Post-processing of additively manufactured metal parts by ultrashort laser pulses for high-quality net shape geometries and advanced functionality

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Abstract. Additive manufacturing by means of laser-based powder bed fusion (LPBF) offers high flexibility with respect to the generation of individualized and light-weight metal parts. However, the produced parts are typically attached to support structures and deviate a few tens of micrometers from the targeted final component in geometrical net shape and surface roughness due to the melt-based fusion process. Therefore, different post-processing techniques were examined in the past to resolve the mentioned quality drawbacks. In our work, we investigated the potential of post-processing of LPBF-generated Ti6Al4V parts with ultrashort pulse laser ablation. As a result, the support structures were effectively removed, the surface roughness was reduced by 81% and complex geometries with high shape accuracy were fabricated. Furthermore, the LBPF-generated parts were laser surface structured to investigate the potential of post-processing with ultrashort laser pulses for advanced functionality, such as water-repellent surfaces. The generation of surface structures on the LPBF-generated Ti6Al4V part changed the wetting behaviour from hydrophilic to hydrophobic with an increased contact angle from 73° up to 130°.
1 Introduction
During the last decade additive manufacturing processes have made their way from rapid prototyping into industrial series production. Additive manufacturing by means of laser-based powder bed fusion (LPBF) offers high flexibility with respect to the generation of individualized and light-weight metal parts. With LPBF complex-shaped, metallic parts are generated from slices of selectively molten powder in the powder bed [1]. However, for most industrial applications the LPBF process does not allow to produce parts that are directly ready to use and thus post-processing is required [2]. For example, support structures are necessary to enable the generation of overhang structures which have to be removed from the part after the LPBF process [3]. Additionally, the surface quality of LPBF-generated parts is reduced by partially fused powder particles that adhere to the surface [4]. Furthermore, macroscopic deviations from the targeted geometry typically result from material shrinkage, build orientation and the staircase effect [5]. One promising approach to remove excess material such as support structures with minimized mechanical load is laser micromachining with short and ultrashort laser pulses. Excess material can be detected and measured in the processing area during micromachining using on-axis depth measurement based on optical coherence tomography (OCT). The online depth measurements can be used within a control system with a defined target depth for each location in the processing area to further process only locations that have not reached the target depth yet. OCT-controlled laser micromachining enabled the machining of highly accurate geometries in inhomogeneous materials, such as wood, bone [6] and carbon-fiber reinforced plastics (CFRP) [7]. In a previous work, we presented OCT-controlled laser micromachining with ultrashort laser pulses for high-quality net shape geometries in LPBF-generated aluminum parts with increased geometry accuracy and reduced surface roughness [8]. Surface structuring with ultrashort laser pulses can create advanced functionalities, e.g. preventing counterfeiting or tampering by encoding numerical information [4] or passive antibacterial behavior [9]. In this work, OCT-controlled laser micromachining with ultrashort laser pulses is demonstrated for post-processing of LPBF-generated parts manufactured from a Ti6Al4V powder. First, OCT-controlled laser micromachining is used for the removal of the support structures attached to the manufactured part. Then, OCT-controlled laser micromachining is used to smooth the underlying surface and to create complex geometries that are difficult or impossible to manufacture with the LPBF process. Finally, an additional laser process for advanced functionality is presented with the fabrication of hydrophobic surfaces by surface structuring of additively manufactured parts with ultrashort laser pulses.

2 Methods and material
The ultrafast laser system Pharos from Light Conversion was used for material processing and emitted pulses at a wavelength of $\lambda_{\text{photon}} = 1030$ nm with a pulse duration of 260 femtoseconds (fs). The laser beam was linearly polarized and had a beam quality factor of $M^2 < 1.3$. The maximum average power on the sample surface was 13 W, which corresponds to a maximum pulse energy of $E_p = 260$ µJ at a pulse repetition rate of $f_p = 50$ kHz. The OCT-based depth measurement system CHRocodile 2 from Precitec was used for on-axis fiber depth measurements [7], [8]. The superluminescence diode of the measurement system is a broadband light source that emits at a wavelength of $\lambda_{\text{OCT}} = 1080 \pm 20$ nm and with a beam quality factor of $M^2 < 1.1$. The measuring rate was set to 50 kHz to correspond to the pulse repetition rate of the processing laser of $f_p = 50$ kHz. The depth measurement system provided an axial measurement range of up to 6 mm with an axial measurement accuracy of ±1 µm. The processing laser beam and OCT measurement beam were superimposed by means of a dichroic mirror as sketched in Figure 1.
Both beams were guided through a Galvo-Scanner for deflection and focused by an F-Theta lens. The experiments regarding OCT-controlled laser micromachining (cf. section 3) were performed using an F-Theta lens with a focal length of 163 mm, resulting in focal diameters of $d_{f,163\text{mm}} = 60\pm 5 \mu m$ for the processing laser beam and $15\pm 5 \mu m$ for the OCT measurement beam. The experiments regarding surface structuring (cf. section 4) were performed using an F-Theta lens with a focal length of 340 mm, resulting in a focal diameter of $d_{f,340\text{mm}} = 120\pm 5 \mu m$ for the processing laser beam. The smaller beam diameter in micromachining allowed for a high lateral precision in the x-y-plane, whereas a larger beam diameter in surface structuring allowed for the usage of high pulse energies at a fixed repetition rate and fluence, which corresponds to a higher processed area per unit time.

The principle of OCT-controlled laser micromachining is described in [7]. In short, the sample surface is measured using the depth measurement system to receive the depth value (z-direction in Figure 1) while the measurement beam is deflected across the sample surface (x-y-plane in Figure 1) in a rasterized manner by the Galvo-Scanner. After each pass across the sample surface, a 3D-measurement of the current surface topography is generated and compared to the target topography. Locations in the x-y-plane with excess material are processed with a fixed pulse energy and locations where the target depth has already been reached are skipped in the following pass, until the measured topography fits to the target topography within a tolerance band of $\pm 5 \mu m$.

The samples were manufactured with a Ti6Al4V powder with a grain size distribution between 15 $\mu m$ and 45 $\mu m$ on an LPBF-system according to ASTM 52911-1 (ASTM 52911). A single-mode fibre laser with a wavelength of 1075 nm, an average power of 155 W and a beam diameter of 30 $\mu m$ was used to generate powder layers with a thickness of 20 $\mu m$ in an inert gas atmosphere of argon without additionally heated substrate. The part was generated with lateral dimensions of 8 mm and a part thickness of approximately 1.5 mm by hatching with a feed rate of 1200 mm/s and a hatching distance of 60 $\mu m$. Block support structures were generated so the parts were fixed metallurgically to the substrate. In other applications, the support structures are often required to enable the generation of overhang structures. The support structures, the manufactured sample and the resulting surface structure are shown in Figure 2.
Figure 2. a) SEM image of block support structures. b) Image of the sample generated from Ti6Al4V powder by LPBF with support structures on top side and the part on the bottom side. c) Surface structure after the manufacturing process.

The block support structures were built with a wall distance of 700 µm and wall height of 800 µm. Excess material adhered locally between the support structures from the mechanical separation of the sample from the substrate plate of the powder bed (Figure 2 a). Powder grains and partially molten material remained on the sample surface after the manufacturing process (Figure 2 c).

The 3D-measurements generated during OCT-controlled micromachining were used to evaluate the resulting quality and productivity of the micromachining process. The quality was quantified with the shape deviation $D_a$ and surface roughness $S_a$ as defined in [8]. The productivity was quantified by calculation of the ablation rate $V_t$, which is the removed material volume per processing time including auxiliary process times, e.g. calculations of the depth-control system. The micromachined surfaces and the surface structures were additionally characterized using a laser scanning microscope (LSM) and scanning-electron-microscopy (SEM). The wetting behaviour on different surfaces was characterized by measurement of the contact angle $\theta$ of deionised water with a camera-based contact angle measuring device.

3 Removal of support structures and fabrication of smooth surfaces with high accuracy

The support structures on the parts were removed using OCT-controlled laser micromachining with the setup as described in Figure 1. The target depth was set to 100 µm below the surface of the actual part in order to completely remove the excess material from the support structures. The maximum average power of 13 W was used for fast removal of the support structures at a peak fluence of $\Phi_0 = 20.2$ J/cm². The pulse distance in and perpendicular to the scanning direction was kept constant at 15 µm, which corresponds to a pulse overlap of 74%. This was achieved by using a feed rate of $v_x = 750$ mm/s and a hatching distance of $p_y = 15$ µm. The axial focus position of both beams was set on the top surface of the support structures. The moving average of 50 measurements of the ablation rate $V_t$ as a function of the number of passes over the sample surface is shown in Figure 3. Two distinct regimes can be identified. The first regime lasts until approximately 67 passes. Within the first regime, the excess material adhering to the support structures and parts of the support structures were removed, which led to a drop of the ablation rate from 3.2 mm³/min to 0.6 mm³/min after 67 passes. As there was no material volume between the excess material and the part underneath, the ablation rate in this regime was artificially enhanced. In the second regime from 68 to 400 passes, the ablation rate gradually decreased, as more and more locations reached the target depth and were not further processed.
After OCT-controlled micromachining for 400 passes over the sample surface, the support structures were completely removed from the sample surface. An SEM image of the resulting surface (left) and the deviation of the OCT-measurement to the targeted flat topography (right) are shown in Figure 4.

Large cones and holes can be seen in the SEM images in the inset of Figure 4 a), which is a well-known outcome of micromachining of metals with high peak fluences [4]. Furthermore, a lattice-shaped surface structure is visible on the sample surface with cavities of up to 100 μm depth between former support structure and samples surface. The cavities are deeper than the targeted ablation depth and presumably result from the reflection of the processing laser beam on the sidewalls of support structures. The formation of large cones and holes on the surface as well as the formation of the cavities on the sidewalls of the support structures yield a rather high surface roughness of $S_a = 33.7 \, \mu$m.

After removal of the support structures, the rough surface topography with large cones and holes was smoothed by additional micromachining with a lower peak fluence of $\Phi_0 = 1.9 \, \text{J/cm}^2$ for 2400 passes. The axial focus position was shifted on the surface of the part. The moving average of the ablation rate $V_t$ as a function of the number of passes over the sample surface is shown in Figure 5.
Figure 5. Ablation rate $V_t$ as function of the number of passes for OCT-controlled laser micromachining with $\Phi_0 = 1.9$ J/cm².

Again, a decrease of the ablation rate can be found in the beginning of the micromachining process until about 400 passes. From 400 to 1500 passes, the entire surface was machined as no location had reached the target depth yet and the ablation rate remained constant at $V_t = 0.12 \pm 0.1$ mm³/min. From 1500 to 2400 passes, the ablation rate gradually decreased, as more and more locations had reached the targeted depth of 600 µm below the initial surface and were not further processed. The cause of the enhanced ablation from 0 to 400 passes is currently unknown and subject to future investigation.

A SEM image of the resulting surface after OCT-controlled micromachining for 2400 passes over the sample surface (left) and the deviation of the OCT-measurement to the targeted flat topography (right) are shown in Figure 6. Even after smoothing the surface for 2400 passes, a fine lattice-shaped surface structure is still visible on the sample surface with cavities of up to 300 µm depth. The measured surface roughness reached an 81% reduced value of $S_a = 6.3$ µm compared to the roughness $S_a = 33.7$ µm measured after removal of the support structures.

Figure 6. a) SEM image of the surface topography and b) deviation of OCT-measurement to the flat target topography after OCT-controlled laser micromachining with $\Phi_0 = 1.9$ J/cm² and 2400 passes.

In addition, OCT-controlled micromachining enables the fabrication of geometries that are difficult to manufacture by LPBF, such as sharp contours, thin tips, and inclined surfaces. The complex target geometry used in this work and the corresponding challenges of each geometry are described in detail in [8]. After removal of the support structures as described in the beginning of section 3, the target geometry was fabricated using OCT-controlled laser micromachining with a peak fluence of $\Phi_0 = 1.9$ J/cm² and 3700 passes. A SEM image of the resulting surface (left) and the deviation of the OCT-measurement to the targeted complex geometry (right) are shown in Figure 7.
Figure 7. a) SEM image of the surface topography and b) deviation of OCT-measurement to the complex shaped target topography after OCT-controlled laser micromachining with $\Phi_0 = 1.9 \text{ J/cm}^2$ and 3700 passes.

High-quality geometries with the features of each shape well pronounced and a rather smooth surface for an inhomogeneous material such as LPBF-generated Ti6Al4V can be seen in the SEM-image in Figure 7 a). As seen in Figure 7 b), deviations of the OCT-measurement to the targeted complex geometry are caused by the steep edges of the stepped geometry in the top left and by the steep area of the half sphere in the bottom right. A mean shape deviation of less than 22 $\mu$m was calculated for each of the geometries. These small deviations can be caused by the micromachining process or measurement errors. The pyramid and cone in the bottom left and top right were fabricated with higher accuracy and a shape deviation of less than 12 $\mu$m. The mean shape deviation calculated across all geometries is low with $D_a = 16.3 \mu$m.

The investigations confirm the high potential of post-processing of additively manufactured metal parts by ultrashort laser pulses for removal of the support structures, smoothing the surface and fabrication of high-quality net shape geometries. In this work, the approach was demonstrated for parts made from Ti6Al4V powder, but can be transferred to other metals and surface conditions, as long as the OCT-based depth measurement system is able to detect the excess material and as long as the used peak fluence is higher than the material-specific ablation threshold fluence. For the application in an industrial environment, the productivity and therefore the ablation rate must be significantly enhanced to remove the support structures within a reasonable period of time. This can be achieved with the power scaling of ultrashort pulse lasers into the kW range and the development of micromachining strategies for high machining productivity while maintaining high surface quality [10]. Furthermore, the ablation rate during selective removal in the later stage of the OCT-controlled ablation process can be increased when the auxiliary times are reduced, e.g. with a scanning path optimization as shown in [11].

**4 Defined wetting behavior by surface structuring**

The same laser system and processing setup can be used for additional manufacturing processes, e.g., functionalization of the sample surface with a defined wetting behavior. To demonstrate this capability, different original surface states were fabricated before the surface structuring process by mechanical polishing one half of the parts. The other half of parts without any mechanical pretreatment was used “raw” as a reference. Mechanical polishing significantly reduced the roughness from $S_a = 12.1 \mu$m of the raw surface shown in Figure 2 c) to $S_a = 0.1 \mu$m. Subsequently, the parts were laser surface structured in one pass with a peak fluence of $\Phi_0 = 0.8 \text{ J/cm}^2$ and a hatching distance of $p_y = 24 \mu$m with different feed rates of $v_x = 1000 \text{ mm/s}$ and $v_x = 100 \text{ mm/s}$. SEM images of the resulting surfaces are shown in Figure 8.
Structuring with a feed rate of $v_x = 1000$ mm/s yielded a surface covered with fine ripples. The ripples were superimposed on the rough surface topography of the raw part, even on the non-melted powder grains (Figure 8 a). The roughness after structuring remained in the range of the raw part with $S_a = 9.2$ µm. Mechanical polishing of the part before structuring with $v_x = 1000$ mm/s yields a homogeneous surface structure (Figure 8 c) and low roughness $S_a = 0.6$ µm. Structuring with a lower feed rate of $v_x = 100$ mm/s resulted in a surface covered with rough spikes. The spikes were partially superimposed on the initially rough surface topography of the raw part. The non-melted powder grains were again covered with ripples (Figure 8 b). By superimposing the rough spikes on the rough surface topography of the raw part, the surface roughness was increased to $S_a = 14.5$ µm. Mechanical polishing of the part before structuring with $v_x = 100$ mm/s resulted in a homogeneous distribution of the spikes (Figure 8 d) and increased roughness $S_a = 3.3$ µm compared to the roughness of the polished surface of $S_a = 0.1$ µm.

The wetting behavior on the different surfaces was characterized with the sessile drop technique by measurement of the contact angle $\theta$ of deionised water after storing the samples in ambient atmosphere for 180 days. A commercial, camera-based measuring device with a frame rate of 25 Hz was used to record the time-dependent wetting behaviour of water droplets with a volume of 0.5 µL over a period of 20 s. The measured contact angle as a function of the time after drop application is shown in Figure 9.

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The mechanically polished part showed to an initial contact angle of $\theta = 73^\circ$ that slightly decreased over time to $\theta = 65^\circ$ (grey triangles). The initially hydrophilic wetting state of additively manufactured parts was observed before [12], however, without consideration of the short-term behavior after application of the drop. The structured polished parts with fine ripples (green triangles) showed a hydrophobic wetting state within the investigated time with a maximum contact angle of $\theta = 114^\circ$ after 20 s. The surface covered rough spikes (red triangles) showed an even higher contact angle of $\theta = 128^\circ$ after 20 s.
Figure 9. Measured contact angle $\theta$ as a function of time after application of a droplet with a volume of 0.5 $\mu$L for different surface topographies.

Further increase of the contact angle for a superhydrophobic behavior of additively manufactured parts can be achieved, e.g. with laser processing in ethanol as shown in [12]. The change of the wetting behavior from hydrophilic without surface structures to hydrophobic with surface structures is a result from the combined effect of surface morphology and surface chemistry and is explained in detail in [13]. The raw part without surface structures showed a time-dependent wetting behavior with a contact angle of $\theta = 79^\circ$ directly after application of the drop (grey squares). Over time, the fluid spreaded over the sample surface with a superhydrophilic wetting state of $\theta \approx 0^\circ$ after about 10 s. The structured raw parts with ripples (green squares) and spikes (red squares) showed a hydrophobic wetting state directly after application of the drop with contact angles of $\theta = 105^\circ$ and $\theta = 102^\circ$, respectively. The contact angles of both surfaces then quickly decreased in the hydrophilic range <90$^\circ$. The time-dependent major decrease of the measured contact angle of the raw part is presumably caused by the large initial roughness of the raw part and is subject to future investigation.

5 Conclusion

In summary, we presented post-processing methods for LPBF-generated Ti6Al4V parts based on OCT-controlled laser micromachining and surface structuring with ultrashort laser pulses that can be used for removal of support structures, smoothing the surface, fabrication of complex geometries and generation of a hydrophobic wetting behavior. By OCT-controlled laser micromachining the block support structures with a wall distance of 700 $\mu$m and wall height of 800 $\mu$m were completely removed using the maximum average power of 13 W, which corresponds to a peak fluence of $\Phi_0 = 20.2$ J/cm$^2$. Large cones and holes resulted in a high surface roughness of $S_a = 33.7$ $\mu$m after removal of the support structures, which was subsequently smoothed with OCT-controlled micromachining at a peak fluence of $\Phi_0 = 1.9$ J/cm$^2$ for 2400 passes, resulting in a reduced roughness of $S_a = 6.3$ $\mu$m. The fabrication of very small complex geometries that are difficult to manufacture by LPBF, such as sharp contours, thin tips, and inclined surfaces was achieved by OCT-controlled micromachining with a low mean shape deviation of $D_a = 16.3$ $\mu$m. Finally, the generation of advanced functionalities on LPBF-generated parts was demonstrated using surface structuring with ultrashort laser pulses, which resulted in the formation of ripples and spikes on the surface. Structuring at a low feed rate of $v_x = 100$ mm/s of mechanically polished parts led to the homogenous formation of spikes on the surface, resulting in a hydrophobic wetting state with a contact angle of $\theta = 128^\circ$. 
Future work will include further smoothing of the surface after OCT-controlled micromachining, e.g. by laser polishing [14], to be able to omit the mechanical polishing step before surface structuring for subsequent hydrophobic wetting behavior.

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