributions are used. For beam diameters in the range of 150-600 µm typical-ly the track offset dy is between 30 and 60 µm. For achieving small roughnesses (Ra=0.05-0.5 µm) scan veloci-ties v_S from 50 to 150 mm/s and n=2-4 stages are necessary. Thus the area rate

$$AR = \frac{v_S \cdot dy}{n} \tag{1}$$

for laser polishing of steels with continuous wave laser radiation and circular intensity distributions is aproximately 1 cm²/min.

To increase the area rate two different approaches have been investigated:

- Increase of the circular shaped intensity distribution up to 1500 µm
- Chance the shape of the intensity distribution from circular shaped to non-rotational symmetric intensity distributions

Using a circular shaped intensity distribution leads to a bulged solidified single laser track (Figure 2, second column). The increase of the resolified track is a result of the plastic deformation due to thermal expansion and shrinking. For a transforming steel, such as the material 1.2343, the plastic deformation from limited thermal expansions can be overlapped by density changes due to changes of the microstructure [Nüsser].

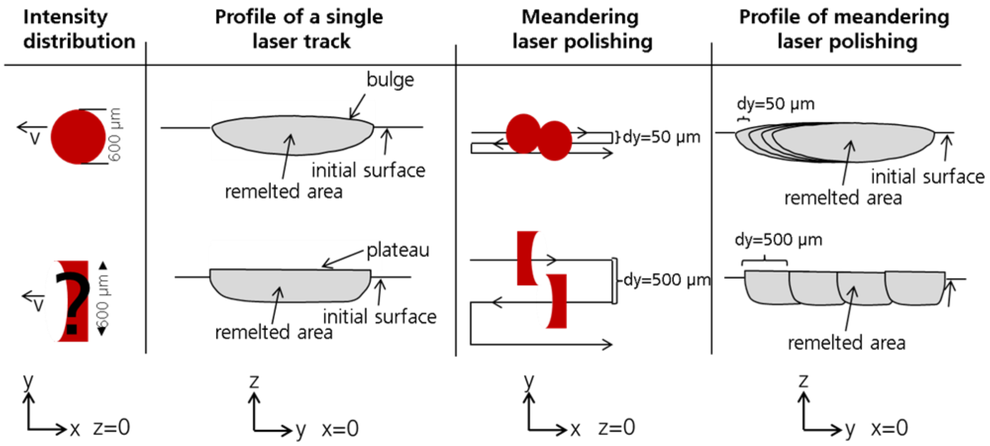


Fig. 2. Schematic of the basic idea for increasing the area rate by using non-rotational symmetric intensity distributions

Due to the bulged resolidified track a big overlap or rather a small track offset of the single tracks is necessary to get a plane surface during the meandering polishing of fields. Otherwise a ripple pattern occur.

The small track offset leads to a limitation of the area rate of the laser polishing process because the area rate is proportional to the track offset (see equation (1)). Furthermore Willenborg has shown that the track offset has to be adapted to the beam diameter proportionally, because the remelting steps of one surface point have to be kept constant [Willenborg]. The first idea for an increase of the area rate is to increase the circular shaped focus diameter. According to Willenborg's theory an increased beam diameter is correlated with an increase of the track offset.

The second idea to increase the area rate is to identify intensity distributions which lead to a plateau profile of the resolidified single laser track instead of a bulge (Figure 2, second row). For a plateau profile the track offset for the meandering laser polishing of fields can be increased. Simplified it's like a stringing together of the single plateaus to a plane surface.

The polishing results of both approaches will be shown in this paper for the transforming tool steel 1.2343. The initial surface is grinded with roughnesses Ra between 0.4 and 0.5 µm. T

2. Increase of the area rate by an increase of the circular shaped intensity distribution up to 1500 µm

The investigations for laser polishing with circular shaped intensity distributions up to beam diameter d_L=1500 µm are performed on a flexible experimental setup consisting of a laser source (Nd:YAG disk laser TruDisk1000 from Trumpf with a wavelength of 1030 nm), an axis system and a laser scanner system (Scanlab) (Figure 3). The laser beam is guided from the laser source to the collimation via an optical fiber. Subsequently the collimated beam passes the laser scanner and is focused on the surface of the work piece by an f-theta objective. The work piece is placed in a process chamber which is filled with the inert gas Argon to prevent oxidations.

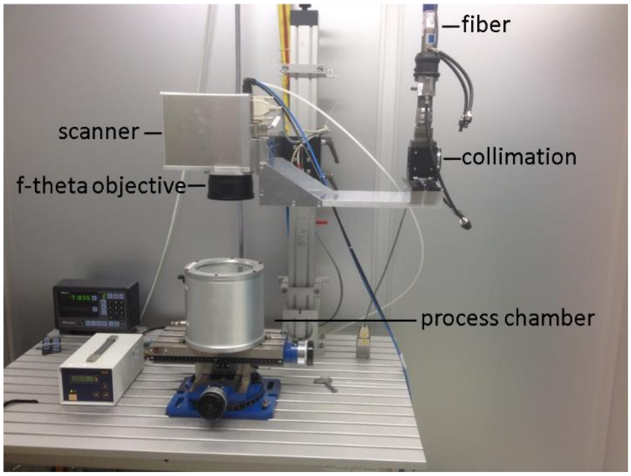


Fig. 3. Experimental setup for circular shaped intensity distributions

Investigations with beam diameters d_L=750 µm and 1500 µm are performed. For comparison also fields with the already known beam diameter d_L=250 µm are polished.

For every beam diameter d_L 12x12 mm² test fields are laser polished in meandering patterns under variation of the scan velocity v_S, the laser power P_L, the track offset dy and the number of stages n. For all investigations the shielding gas atmosphere is kept constant with 1000 ppm. Based on the standard process parameter combination for d_L=250 µm[†] in a first step for the beam diameters d_L=750 and 1500 µm the track offset dy is adapted to the beam diameter d_L in the way, that the number of remelting steps per surface point is kept constant (Table 1).

Table 1. Used track offset dy for different beam diameters d_L

Beam diameter d_L [µm]	Track offset dy [µm]
750	120
1500	240

Additionally the laser power P_L is adapted to the beam diameter d_L and the track offset dy. According to the standard parameter for d_L=250 µm the scan velocity v_S and the number of stages n is kept constant in this first step.

For statistical reasons every process parameter combination is polished three times. The roughness of every laser polished field is measured tactile in accordance with the norm DIN EN ISO 4287/4288.

In Figure 4 the resulting roughness for the three different beam diameter is shown.

[†] v_S= 100 mm/s, dy=40 µm, n=2

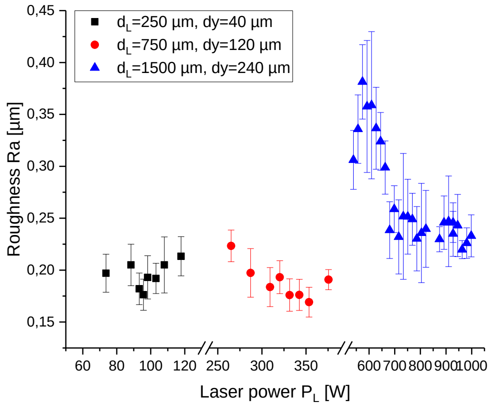


Fig. 4. Achievable roughness for different beam diameter, constant: v_S=100 mm/s, n=2

The roughnesses for d_L=250 and 750 µm are nearly the same, the roughness for d_L=1500 µm is significantly higher. To ensure that the track offset dy=240 µm isn't the reason for the increased roughness in a next step the track offset for d_L=1500 µm is varied in a wide range (Figure 5) and the laser power P_L is adapted to the used track offset.

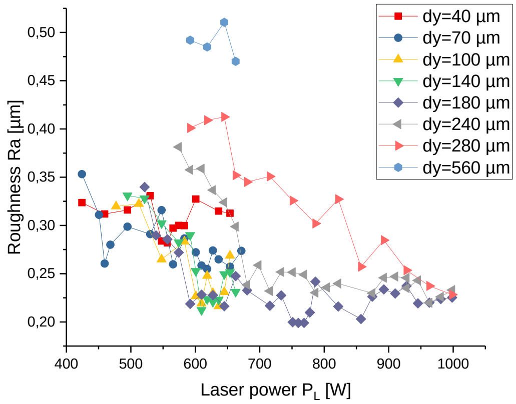


Fig. 5. Roughness Ra in dependency on the laser power P_L for beam diameter d_L=1500 µm and different track offsets dy, constant: v_S=100 mm/s, n=2

For reasons of clarity the error bars are not plotted. Probably the smallest roughness Ra for track offsets dy>240 µm cannot be reached in this experiment due to the limited laser power of P_L=1000 W. The smallest roughness Ra=0.199±0.018 µm is achieved for dy=180 µm and P_L=760W. Track offsets dy=100 µm and dy=140 m lead to roughnesses as small as for dy=180 µm. For dy<100 µm the roughness is significantly increases. Probably the surface is remelted too often.

In a next step besides the track offset dy and the laser power P_L also the scan velocity v_S and the number of stages n are varied.

Figure 6 shows the relation between the roughness Ra and the area rate AR (logarithmic display) for different beam diameter. Every point represents the smallest achieved roughness for the respective area rate. Thereby the laser power P_L, scan velocity v_S, number of stages n and track offset dy are variable.

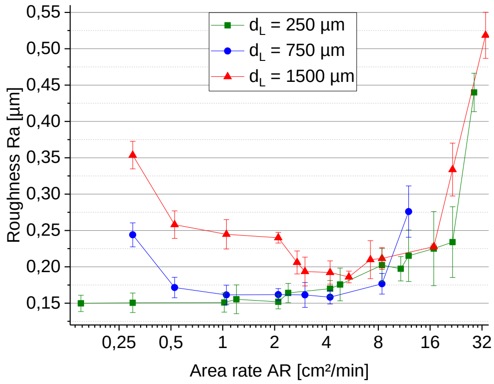


Fig. 6. Relation between the roughness Ra and the area rate AR for different beam diameter

Compared to d_L=250 and 750 µm the roughness for d_L=1500 µm is increased also for higher area rates. This is probably due to the significantly increased melt pool volume and the higher used laser power (adapted to the beam diameter).

Both facts can strengthen melt pool turbulences, which results in an increased roughness of the resolidified surface.

In summary the area rate cannot be increased by the use of larger beam diameters. An increase of the area rate always comes along with an increased surface roughness.

3. Increase of the area rate by the use of non-rotational symmetric intensity distributions instead of circular shaped intensity distributions

The investigations for laser polishing with non-rotational symmetric intensity distributions up are performed on another flexible experimental setup. The same laser source (Nd:YAG disk laser TruDisk1000 from Trumpf with a wavelength of 1030 nm), axis system and laser scanner system (Scanlab) like for the circular shaped intensity distribution are used, however the optical system differs significantly (Figure 7).

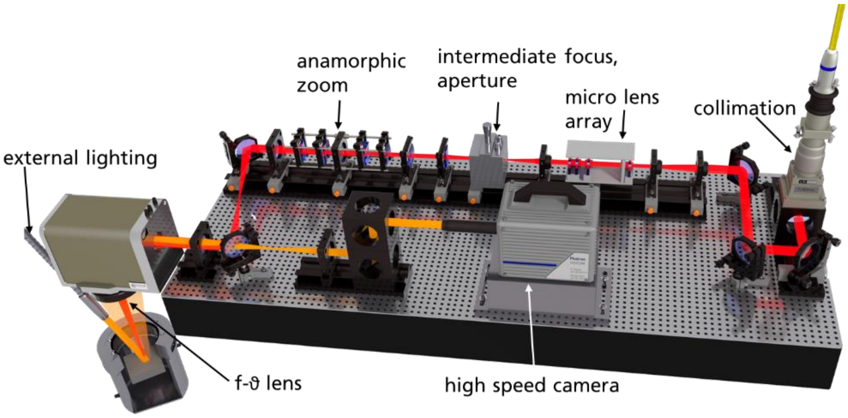


Fig. 7. Drawing of the experimental setup for the investigations of laser polishing with non-rotational symmetric intensity distributions

Different shaped intensity distributions are realized by an aperture in an intermediate focus. Therefore in a first step a rectangular top-hat intermediate focus is generated by a micro lens array. The micro lens array resorts the collimated circular Gaussian beam into a rectangular top-hat beam. The intermediate focus is cut by an aperture to the desired form. This approach allows a flexible and cost efficient realization of different shaped intensity distributions, because the manufacture of different apertures is very quickly and cheaply. Then the cut intermediate focus is projected on the surface of the work piece via a complex optical system, a laser scanner and a f-ϑ lens. For the variation of the aspect ratio of the beam an anamorphic zoom telescope is integrated. Furthermore a high speed camera for a coaxial image recording of the melt pool and the resolidification is added into the experimental setup. Due to the high framerates up to 10000 frames per second and a resolution of 512x512 pixel an external lighting has to be used for the image recording.

Exemplary some tested intensity distribution are represented in figure 8.

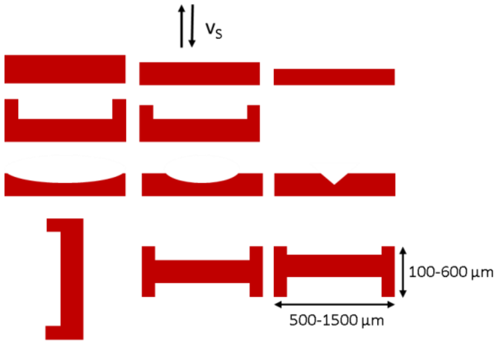
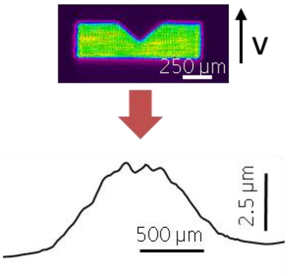


Fig. 8. Some tested intensity distributions

First single laser tracks with different shaped intensity distributions and different process parameters are polished to investigate the cause-and-effect relationship between the single track profile and the process parameters. The resulting topography of the single tracks is analyzed with a white light interferometer and the average profile of the track is calculated.

The “line with a cut triangle” is up to now the best compromise between a plateau profile of the track and edge regions without cuts (Figure 9, left).



Material	Roughness Ra [µm]		Area rate [cm²/min]	
	●		●	
1.2311	0.26	0.18	0.9	10
1.2343	0.15	0.15	0.6	6.2
1.4435	0.72	0.62	1.8	10

Fig. 9. Left: „line with cut triangle“ intensity distribution with resulting single track profile (material: 1.2343), right: Overview about the results for laser polishing with non-rotational symmetric intensity distribution in comparison to the results achieved with a circular shaped intensity distribution

So laser polishing of 12x12 mm² test fields is performed using an unidirectional scanning strategy under variation of the scan velocity v_S, the laser power P_L, the track offset dy and the number of stages n. The roughness of every laser polished field is measured tactile in accordance with the norm DIN EN ISO 4287/4288.

For every tested material the area rate could be increased significantly using a non-rotational symmetric intensity distribution instead of the circular shaped one, furthermore for two materials also the achievable roughness is decreased (Figure 9, right).

One reason for the better achievable surface qualities with the “line with cut triangle” intensity distribution is observed in high speed videos of the melt pool and the resolidification. It is well known that a melt pool with minimized fluctuations leads to smallest roughnesses of the resolidified surface. In high speed videos it is seen that the constriction in the middle of the line leads to a damping of the melt pool in cross direction. Therefore melt pool fluctuations due to inhomogeneities in the materials or laser power fluctuations can be damped.

4. Conclusion

It is shown that the shape of the intensity distribution influences the laser polishing process significantly. Up to now the area rate could be increased by a factor of 10, better surface qualities seem to be achievable as well. However it cannot be said that this is the optimum. There is an endless variety of possible intensity distributions and it is not guaranteed that the optimum has been reached yet.

References

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