

# Laser Polishing

A. Temmler<sup>\*a</sup>, E. Willenborg<sup>b</sup>, K. Wissenbach<sup>b</sup>

<sup>a</sup>RWTH Aachen University, Chair for Lasertechnology, Steinbachstraße 15, 52074 Aachen, GER.

<sup>b</sup>Fraunhofer Institute for Lasertechnology, Steinbachstraße 15, 52074 Aachen, GER.

## ABSTRACT

A new approach to polish metallic freeform surfaces is polishing by means of laser radiation. In this technology a thin surface layer is molten and the surface tension leads to a material flow from the peaks to the valleys. No material is removed but reallocated while molten. As the typical processing time is 1 min/cm<sup>2</sup> laser polishing is up to 30 times faster than manual polishing. Reducing the roughness by laser polishing is achieved for several different materials such as hot work steels for the die and molding industries or titanium alloys for medical engineering. Enhancing the appearance of design surfaces is achieved by creating a dual-gloss effect by selective laser polishing (SLP). In comparison to conventional polishing processes laser polishing opens up the possibility of selective processing of small areas (< 0.1 mm<sup>2</sup>). A dual-gloss effect is based on a space-resolved change in surface roughness. In comparison to the initial surface the roughness of the laser polished surface is reduced significantly up to spatial wavelengths of 80 microns and therefore the gloss is raised considerably. The surface roughness is investigated by a spectral analysis which is achieved by a discrete convolution of the surface profile with a Gaussian loaded function. The surface roughness is split into discrete wavelength intervals and can be evaluated and optimized. Laser polishing is carried out by using a special tailored five-axis mechanical handling system, combined with a three axis laser scanning system and a fibre laser.

**Keywords:** laser polishing, selective laser polishing, dual-gloss effect, remelting, melt pool tension, surface, roughness

## 1. INTRODUCTION

Current automated polishing techniques, e.g. electro polishing, electro-chemical polishing or slide grinding are based on large-area ablation. These polishing technologies lead to problems in edge rounding and unprocessed areas because deeper shafts are not processed. Therefore the current automated techniques are almost not applicable on parts with freeform surfaces and function relevant edges like most tools. Due to the lack of available automated polishing technologies for freeform surfaces, the finishing in the tooling industry is predominantly done by manual polishing. The quality of manual polishing strongly depends on the worker's skill and experience. As manual polishing is a very demanding but monotone work, skilled workers are a scarce resource and companies all over Europe have great problems to recruit suitable employees. Due to the low processing speed (typically in the range of 10 to 30 min/cm<sup>2</sup>) and the sequential workflow, production of molds and dies with manual polishing is time-consuming and cost-intensive. A new approach to polish metallic freeform surfaces is polishing by means of laser radiation.

## 2. PROCESS FUNDAMENTALS

### 2.1 Polishing with laser radiation

Laser polishing of metals by laser radiation is based upon the remelting of a thin surface layer by laser radiation. Similar to conventional polishing, laser polishing is a multistep process [1]-[7]. Consecutive process steps are carried out from smoothing of milling grooves (macro polishing) up to improving the gloss-level (micro polishing). The smoothing of macrostructures is achieved by using continuous wave laser radiation. A melt pool is created by the incident laser beam. The laser beam is moved over the surface with a defined scanning velocity, so that new material is molten on one side of the melt pool and resolidifies on the other side. Due to the surface tension of the molten material the surface roughness is smoothed during the remelting process. The resulting surface solidifies without cracks, pores or hidden defects out of the molten material. Using continuous wave laser radiation the macro laser polishing process creates a continuous remelted surface layer which is between 10 µm – 80 µm deep (Figure 1a).

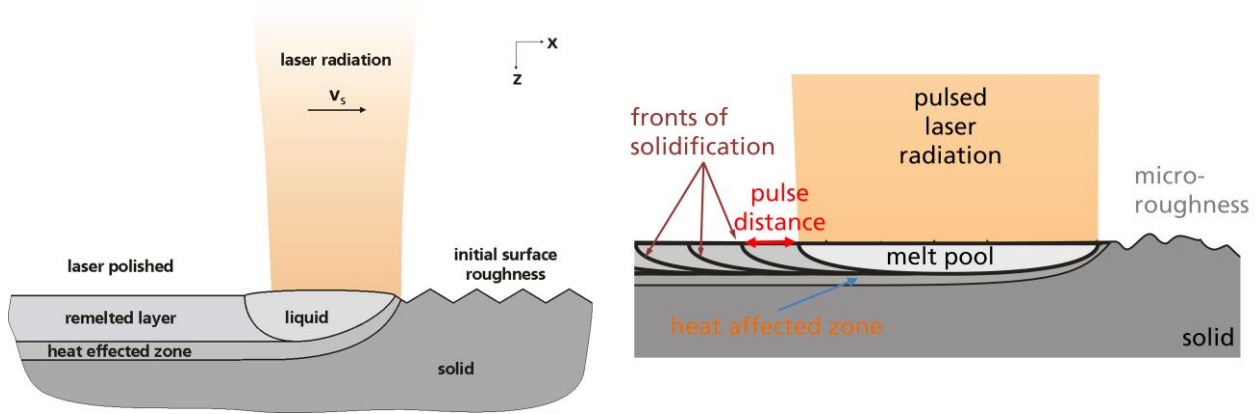


Figure 1: (a) Schematic of laser polishing by remelting a thin surface layer with continuous laser radiation. (b) Schematic of laser polishing by remelting a thin surface layer with pulsed laser radiation

For micro laser polishing pulsed laser radiation is used, which is a combination of remelting a thin surface layer smaller than  $5 \mu\text{m}$  and vaporization of micro edges (Figure 1b) [1][2][8][9][10][11]. In contrast to macro laser polishing, micro laser polishing is a discrete rather than a continuous remelting process.

Due to the procedural parameters, pulse duration of several 100 nanoseconds, repetition frequencies up to 20 kHz and scanning velocities bigger than 100 mm/s the molten material is already resolidified when the next laser pulse hits the surface and creates a new melt pool. Especially important for micro laser polishing is the intensity distribution of the laser beam within the interaction zone of material and laser radiation [10]. Crucial for the choice whether macro or micro polishing will be used are the initial surface roughness and its spatial wavelength. Using macro laser polishing e.g. for milled or turned surfaces the roughness within the interval of spatial wavelength from  $\lambda = 80 - 1280 \mu\text{m}$  is smoothed effectively. However, the roughness with spatial wavelengths lower than  $80 \mu\text{m}$  is limited due to solidification processes and formation of martensitic structures during cooling of the solidified material, especially for martensitic steels.

In most cases the initial roughness for grinded or diamond-milled surfaces is already very low in the domain  $\lambda > 80 \mu\text{m}$  and therefore no further improvement of the surface roughness is achieved by using macro laser polishing. However, the roughness with spatial wavelengths lower than  $80 \mu\text{m}$  can be reduced by micro laser polishing. Due to the smaller geometries of the melt pool and its relatively short life-time due to pulse durations of several hundred nanoseconds a significantly higher solidification rate is achieved. One effect is the suppression of martensite formation due to higher cooling rates and therefore a further reduction of the roughness in the domain lower  $80 \mu\text{m}$ . The roughness with spatial wavelengths larger than  $80 \mu\text{m}$  stays approximately unaffected, while the lowered roughness for  $\lambda < 80 \mu\text{m}$  results in a significantly higher gloss of the surface. Therefore, by using micro laser polishing the functional properties even of grained surfaces can be improved.

## 2.2 Selective Laser Polishing

In comparison to conventional polishing processes laser polishing opens up the possibility of selective processing of small areas ( $< 0.1 \text{mm}^2$ ) [8]. Selective laser polishing is a variant of laser polishing, where locally defined areas are remelted and therefore smoothed using pulsed or continuous wave laser radiation (Figure 2a). In this context a dual-gloss effect describes a visual impression, that is created by the selectively laser polished areas in contrast to the untreated parts of the surface. A dual-gloss effect is based on a space-resolved change in surface roughness (Figure 2b). In comparison to the initial surface the roughness of the laser polished surface is reduced significantly up to spatial wavelengths of 80 microns and therefore the gloss is raised considerably. To achieve selective laser polishing the laser beam is moved meanderly over the surface. The treatment in primary direction of processing is done with a scanning velocity  $v_{\text{scan}}$ , while the velocity in the secondary direction of processing can be calculated to  $v_{\text{sec.}} = dy * v_{\text{scan}} / (x + dy)$  (Figure 3a). At defined places (x,y) the laser power is modulated rectangular between a base level, where no treatment takes place and a processing level, where the laser power is sufficient to remelt the surface. Therefore, only defined areas of the surface get smoothed and a dual-gloss effect can be created.

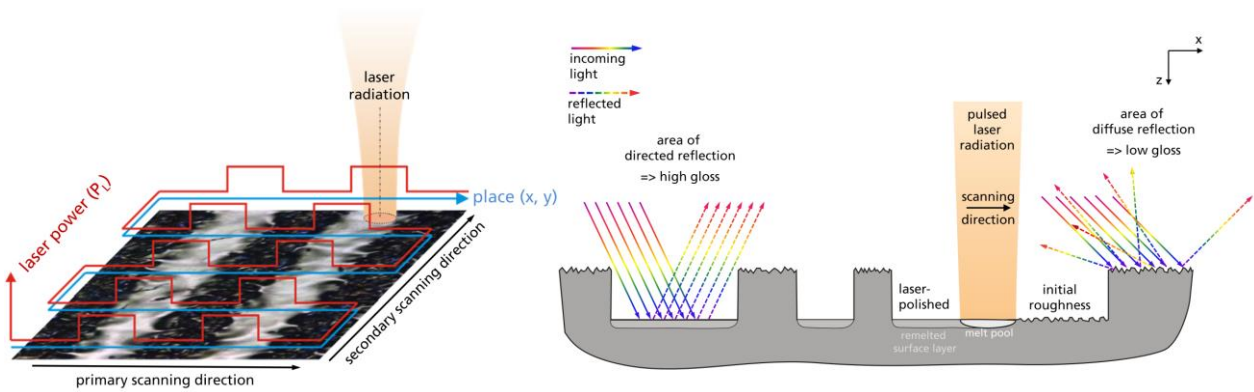


Figure 2: (a) Schematic of selective laser polishing. (b) Schematic of dual-gloss effect due to directed/diffuse reflection of laser polished/untreated areas of a leather texture

Leather textures for example are structures consisting basically of two different levels of heights, which can be divided into dips and elevations. Therefore, a dual-gloss effect for leather textures can be achieved by laser polishing selectively just one of these two levels, e.g. the dips of the structure (Figure 2b).

### 3. SCIENTIFIC APPROACH

#### 3.1 Procedural Parameters

During laser polishing the laser beam is moved meanderly over the surface. For macro polishing the main procedural parameters are laser power  $P_L$ , scanning velocity  $v_{scan}$ , laser beam diameter  $d_L$  and track offset [1][2][3][5]. For micro laser polishing additionally pulse duration  $t_p$  and repetition frequency  $f_p$  are relevant for surface treatment (Figure 3a). Because of using flat samples for process development the angle of incidence  $\beta$  is kept constant at zero degrees. The scanning vector is kept constant at 10 mm, while the processing length is also 10 mm, therefore fields for laser polishing are 10 mm in square.

#### 3.2 Spectral Analysis of Roughness

In order to quantify the roughness of a surface area, e.g. the mean roughness index  $R_a$ , often mechanical measurement contact-based methods are used. The laser micro polishing process leads to a smoothing of micro roughness, which often leaves the conventional used roughness indices unaffected. These changes in roughness and therefore gloss of the surface cannot be represented sufficiently by conventional mechanical methods [8].

Thus, the measurement of the laser micro polished surface areas is done contactless by white light interferometry. The captured surface profile is investigated by a spectral analysis of the surfaces roughness (Figure 3b). Every laser polished area investigated is mapped at five different locations using two different resolutions. Due to the resolution of the WLI images discrete spatial wavelength intervals are defined. The spectral analysis is achieved by a discrete convolution of the surface profile with a Gaussian loaded function similar to ISO 11562. In this way the surfaces roughness is split into discrete wavelength intervals. In Comparison to the unfiltered surface profile the filtered one shows no phase-shift and therefore no dislocation [8]. For this investigations the maximum spatial wavelength of the roughness analysis is limited to  $\lambda_{max} = 320 \mu m$ . The minimum spatial wavelength is limited to  $\lambda_{min} = 0,625 \mu m$  and results from the lateral resolution of the white light interferometer used. The spatial wavelength intervals in between  $\lambda_{min}$  and  $\lambda_{max}$  result from a subsequent duplication of the spatial wavelength intervals limits, so that nine different intervals are analyzed. Because of this duplication and the big differences in surface roughness dependent on the wavelength interval chosen, the illustration of spatial roughness is done logarithmical. Each point of measurement within the spatial roughness analysis is based on the average value and its standard deviation for five independent measurements.

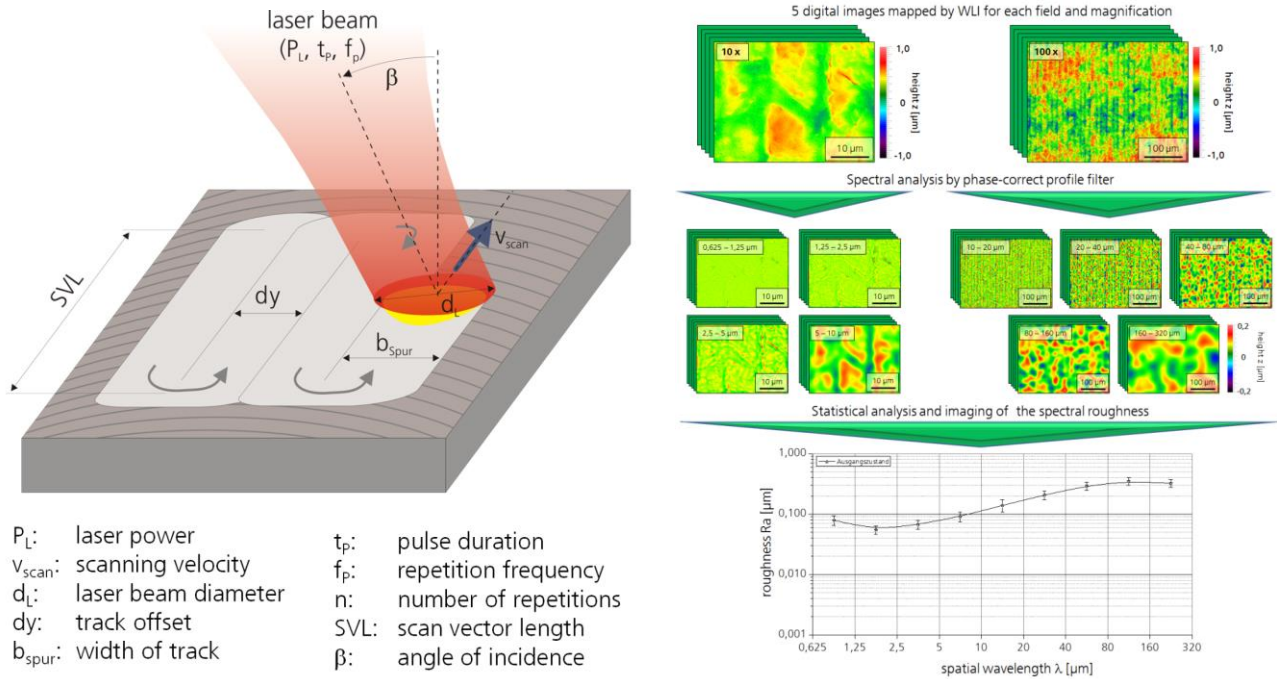


Figure 3: (a) Schematic of process principle and main procedural parameters for laser polishing. (b) Schematic for spectral analysis of surfaces based on different WLI mappings.

The experimental investigations are carried out on flat samples made of hot work steel 1.2343 (X38CrMoV5-1). The roughness of initial surfaces result from glass-bead blasting, as it is usual for common applications of matted tools for casting purposes in an industrial environment, e.g. for injection molding. The roughness in dependency on the spatial wavelength for an initial state of an untreated test sample is shown in Figure 3b.

#### 4. EXPERIMENTAL SET-UP

For the experimental set-up (Figure 4a), a fibre-coupled, Q-switched, Yb:YAG, solid state, disc laser is used (TruMicro 7050: emitting wavelength:  $\lambda_{em.} = 1030$  nm; maximum output laser power:  $P_{L,max} = 550$  W; repetition frequency:  $f_p = 5 - 20$  kHz, pulse duration:  $t_p = 0,7 - 3,5$   $\mu s$ , pulsed and cw-operation). Main function of the optical set-up (Figure 4b) is projecting the end of the laser fiber onto the work pieces surface. By using motorized apertures and a zoom telescope (PowerZoom from Sill) the laser beam diameter can be changed continuously in the range of  $d_L = 125$   $\mu m$  up to  $d_L = 800$   $\mu m$ . A 3D laser scanning system is realized by the combination of a varioScan 40 and a HurryScan 30 both from ScanLab, which allows a fast, three-dimensional deflection of the laser beam relatively on the work pieces surface. During the laser polishing process the laser beam can be moved with a velocity of up to 5 m/s and acceleration up to 100 g relatively to the treated surface. For focusing the laser beam a f-theta-objective with an focal length of  $f_T = 163$  mm is used, which results in a scanning volume of  $80 \times 80 \times 22$   $mm^3$ . The laser polishing takes place in a process chamber, which can be filled with inert gas to avoid unwanted oxidations while remelting the surface. The remaining oxygen concentration within the chamber is monitored and is adjusted to a defined level by an adapted closed-loop control. In addition to three “optical” axes for fast laser beam control, five mechanical axes (three linear and two rotatory) are used for a slow positioning of the work piece relatively to the laser beam. This experimental set-up enables a 5 + 3 axes laser processing of a work piece with maximal dimensions of  $300 \times 300 \times 100$   $mm^3$  within a process chamber filled with inert gas.

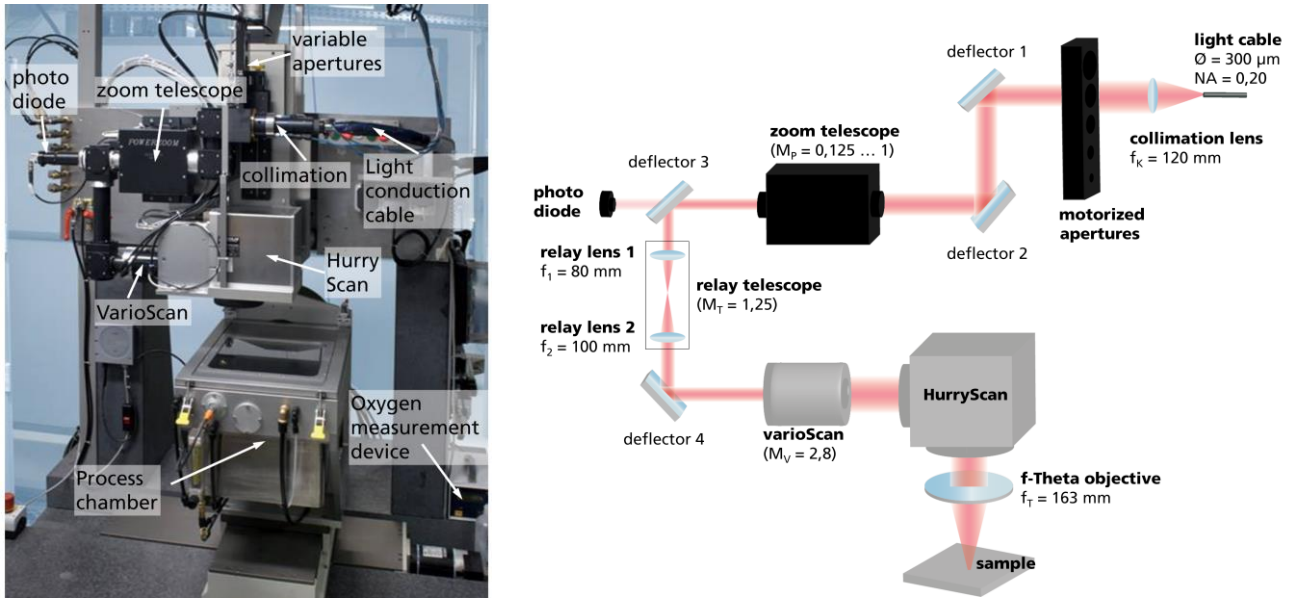


Figure 4: (a) Picture of the experimental set-up. (b) Schematic of the configuration of optical components.

## 5. RESULTS

### 5.1 Polishing with pulsed laser radiation

In general, scanning velocity and average laser power are two crucial procedural parameters for laser polishing with significant influence on the resulting surface roughness. For micro laser polishing these procedural parameters are investigated first and varied systematically, while the other procedural parameters, such as laser beam diameter  $d_L = 250 \mu\text{m}$ , track offset  $dy = 25 \mu\text{m}$ , pulse duration  $t_p = 2,4 \mu\text{s}$ , repetition frequency  $f_p = 20$  kHz were kept constant. Aim of this investigation is a reduction of roughness, especially for the wavelength interval  $\lambda < 320 \mu\text{m}$ . Figure 5a shows the spatial roughness for nine different surfaces, which are laser polished with nine different average laser powers, while keeping the scanning velocity constant at  $v_{\text{scan}} = 100$  mm/s.

For small laser power ( $P_L = 10$  W) the effect of laser polishing is small and roughness is reduced just a bit. With increasing laser power a significant reduction of roughness is achieved throughout the whole spectrum of spatial wavelengths. In comparison to the other laser powers used, the reduction of roughness is maximal for  $P_L = 50$  W. A further increase in laser power, e.g.  $P_L = 80$  W, reduces the effect of laser polishing in comparison to  $P_L = 50$  W. Likewise the standard deviation of the spatial roughness allows to make a conclusion concerning the quality of a laser polished surface.

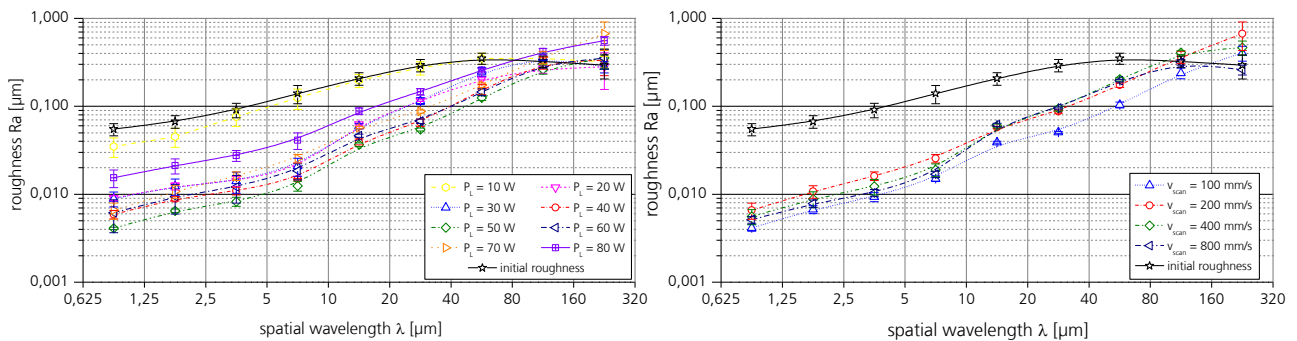


Figure 5: (a) Roughness in dependence on spatial wavelength for different laser powers. (b) Roughness in dependence on spatial wavelength for different scanning velocities.

For small laser power a high standard deviation is observed, because the surface is just partially remelted. Using high laser power, the local vaporization of material lead to some kind of texturing of the treated surface and therefore also in a high standard deviation. In that case a reduction of surface roughness is still achieved, but in parallel the formation of process-induced structures have negative effects on laser polishing results.

In order to investigate the influence of scanning velocity on the roughness of laser polished surfaces, the scanning velocity is varied systematically in the range of  $v_{scan} = 100 - 800$  mm/s. Starting with  $v_{scan} = 100$  mm/s the scanning velocity is doubled until  $v_{scan} = 800$  mm/s is reached, so that four different scanning velocities were investigated. Using a constant laser power of  $P_L = 70$  W the biggest reduction of roughness is achieved for spatial wavelengths  $\lambda < 20 \mu\text{m}$  and a scanning velocity of  $v_{scan} = 800$  mm/s (Figure 5b). For bigger spatial wavelengths the scanning velocity has approximately no influence on a further reduction of spatial roughness. However, as already shown for the investigation of laser power at  $v_{scan} = 200$  mm/s a reduction in roughness is already achieved with a smaller laser power than  $P_L = 70$  W. Therefore, for every scanning velocity investigated also a variation of laser power is carried out. The spectral roughness is imaged depending on laser power and scanning velocity with the help of a miscoloured isoplethic diagram. The varied procedural parameters are plotted on the x- and y- axis, while the spatial roughness  $Ra(\lambda_1 - \lambda_2)$  is plotted as height-dependent color. Black crosses mark pairs of procedural parameters used for laser polishing. An interpolation between points of measurement is achieved by using a two-dimensional spline function (Figure 6).

For further analysis some spatial wavelengths intervals, which show similar interdependencies, are summarized in three main scales for roughness. Therefore the roughness is divided into micro-roughness for spatial wavelengths  $\lambda < 10 \mu\text{m}$ , meso-roughness for the spatial wavelength interval  $10 \mu\text{m} < \lambda < 80 \mu\text{m}$  and macro-roughness for spatial wavelengths  $\lambda > 80 \mu\text{m}$ . The qualitative interdependencies between laser power, scanning velocity and roughness are all the same within one roughness scale and are represented by one process diagram for each roughness scale. Therefore, the spatial roughness interval  $Ra(1.25 \mu\text{m} - 2.5 \mu\text{m})$  represents micro-roughness,  $Ra(20 \mu\text{m} - 40 \mu\text{m})$  represents meso-roughness and  $Ra(80 \mu\text{m} - 160 \mu\text{m})$  represents macro-roughness.

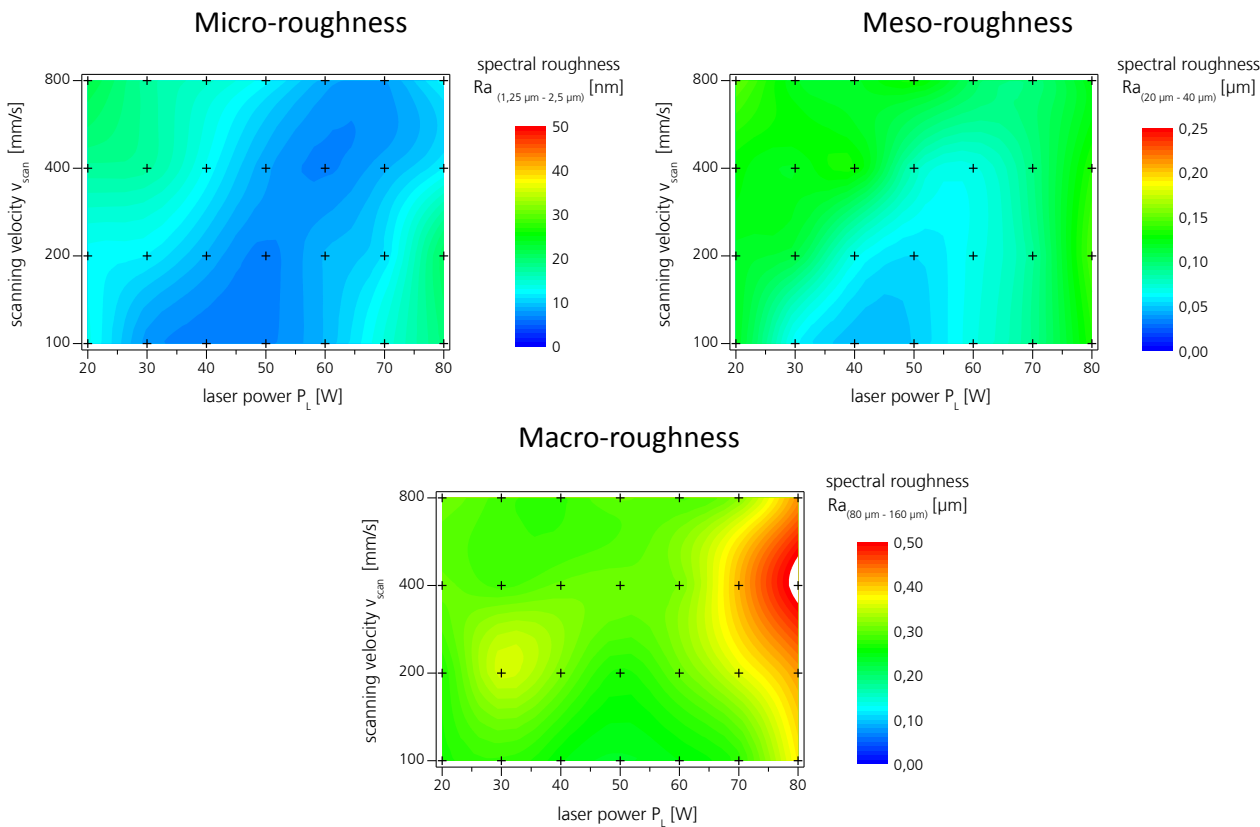


Figure 6: Spectral roughness in dependence on laser power and scanning velocity as a miscoloured isoplethic diagram for micro-, meso- and macro-roughness for polishing with pulsed laser radiation.

In case of micro-roughness a similar reduction of roughness is observed for all scanning velocities investigated. The minimal roughness is achieved using  $v_{\text{scan}} = 800$  mm/s and laser power of  $P_L = 60$  W and  $P_L = 70$  W. With decreasing scanning velocity the laser power has to be reduced as well, so that the minimal roughness at  $v_{\text{scan}} = 100$  mm/s is achieved using laser power  $P_L = 30$  W – 50 W. Therefore, an effective reduction of roughness does not only depend on pulse energy but also on how many times the surface layer is remelted, respectively the local preheating of the material by previous remelting processes. Considering the procedural parameters  $f_p = 20$  kHz,  $d_L = 250$   $\mu\text{m}$  and  $v_{\text{scan}} = 800$  mm/s, the distance of successive laser pulses is 40  $\mu\text{m}$  on the work pieces surface, while it is 5  $\mu\text{m}$  at  $v_{\text{scan}} = 100$  mm/s. This equals 6.25, respectively 50 remelting processes of the surface layer with pulse energies from  $E_p = 2$  mJ to  $E_p = 4$  mJ and pulse durations of approximately  $t_p \approx 2.4$   $\mu\text{s}$ . This results in pulse peak power of  $P_p = 0.8$  kW – 1.6 kW. Considering a laser beam diameter of  $d_L = 250$   $\mu\text{m}$  with flat-top intensity distribution this results in an energy per area of 40 mJ/mm<sup>2</sup> – 80 mJ/mm<sup>2</sup> or peak laser power per area of 16 kW/mm<sup>2</sup> – 32 kW/mm<sup>2</sup>.

In comparison to micro-roughness, meso-roughness is not much affected by laser polishing with pulsed laser radiation. Especially, for high scanning velocities  $v_{\text{scan}} = 800$ mm/s the laser power cannot be adapted in that way, that a similar reduction of roughness is achieved as for  $v_{\text{scan}} = 100$ mm/s. Local preheating based on a high number of previous remelting processes are leading even to a small reduction of macro-roughness. The minimal meso-roughness is achieved at  $v_{\text{scan}} = 100$  mm/s and laser power  $P_L = 40$  W. However, a significant reduction of roughness for spatial wavelengths greater than the laser beam diameter used is achieved in no case. Therefore the macro-roughness stays mainly unaffected by the treatment with laser power less than  $P_L = 60$  W. The use of greater laser power leads to local vaporization of material, which results in a higher roughness in comparison to the initial surface.

## 5.2 Polishing with continuous wave laser radiation

As for polishing with pulsed laser radiation the procedural parameters laser power and scanning velocity have a significant influence on the roughness of the treated surface. Therefore laser power and scanning velocity are also varied systematically. Scanning velocity is varied in the range of  $v_{\text{scan}} = 50 - 400$  mm/s. Starting with  $v_{\text{scan}} = 50$  mm/s, the scanning velocity is doubled until  $v_{\text{scan}} = 400$  mm/s is reached, so that four different scanning velocities were investigated. The laser power is adapted to the scanning velocity and varied equidistantly in eight steps, adjusted to the scanning velocity used. For micro laser polishing pulse energy and laser beam diameter affecting the geometry of melt pool significantly, while pulse duration determines the interaction time of laser radiation and material. The interaction time of laser beam and material surface has the same order of magnitude as the life time of the melt pool and is smaller than  $t < 10$   $\mu\text{s}$ . Therefore, the molten material is already resolidified before a consecutive laser pulse remelts the surface again at a slightly shifted place. Additionally, the interaction of the laser beam takes mainly place with solid material. Thus, the scanning velocity has only an indirect effect through local preheating upon the lifetime of the melt pool.

In contrast to micro polishing the geometry of the melt pool for remelting with continuous wave laser radiation is affected significantly not only by laser beam diameter and average laser power, but also by scanning velocity. The laser radiation for the continuous process couples mainly in molten material and the lifetime of the melt pool is dominated by the scanning velocity used. Therefore the laser power is adapted to scanning velocity as followed.

Using a scanning velocity of  $v_{\text{scan}} = 50$  mm/s the laser power is varied in eight equidistant steps in the range of  $P_L = 25$  W - 130 W, while the laser power is varied in the range of  $P_L = 25$  W - 230 W at a scanning velocity of  $v_{\text{scan}} = 400$  mm/s.

Figure 7 shows the dependency of micro-, meso-, and macro-roughness on the procedural parameters scanning velocity and laser power. The laser beam diameter was held constant at  $d_L = 250$   $\mu\text{m}$ , while the track offset was set to  $dy = 25$   $\mu\text{m}$ . A reduction of roughness is achieved with laser power greater than 25 W at all scanning velocities investigated. However, great laser power and low scanning velocities lead to visible vaporization of material and coincidental to a decarburization of the remelted surface layer.

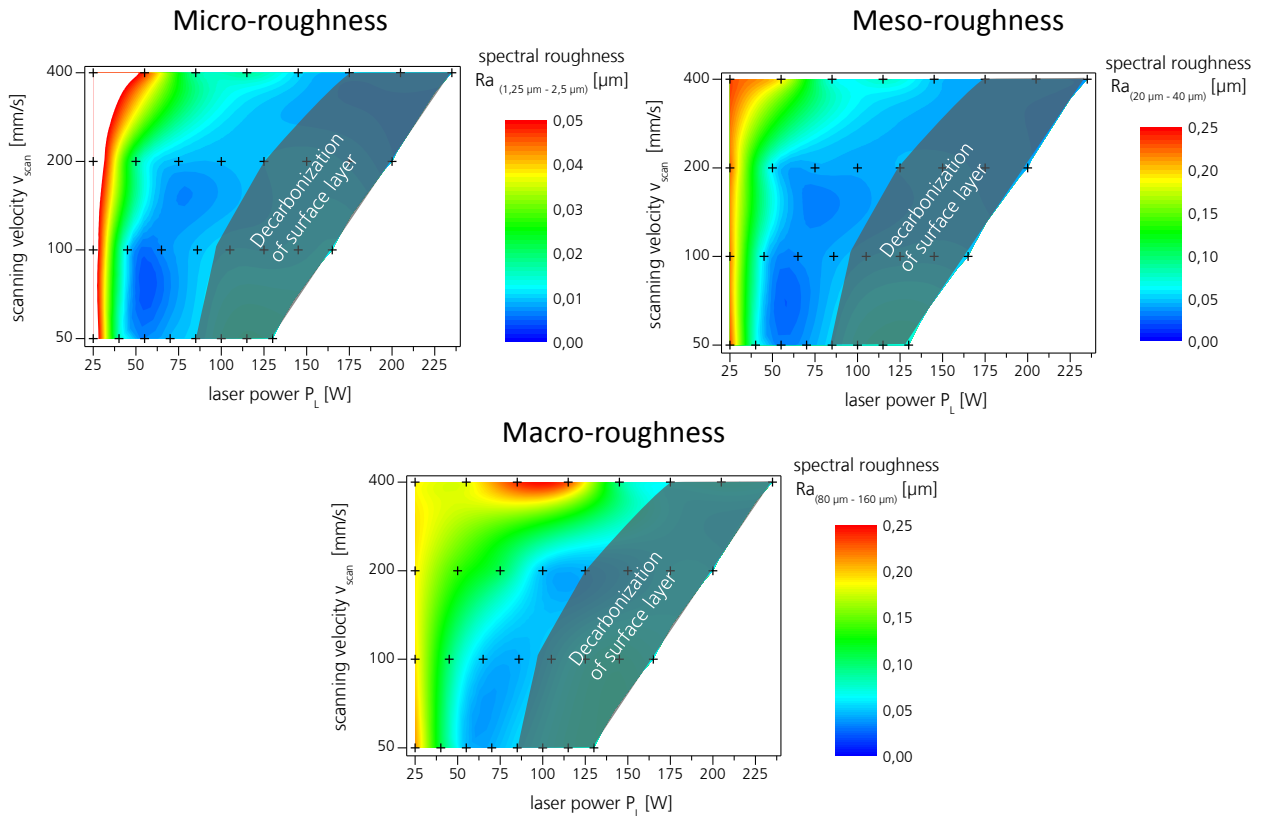


Figure 7: Spectral roughness in dependence on laser power and scanning velocity as a miscoulored isoplethic diagram for micro-, meso- and macro-roughness for polishing with cw laser radiation.

Due to the decarburization a black carbon layer is generated on the laser polished surface. After mechanical removal of this carbon layer the spatial roughness analysis shows a comparatively big reduction of roughness for the treated area. Thus, the procedural parameters, which lead to such a decarburization, will be excluded from an appropriate range of procedural parameters, because an additional process step would be needed before fitting for purpose.

A low roughness throughout the whole spectrum of spatial wavelengths can be achieved for all scanning velocities investigated by adapting the laser power. A minimum in roughness is achieved for  $v_{scan} = 50$  mm/s at  $P_L = 55$  W, for  $v_{scan} = 100$  mm/s at  $P_L = 85$  W, for  $v_{scan} = 200$  mm/s at  $P_L = 100$  W, and for  $v_{scan} = 400$  mm/s at  $P_L = 175$  W. The minimal macro-roughness is maintained for a scanning velocity of  $v_{scan} = 50$  mm/s. Altogether there is no linear correlation of laser power and scanning velocity at which the minimal roughness is attained. Rather, the minimal roughness is influenced by several independent parameters such as intensity of laser radiation, interaction time of laser beam and material, or fraction of absorption in the molten, respectively solid material. Basically can be said, the lower the scanning velocity the bigger is the reduction of macro-roughness. The cause for this observation is presumably the proportion of melting depth to initial surface roughness.

### 5.3 Combination of Polishing with continuous wave and pulsed laser radiation

The resulting roughness after polishing with pulsed laser radiation is presumably based on roughness and inhomogeneity of the initial surface. Using continuous wave laser radiation for remelting the surface is already smoothed significantly and inhomogeneity within the remelted material are homogenized due a material flow within the melt pool [6]. This kind of remelted surface is much more qualified for a successive treatment with pulsed laser radiation, because unwanted structures induced by roughness and inhomogeneity of the initial surface are reduced. The basis for an investigation of the combined treatment with continuous wave and pulsed laser radiation is a set of procedural parameters that showed

significant reduction of roughness and also an adequate processing time. The first step is to laser polish the initial surface with cw laser radiation, laser beam diameter  $d_L = 250 \mu\text{m}$ , scanning velocity  $v_{\text{scan}} = 200 \text{ mm/s}$ , track offset  $dy = 25 \mu\text{m}$ , and laser power  $P_L = 100 \text{ W}$ . The second step is a systematic variation of laser power and scanning velocity for a successive treatment with pulsed laser radiation and an analysis of the resulting spatial roughness spectrum, similar to the investigations made before.

Figure 8 shows the dependency of micro-, meso-, and macro-roughness on laser power and scanning velocity for a laser beam diameter of  $d_L = 250 \mu\text{m}$  and the use of pulsed laser radiation. The light continuous isopleths within the diagrams indicate that for this set of procedural parameters the roughness is reduced, while black dashed isopleths indicate that the roughness is increased in comparison to roughness after macro laser polishing. The micro-roughness is reduced, especially for scanning velocities  $v_{\text{scan}} = 100 \text{ mm/s}$  and  $200 \text{ mm/s}$  within a range of laser power of  $P_L = 30 \text{ W} - 80 \text{ W}$ . At a scanning velocity of  $v_{\text{scan}} = 400 \text{ mm/s}$  the range of laser power is significantly smaller for a reduction of micro-roughness. The meso-roughness is reduced significantly at all scanning velocities for laser power in the range of  $P_L = 50 \text{ W} - 80 \text{ W}$ . The macro-roughness stays virtually unaffected for all scanning velocities and laser power smaller than  $70 \text{ W}$ . Just for a small range of laser power  $P_L = 70 \text{ W} - 80 \text{ W}$  a slight reduction of macro-roughness is observed, which results from a modest vaporization of material. However, micro- and meso-roughness are still higher than for  $P_L = 30 \text{ W}$ . For even higher laser power vaporization becomes a dominating process, which lead to irregular structures and therefore to a significant increase in macro-roughness. Depending in which domain the roughness should be minimized by an additional treatment with pulsed laser radiation, an appropriate set of procedural parameters can be chosen from this process diagrams. Especially, if the micro-roughness should be minimized, high scanning velocities and moderate laser power, such as  $P_L = 30 \text{ W} - 50 \text{ W}$  should be preferred.

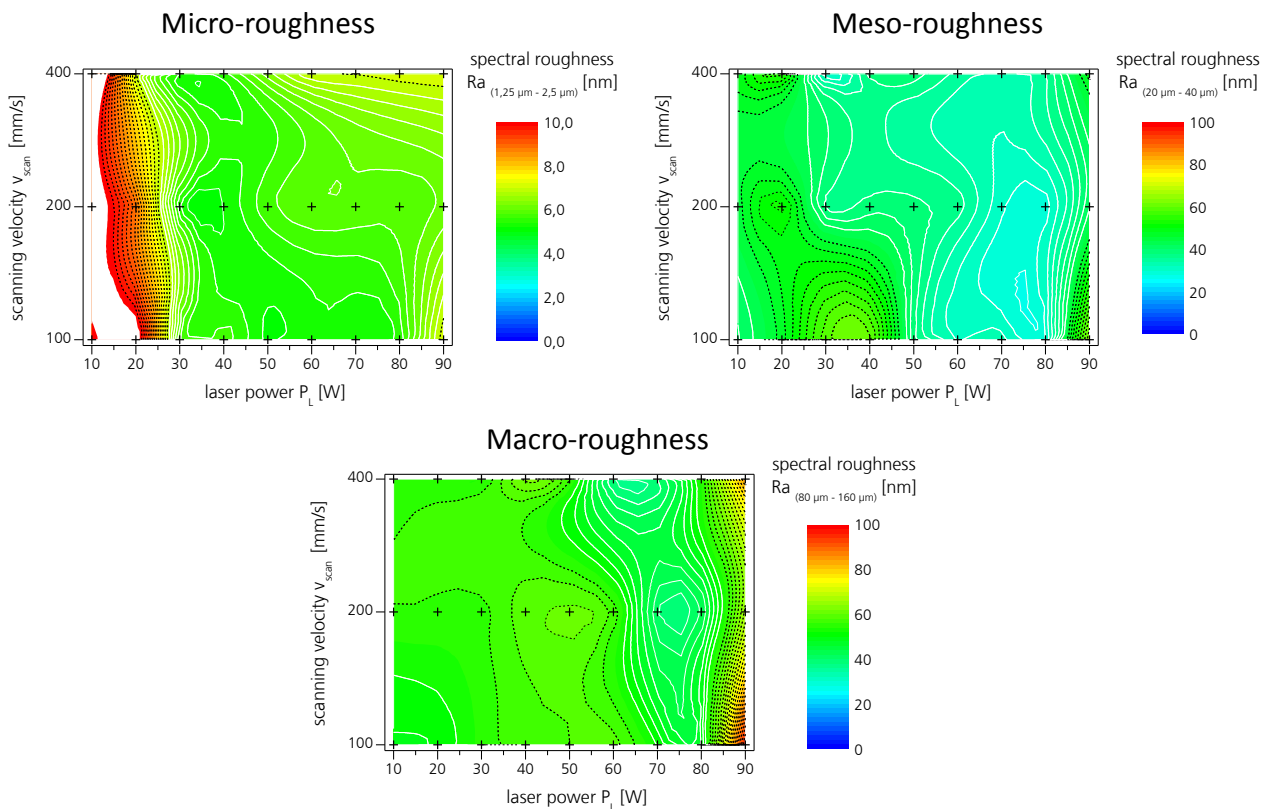


Figure 8: Spectral roughness in dependence on laser power and scanning velocity as a multicolored isoplethic diagram for micro-, meso- and macro-roughness for combined polishing with cw + pulsed laser radiation.

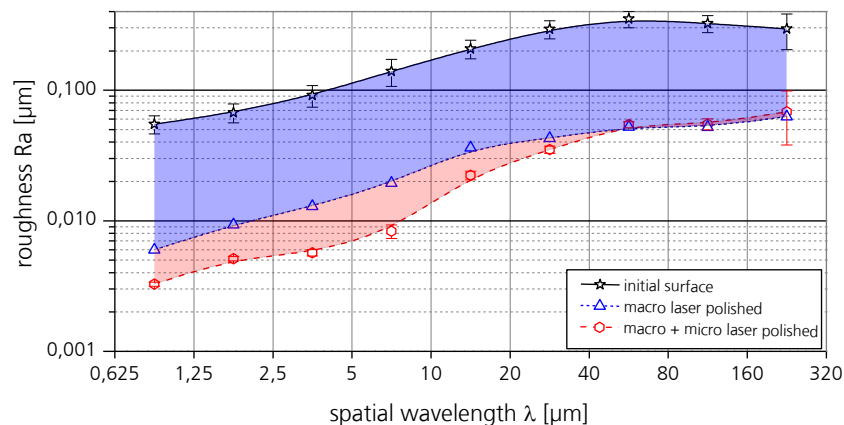


Figure 9: Roughness in dependence on spatial wavelength for comparison of initial surface, macro laser polished surface and combined macro and micro laser polished surface.

Figure 9 shows that a reduction of roughness is achieved throughout the whole spectrum of spatial wavelengths by macro laser polishing with cw laser radiation and a subsequent micro laser polishing using pulsed laser radiation. The initial roughness is reduced in the range of 70% - 90% by macro laser polishing, in parallel the remelted surface layer is homogenized with regard to its alloying elements. A subsequent laser polishing step using pulsed laser radiation leads to an further reduction of micro- and meso-roughness up to 50% including spatial wavelengths up to  $\lambda = 40 \mu\text{m}$ . Therefore, in order to minimize the micro-roughness and maximize the gloss-level, a combined treatment of cw and pulsed laser radiation should be carried out.

#### 5.4 Development of a process chain for selective laser polishing

In order to selective laser polish a leather-textured free-form surface several process steps are necessary, which can be divided in three consecutive steps (Figure 10a).

At first a sensorial capture and digitalization of a leather-textured free-form surface has to be performed by an adapted sensorial system, which requires a sufficient lateral resolution and a preferably high measuring velocity including little error in measurement. For the sensorial capture the chromatic confocal sensor system Chrocodile X is used. The sensorial system used provides a lateral resolution of  $12.5 \mu\text{m}$  for x- and y- direction and approx.  $335 \text{ nm}$  for the height in z-direction. The measurements are carried out by moving the punctual measuring spot meanderly over the surface with a velocity up to ten meters per minute. Under consideration of non-productive time, this leads to an average measuring rate of approx.  $30 - 40 \text{ s/cm}^2$ , including an error of measurement less than two percent.

Secondly the data of the digitalized free-form surface has to be prepared for selective laser polishing by several adapted operators mainly used in signal and digital image processing. The process chain is demonstrated with the help of a specific cut-out of a leather-textured surface (Figure 10b). The leather texture is captured by a contactless sensorial system and can be visualized as a miscoloured plot (Figure 10b-i). A specially adapted software enables an effective detection and elimination of errors by using a selective median filter, just as preserving the sharpness of the surfaces edges. Followed by a Fourier-Transformation, the surface is transformed into its frequency spectrum of amplitudes and dedicated spatial frequencies. An analysis of the spatial frequencies enables an adapted band-pass filtering in order to separate the leather texture from the work pieces geometry. Furthermore the resulting surface is transformed back into position space and analyzed by using a histogram. An adapted inclination of the heights in two levels leads to a black and white image of the leather texture (Figure 10b-ii), where the white areas represent the indentations and black ones the elevations. ). Before compiling a machine-adapted NC-Code, this image is modified under special consideration of the used laser beam diameter and processing velocity. As a consequence the black and white image of the leather texture has to be modified by expanding the white areas into the black ones (Figure 10b-iii).

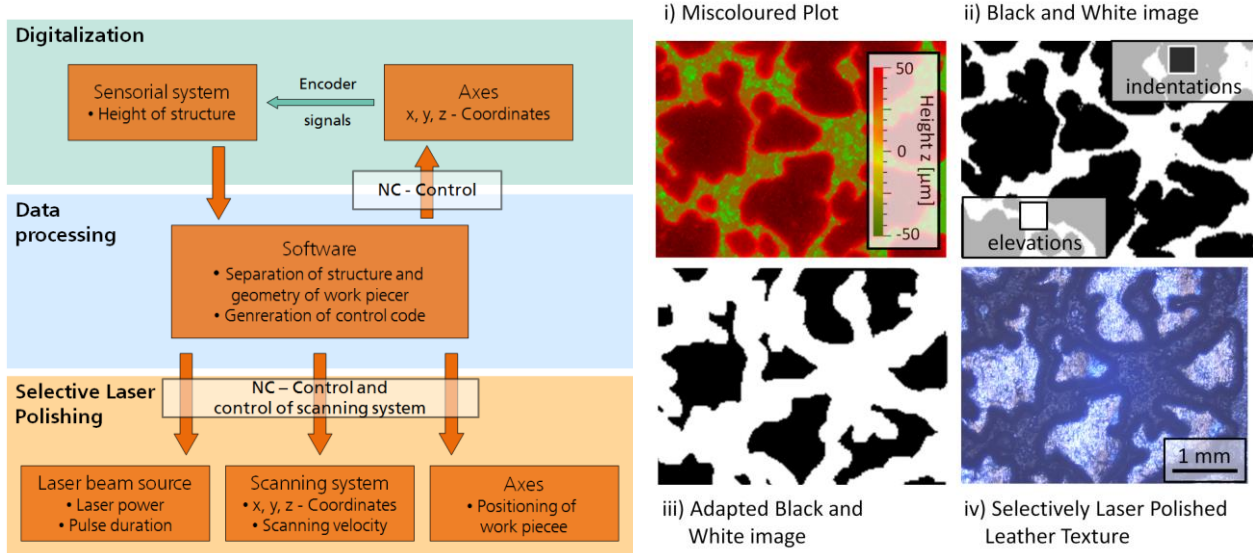


Figure 10: (a) Schematic of the process chain necessary for selective laser polishing leather-textured free-form surfaces and (b) visualization of essential data processing steps (i-iv) based on a cut-out of a flat leather texture.

Furthermore a machine adapted control code is generated, which enables the selective laser polishing of leather-textures indentations using a 3D laser scanning system and an appropriate laser beam source. A two gloss effect results from the contrast of selectively laser polished indentations and untreated elevations (Figure 10b-iv) [8].

### 5.5 Selective laser polishing of a leather textured free form surface

The process steps described in paragraph 5.4 were carried out for a leather-textured free-form surface with lateral dimensions of 160 mm x 195 mm and a maximum depth of approx. 20 mm. The maximum inclination angle between surface normal and laser beam is 25 degrees. The surfaces capturing and digitalization took approx. eight. Due to the limited measuring range (11 mm in z-direction) of the sensing head used, the surface had to be scanned twice in different z-positions to cover the depth of 20 mm. This explains the relative high measuring time of approx. 80 s/cm<sup>2</sup>. The dimension of the captured data matrix consists of about 52 million points. The data processing, including a selective median filter, Fourier-analysis, histogram spreading and the generation of a tool- and machine adapted numerical control code, took another hour. The selective laser polishing of two-thirds of the leather textured was carried out with a scanning velocity  $v_{scan} = 250$  mm/s. The track offset between the meandering scanning paths is 25 microns, which leads to a process time for the selective laser polishing of approximately one hour. Figure 11 shows the resulting appearance of the selectively laser polished free-form surface in two different magnifications. The overall time for the selective laser polishing of this free-form surface is therefore ten hours, including all processing steps necessary [8].

## 6. CONCLUSIONS

In comparison to conventional polishing processes laser polishing opens up the possibility of selective processing of small areas (< 0.1 mm<sup>2</sup>) on a tools surface. Selective laser polishing enhances the appearance of design surfaces by creating two-gloss effects, which cannot be achieved with conventional machining methods without a high demand in human resources and time. A two-gloss effect can be created by selective variation of process parameters like laser power and process velocity and is therefore based on a space-resolved change in surfaces roughness.

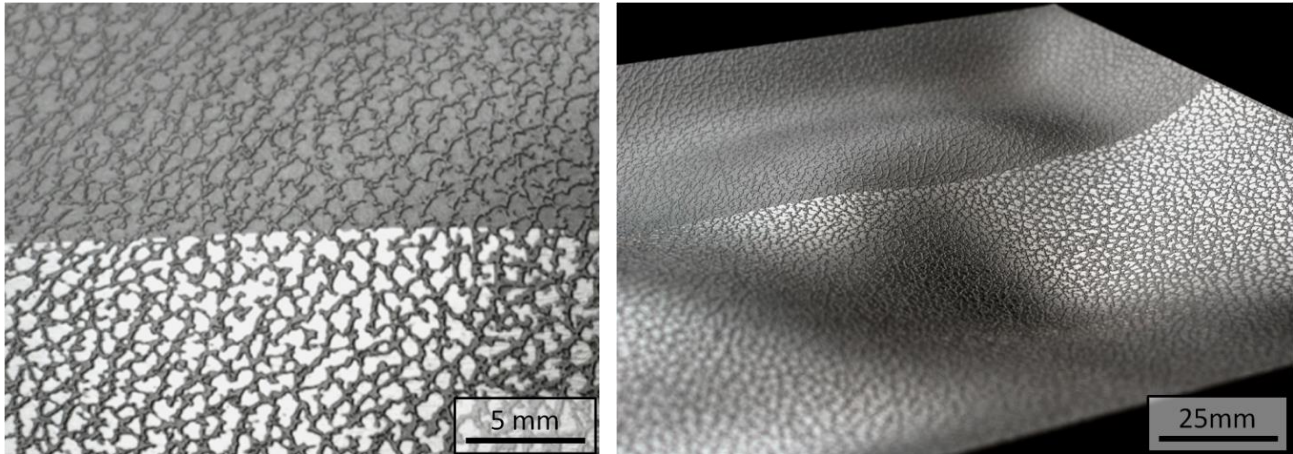


Figure 11: Photograph of a (a) cut-out from a selective laser polished leather-textured free-form surface and (b) selective laser polished leather-textured free-form surface made of tool steel 1.2343 [8].

A reduction of roughness is achieved throughout the whole spectrum of spatial wavelengths by macro laser polishing with cw laser radiation and a subsequent micro laser polishing using pulsed laser radiation. The initial roughness is reduced in the range of 70% - 90% by macro laser polishing, in parallel the remelted surface layer is homogenized with regard to its alloying elements. A subsequent laser polishing step using pulsed laser radiation leads to a further reduction of micro- and meso-roughness up to 50% including spatial wavelengths up to  $\lambda = 40 \mu\text{m}$ . Therefore, in order to minimize the micro-roughness and maximize the gloss-level, a combined treatment of cw and pulsed laser radiation should be carried out. Therefore, a broad process window for the crucial procedural parameters for selective laser polishing was identified. A proper working process chain was developed, including the integration of an adequate sensorial system into the existing set up and the development of an adapted data processing. The successful operation of all process steps for selective laser polishing was demonstrated with a leather-textured free-form surface made of tool steel 1.2343.

Nevertheless, adapting the process steps for all kinds of free-form surfaces especially those with greater inclination angles than 25 degrees, development of a continuous CAD-CAM-NC interlinking and reduction of overall processing time are challenges need to be solved for a successful introduction of (selective) laser polishing into an industrial environment.

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