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Novel strategy for quality improvement of up-facing inclined surfaces of LPBF parts by combining laser-induced shock waves and in-situ laser remelting

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Abstract

Insufficient surface quality is one of the common issues encountered in laser powder bed fusion (LPBF). In order to meet the industrial requirements, it is typically necessary to proceed to expensive and time-consuming post-processing. Improving surface quality during the building process would hence be very beneficial. However, in-situ remelting (laser polishing) is possible only for horizontal up-facing surfaces. The quality of inclined surfaces remains limited to the as-built state, as after building they are covered with loose powder, excluding the possibility for in-situ polishing. This work presents a novel strategy to improve the quality of up-facing inclined surfaces using a dual-laser setup with a continuous wave and a pulsed laser. This approach consists in two steps: after building, the powder is selectively removed from the inclined surfaces using shock waves generated by a nanosecond pulsed laser. These newly exposed surfaces can be subsequently remelted with a continuous wave laser or alternatively treated with a pulsed laser. This paper discusses various scanning strategies for selective powder removal, their efficiency and the surface quality of the treated parts. The initial results are promising and indicate that the surface texture of LPBF parts in maraging steel 300 can be significantly improved for surface inclinations up to 45°, provided a sufficient powder removal efficiency is reached. The latter was found to be dependent on the maximal depth and volume of the powder to be removed, but also on part geometry.

Keywords: laser powder bed fusion, surface quality, staircase effect, laser-induced shock waves, maraging steel 300

1. Introduction

Laser powder bed fusion (LPBF) is an additive manufacturing technique, consisting in depositing fine layers of metal powder which are scanned by a laser, creating thus the desired solid cross section by selectively melting it. It is often used for its ability to produce highly customized parts with a high performance-to-weight ratio. This potential could be used in high-end applications e.g. in aircraft, medical or mold making industry (DeRoy et al., 2018).

Inclined up-facing surfaces represent a non negligible challenge, as their surface texture is typically higher compared to horizontal or vertical surfaces. According to Strano et al. (2013), this is mainly due to the part discretization into layers (staircase effect) combined with elevated edges on top of the stairs (edge effect). Industrial applications frequently involve demanding requirements in terms of surface texture and dimensional accuracy (Leach et al., 2019), therefore LPBF parts need to be almost systematically post-processed.

As discussed by Elangeswaran et al., surface quality has a significant impact on fatigue life of components, as investigated for 316L stainless steel (2020) as well as for maraging steel 300 (2019) used in the present study. The surface quality can be improved by mechanical, chemical or laser-based post-processing. Various finishing techniques were reported in the literature for surface quality increase of LPBF parts: Hintze et al. (2020) milled the parts, Bouland et al. (2019) used abrasive flow machining, Anilli et al. (2018) applied a combination of electrochemical machining and abrasive flow machining, Bai et al. (2020) used ultrasonic vibration-assisted machining and Van Hooreweder et

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al. (2017) used chemical etching. Laser-based post-processing is also often reported. Bhaduri et al. (2017) provided a comprehensive study on the influence of pulsed laser polishing on the final surface quality, and Alrbaey et al. (2014) provided a similar study using a continuous wave laser.

Post-processing can significantly increase surface quality of LPBF parts, but it increases manufacturing cost and time: among others, the part needs to be transferred to the post-processing machine and the coordinate system needs to be re-aligned. Increasing surface quality during the building process would hence be very beneficial. Some researchers presented hybrid setups combining LPBF with in-situ mechanical machining. A solution with milling was presented by Wüst et al. (2020) and a similar one was also reported by Du et al. (2018). Colosimo et al. (2020) also discussed a solution including grinding. However, the presence of metal chips from the machining process might be a quality risk for the powder bed homogeneity. Alternatively, laser-based processing such as in-situ remelting of horizontal up-facing surfaces can take place during the building phase without significantly affecting the quality of the powder bed (Yasa and Kruth, 2011). Other researchers also explored the option of in-situ machining of vertical walls using a femtosecond (Ghosh et al., 2018) or a nanosecond laser (Yasa et al., 2011). The quality of inclined up-facing surfaces is, however, limited: in-situ remelting is impossible as they are covered by loose powder excluding the option of laser polishing during the LPBF process.

Laser ablation has been reported as a suitable technique for increasing dimensional accuracy of components (Hallmann et al., 2015) or for surface functionalization (Kumari et al., 2015). It is a subtractive photo-thermal process, during which energy from high intensity laser pulses is absorbed by solid material and transformed into heat. Depending on the pulse duration and other process variables, different types of laser-matter interaction dominate the material removal. In case of short laser pulses (microsecond to nanosecond range), the heated target material is melted, followed by its vaporization if the liquid-vapor critical temperature is exceeded (Elsied, 2018). Subsequently, the metal vapor can be ionized by the remaining laser pulse, resulting in a plasma plume.

The laser ablation process is typically accompanied by generation of shock waves. As stated by Harilal et al. (2013), a first shock wave is induced at the stage of the vaporized material detachment from the target surface. A second shock wave is created during plasma plume explosion. The hot plasma presents a severe thermal discontinuity which by expansion produces a strong pressure wave.

A theoretical background for laser-induced shock waves is given by the point strong explosion theory originally developed for blast waves in nuclear explosions. This theory describes a release of a high amount of energy during the explosion in a negligible time and volume. The expansion is assumed to be adiabatic, which leads to a purely dimensional approach. The resulting shock wave is propagating radially to the origin of explosion, until its pressure reaches the ambient pressure (Chiba, 2017). Pioneering works on the point strong explosion theory of Bethe et al. (1947), Taylor (1950) and Sedov (1946) were recently summarized and put in context of shock waves in laser-induced plasma by Campanella et al. (2019).

Most of the applications of laser-induced shock waves include laser shock peening (Ding and Ye, 2006), which is a versatile tool used also for microstructure tailoring (Kalentics et al., 2019). Moreover, laser-induced shock waves were reported for film deposition methods or adhesion tests (Li et al. 2004), but also for foil forming (Nagarajan et al., 2013) and laser induced breakdown spectroscopy (Campanella et al., 2019).

In the context of LPBF, many authors such as O'Neill et al. (1998), Morgan et al. (2001) or Fischer et al. (2002) reported shock waves as an undesired by-product of pulsed laser processing. Most of these studies were aiming to build dense parts using a pulsed laser. The part quality achieved by Demir et al. (2017) or by Caprio et al. (2019) would be impossible if shock waves disturbed the surrounding powder bed.

The aim of this work is to intentionally generate strong shock waves during the LPBF process in order to remove powder from selected areas, such as inclined up-facing surfaces. The powder-free surfaces can be subsequently remelted in order to achieve a lower surface texture. The concept of selective powder removal followed by remelting was first presented by Metelkova et al. (2020). The authors investigated the effect of process parameters on the powder removal efficiency. They performed laser ablation with a pulsed laser on the top surface of cubic samples and observed the disturbance of the surrounding powder. In order to evaluate the 3D shape of the disturbed powder bed, a frame was built around the samples and the disturbed powder bed was scanned with a continuous wave laser within the frame limits. The macroscopic shape seems to be sufficiently well preserved for post-process measurements by confocal microscopy. The same authors also showed very promising results for powder removal from 5° inclined samples and their subsequent remelting.

This paper, on the other hand, explores various scanning strategies applied to surfaces with a slope angle up to

45°. It considers the powder removal efficiency and the impact on the surface quality of the manufactured part. The study investigates the part and scan vector orientation with respect to the gas flow direction, number of scans, focal plane offset and other more complex scanning strategies.

2. Experimental setup and methodology

The experiments were realized in a modified LPBF machine from 3D Systems (ProX DMP 320A), in which an additional pulsed laser was installed. The setup contains a single scanner and a flipping optic, enabling a consecutive use of both lasers.

The parts were built using a fiber laser with central wavelength of 1070 nm. The laser is operated in continuous wave (CW) mode, with a maximum output power of 500 W and a nominal spot size $d_{1/e^2} = 60 \mu\text{m}$.

Selective powder removal was carried out with a nanosecond Ytterbium fiber laser, operated in pulsed mode in the pulse duration range from 2-250 ns. It allows delivering high intensity pulses with a maximal average power of 50 W and a maximal pulse energy 520 μJ at 30 ns. The used wavelength is comparable to the CW laser, as well as the nominal spot size ($d_{1/e^2} = 50 \mu\text{m}$).

As illustrated in Fig. 1, the experimental methodology consists in the following steps: (1) sample manufacturing by LPBF, (2) removing powder from selected areas using shock waves induced by a pulsed laser, followed by either (3a) powder fixation in order to quantify the efficiency of the powder removal process, or (3b) surface remelting in order to improve the surface quality of the final product. All the experiments took place under inert argon atmosphere. The gas was delivered by a fan placed in front of the building zone.

(1) Building samples by LPBF

The main investigated sample geometry illustrated in Fig. 2a consists of a 6 mm wide block with a horizontal surface (HS) and an inclined surface (IS) with a slope angle $\alpha = 5^\circ$ or 15° . The IS length L is 15 mm for $\alpha = 5^\circ$, and 12 mm for $\alpha = 15^\circ$ (corresponding to $d = 1.3$ mm and 3.1 mm, respectively). At the end of this study, the method was applied also to other geometries, such as V-shaped prisms, a sample with a V-groove or a sinusoidal sample. The V-shaped prisms (Fig. 2b) have a constant inclination $\alpha = 15^\circ$, 30° or 45° and depth $d = 2$ –4 mm. The sample with a V-groove (Fig. 2d) is defined by $\alpha = 45^\circ$ and $d = 2$ mm. The sinusoidal sample (Fig. 2c) consists of two horizontal surfaces with a height step $d = 4$ mm, connected by a sinusoidal surface, gradually varying between 0° and 40° . Both samples design and building files preparation were done with the 3DXpert software from 3D Systems.

The material selected for this study was maraging steel 300, with a nominal particle size distribution 15–45 μm . The powder flowability was evaluated using a dynamic angle of repose test. The in-house made setup described by Van den Eynde et al. (2018) consists in rotating a drum containing the powder. The rotation speed was set constant to 3 rpm, the angle of repose was assessed at a frame rate 25 fps during 2 min. The "critical avalanche angle" refers to maximum angle just before sliding, and the "average angle of repose" refers to the arithmetic mean of all recorded avalanche angles.

Figure 1: Process flowchart of the experimental methodology.

Figure 2: Illustration of the sample geometry with slope angle α , length L and depth d . (a) main investigated geometry with horizontal surface (HS) and inclined surface (IS), (b) V-shaped prism, (c) sinusoidal sample, (d) V-shaped groove.

The samples were built at laser power $P=150$ W, scanning speed $v=1100$ mm/s, hatch spacing $h=70$ μm and layer thickness $t=30$ μm . The used scanning strategy was bidirectional hatching without contours, oriented 45° with respect to the gas flow direction, and with a 90° rotation between layers.

(2) Selective powder removal

The laser parameters for selective powder removal remained constant throughout the experiments, selected based on the results published by Metelkova et al. (2020). The pulsed laser was set to average power $P=42$ W, pulse repetition rate $PRR=100$ kHz, pulse duration $\tau=30$ ns and scanning speed $v=500$ mm/s, resulting in a pulse energy $E_p=420$ μJ and pulse-to-pulse distance $d_p=5$ μm . Four scanning configurations were investigated, illustrated in Fig. 6 (Configuration I-IV): scanning along or against the gas flow, as well as scanning "downstairs" (starting on HS) or "upstairs" (starting on IS in the loose powder). The scanning direction, hatch spacing h , number of scans N , and focal plane offset (defocus) Δf were varied throughout the study. As the system has a fixed position of the focal plane, the focal plane offset was realized by manually moving the build platform upwards. In this way the focal plane is set below the top horizontal surface (HS).

(3a) Quantification of the powder removal efficiency

To quantify the powder removal efficiency, an additional process step was implemented. This step, referred to as "powder fixation", serves to preserve the macroscopic shape of the disturbed powder bed (Fig. 3f) for subsequent ex-situ measurements with an optical microscope. For this purpose a frame is built together with the part (Fig. 3a,b). After the powder removal step using pulsed laser (Fig. 3c,d), the inside of the frame is scanned with the CW laser (Fig. 3e) to fix the shape of the disturbed powder bed. The powder fixation step follows immediately after the powder removal.

The suitable powder fixation procedure as reported by Metelkova et al. (2020) consists in two consecutive scans under 45° with respect to the gas flow direction, perpendicular to each other. Both are at $P=100$ W and $h=40$ μm , but different scanning speed ($v_1=1500$ mm/s, $v_2=1300$ mm/s). The double scanning allows a reasonable balance between the fragility and a sufficient shape preservation.

The sample surface was characterized with a 3D digital microscope Keyence VHX-6000. First, a slope correction was applied to the inclined surface (Fig. 4a). As illustrated in Fig. 4b, the cleaned area was evaluated either as the largest rectangular area as wide as the part (A_R) or based on the contour of the cleaned zone (A_C). The ratio of the cleaned area (A_R or A_C) to the total area of the inclined surface (A_{total}) gives the powder removal efficiency parameters η_R and η_C , respectively, as defined in Eq. 1.

$$\eta_R = \frac{A_R}{A_{total}} \cdot 100\%, \quad \eta_C = \frac{A_C}{A_{total}} \cdot 100\% \quad (1)$$

Figure 3: Illustration of the powder fixation process necessary for ex-situ quantification of the powder removal efficiency. (a) CAD model with a horizontal surface (HS), an inclined surface (IS), and a frame for powder fixation, (b) parts and their frame after the building process, (c) selective powder removal using laser-induced shock waves, (d) powder-free inclined surface, (e) fixation of the disturbed powder bed, (f) sample prepared for ex-situ measurements.

Figure 4: Evaluation of the powder removal efficiency. a) slope correction, (b) rectangular (A_R) and contour area (A_C) evaluation.

Figure 5: Process variation as a function of the part position. (a) graphical representation, (b) top view on a typical base plate layout. Surface inclination $\alpha=15^\circ$, process parameters $h=40\ \mu\text{m}$, $\Delta f=0\ \text{mm}$, $N=5$, scanning direction downstairs with the gas flow (configuration IV).

(3b) Surface quality improvement

After optimizing the powder removal efficiency, the goal for the final product is to proceed to the surface remelting step using CW laser. In order to increase the evaluated surface, the sample width was increased to 8 mm. Four consecutive scans under 45° were applied, with a 90° rotation in between, at $P=100\ \text{W}$, $v=700\ \text{mm/s}$ and $h=35\ \mu\text{m}$. As the optical system has a static focal plane, it was set in the middle of the scanned area by manually moving the platform (e.g. for a height difference $d=4\ \text{mm}$, $\Delta f=-2\ \text{mm}$).

The surface quality in the as-built state, after ablation or remelting was assessed using a tactile profilometer Mitutoyo Formtracer CS3200 equipped with a 60° conical probe ended by a $2\ \mu\text{m}$ tip radius. On each surface, 50 profiles 10-mm long spaced by $60\ \mu\text{m}$ were acquired, parallel to the longer dimension of the evaluated surface. On each profile, the arithmetic mean height P_a was evaluated according to ISO 4287, without applying any filtering. Selected surfaces were also analyzed with a confocal microscope Sensofar S-Neox over a $3\times 3\ \text{mm}$ area.

3. Results

3.1. Powder removal repeatability

Removing powder from an inclined surface can involve relocation of a large amount of powder. As the powder can be entrained by the argon gas flow, the influence of the part position on the powder removal efficiency should be investigated. Fig. 5b shows a typical layout used in this study, with 6 identical parts arranged in a 2×3 matrix and having a surface inclination $\alpha=15^\circ$. The powder was removed in the same way for all parts, starting on the horizontal surface (HS) and scanning parallel to the stair edge, downwards on the inclined surface (IS) along with the gas flow direction (illustrated in Fig. 6b).

As shown in Fig. 5, a larger cleaned area was observed for the front row, closer to the argon gas flow origin. This can be explained by particle entrainment by the gas flow, as the particle pick-up speed will possibly decrease with distance from the fan distributing the gas.

The rectangular removal efficiency η_R seems to be relatively little influenced by the part position (Fig. 5), the difference between the front and the back row being about 5%. However, the results show a distinction between the rectangular and contour efficiency, as the difference between the rows for η_C is about 20%. η_R characterizes an area where a stable powder removal process was performed. η_C , on the other hand, shows the actual cleaned area. The difference between η_R and η_C can be also an indicator of instabilities during the powder removal process, meaning powder collapsing back on the already cleaned surface.

For the remaining of this study, η_R is considered to be the primary criterion, as it is a more practical information for further in-situ processing, but also it is less affected by the process instabilities. It has a lower process variability, as

Figure 6: Effect of the scanning direction and part orientation with respect to the gas flow, (a) graphical representation, (b) illustration of the scanning strategy parallel to the staircase with gas flow downstairs (configuration IV). Surface inclination $\alpha=5^\circ$, process parameters $h=343 \mu\text{m}$, $\Delta f=0 \text{ mm}$, $N=1$.

Figure 7: Effect (a) of the number of scans N fitted with a logarithmic trend line (with $\Delta f=0 \text{ mm}$), and (b) effect of the focal plane offset (defocus) Δf fitted with a second degree polynomial trend line (with $N=5$). Surface inclination $\alpha=15^\circ$, process parameters $h=40 \mu\text{m}$, scanning direction downstairs with the gas flow (configuration IV).

the repeatability job resulted in average efficiency $\eta_{R,avg} = 49.2\% \pm 3.2\%$ and $\eta_{C,avg} = 64.9\% \pm 11.2\%$. Moreover, the reproducibility between jobs was evaluated on a 15° inclined part built with identical parameters and on the exact same location as part 6 from Fig. 5b. It resulted in 3.2% difference between the two repeats ($\eta_{R,1} = 53.0\%$, $\eta_{R,2} = 56.2\%$), considered sufficient for the study. This evaluation method is relatively time-consuming, therefore all the samples could not be produced multiple times.

3.2. Effect of the scanning direction and part orientation with respect to the gas flow

As illustrated in Fig. 6, four distinct cases of scanning direction and part orientation with respect to the to gas flow were investigated: scanning (I) against gas flow upstairs, (II) against gas flow downstairs, (III) with gas flow upstairs and (IV) with gas flow downstairs. In all four cases the scan vector orientation was parallel to the stairs edge and the "scanning direction" refers to the consecutive order of scanning vectors. "Downstairs" implies scanning first on the horizontal surface and then progressively removing powder from the inclined surface, "upstairs" means that the scan path starts in the loose powder and ends on the solid part surface.

The results presented in Fig. 6a confirm the above mentioned effect of the gas flow. When scanning parallel to the stair edge, the order of scanning along the gas flow direction leads to a significantly higher powder removal efficiency. The largest amount of powder is removed when scanning with gas flow and downstairs (configuration IV). When scanning downstairs, first the solid part surface is ablated, leading to a very efficient powder removal.

Discretizing inclined surfaces into layers leads to a stair-like manufactured surface. In the case of $\alpha=5^\circ$ divided into layers with thickness $t=30 \mu\text{m}$, the stair width $w=t/\tan(\alpha)=343 \mu\text{m}$. In the initial stage of this study, the hatch spacing h was selected with respect to the stair width: when scanning parallel to the stair edge, at $h=343 \mu\text{m}$ each stair is scanned only. However, after one scan the full powder removal efficiency was not achieved for $\alpha=5^\circ$ and had only a little effect on parts with higher inclinations. Decreasing hatch spacing was reported to considerably improve the powder removal efficiency, and as suggested by Metelkova et al. (2020) for further experiments h was set to $40 \mu\text{m}$. This led to the entire 5° surface cleaning ($\eta_R=100\%$), even in case of the least efficient configuration (I) reaching only $\eta_R=51.7\%$ at $h=343 \mu\text{m}$.

3.3. Effect of the number of scanning passes

In order to investigate the effect of the number of scanning passes, the samples were processed with the most convenient configuration (IV) from the previous section. As shown in Fig. 7a, the first pass removed only 4.1% (η_R) as a large amount of powder collapsed back on the surface. However, already the second pass significantly increased the cleaned area to 24.4% and kept increasing following a logarithmic trend until $N=20$ ($\eta_R=79.2\%$, corresponding to a maximal cleaned depth $d_R=2.4 \text{ mm}$).

Figure 8: Complex scanning strategies applied to $\alpha=15^\circ$. (A)-(G): Surface inclination, process parameters $h=40\ \mu\text{m}$, $\Delta f=0\ \text{mm}$, $N=5$.

3.4. Effect of the focal plane offset

The effect of the focal plane offset (defocus) was investigated up to 3 mm below the horizontal surface HS of the part (scanning configuration IV). As shown in Fig. 7b, the data points follow a second degree polynomial trend line with a maximum at -2.1 mm. Shifting the focal plane resulted in a considerable increase of the cleaned area. With only 5 scans at $\Delta f=-2\ \text{mm}$, 91.8% (η_R) of the inclined surface could be freed from powder, compared to 44.7% when in focus on HS.

3.5. Effect of more complex scanning strategies

Various scan strategies (A-G) illustrated in Fig. 8 were investigated for the 15° inclined parts. All the parts were scanned starting at the horizontal surface, progressively cleaning the inclined surface. The main difference between the applied scan strategies is the scan vector orientation (parallel, perpendicular or 45° with respect to the stairs edge) and the size of the scan blocks.

Fig. 8 shows that scanning parallel to the stair edge, either over the full sample width (A) or by shorter scan blocks (B) resulted in η_R up to 50%. The strategy of iterative steps into the deeper powder (C) led to a significant increase of the cleaned area (68.3%). Perpendicular scanning with respect to the staircase resulted in an even higher removal efficiency, 80.9% and 75.0% for standard (D) and iterative steps (E), respectively. Iterative scanning by blocks seems to be an interesting alternative to the full-part parallel scanning. It helps limit powder collapsing, as the starting zone is well cleaned before moving to the next one. However, perpendicular iterative scanning did not exceed the efficiency of the standard strategy. The efficiency η_R after scanning under 45° to the stairs (F,G) led to results comparable to the parallel iterative steps (60-65%). The aim of vector rotation by 45° was to push the powder not only forward, but also sideways, which could reduce the amount of powder to be moved in the following pass. The vector rotation as well as the rotation between the scanning passes does not seem to influence significantly the outcome.

Based on the results presented in Figs. 6-8, the following powder removal strategy will be used in the next sections: the scanning strategy D (standard scanning perpendicular to the stairs) with $h=40\ \mu\text{m}$, $N=5$ and the focal plane offset Δf set to 2 mm below the horizontal surface HS.

Figure 9: Influence of the powder removal process on the final surface texture of a sample with $\alpha = 5^\circ$. (a) graphical representation, (b) as-built surface, (c) after powder removal ($N=20$), (d) after four remelting passes. (e-g) correspond to (b-d) after slope correction, respectively.

3.6. Effect of the powder removal strategies on the surface quality

Fig. 9a shows that the surface texture with 5° inclination significantly increases with number of powder removal passes. The arithmetic mean height of the unfiltered profile P_a increases from $15.0 \mu\text{m} \pm 1.3 \mu\text{m}$ for the as-built part (Fig. 9b,e) up to $27.4 \mu\text{m} \pm 2.5 \mu\text{m}$ after 20 ablation passes (Fig. 9c,f). With increasing number of scans, the surface seems to be partially smoothed, but also large spherical particles can be observed on the surface, especially in the vicinity of the stair edge (Fig. 9c). These particles can be related to the pulsed laser interaction with the powder to be removed. Nevertheless as the number of particles is increasing with increasing number of ablation scans, they are more probably spatters expelled from the interaction zone by the shock wave pressure.

The texture of the inclined surface after four remelting passes was considerably improved (Fig. 9d). Even after 20 powder removal passes followed by the remelting step, a P_a of $6.4 \mu\text{m} \pm 0.8 \mu\text{m}$ could be reached, corresponding to a 58% improvement compared to the reference as-built state, and 77% improvement compared to after powder removal. Against the expectations, the final texture of the 5° inclined surface does not seem to be significantly affected by the initial surface quality (Fig. 9a). The average texture after remelting $P_a=6.8 \mu\text{m} \pm 0.5 \mu\text{m}$ does not indicate an important difference between the lowest and highest initial texture, meaning after powder removal by manual brushing (no ablation) and 20 pulsed laser scans. As shown in Fig. 9g, the major contributor to the surface texture after remelting is its long-wavelength components (waviness), comparable to the waviness of the as-built surface.

The impact on the surface texture was investigated on samples with 5° inclination, with the focal plane set to the middle, resulting in a maximal defocusing of $650 \mu\text{m}$. It is possible that at higher degree of defocusing, the initial surface texture would have a more significant effect. An alternative to the used setup would be a setup equipped with an active defocusing device following surface slope. It would allow maintaining a constant laser spot size, as a large spot size variation can modify the melt pool behavior (Metelkova et al., 2018). However, in this study, horizontal surfaces ablated and remelted at a $\Delta f = -2, 0$ and $+2 \text{ mm}$ led to a little difference in P_a , which can be as well related to the process variability and influence of part position on the base plate.

4. Discussion

4.1. Powder removal instabilities

The powder removal process can become unstable due to collapsing of the surrounding powder on the already cleaned surface. This occurs in particular when increasing the cleaned depth and volume. If the slope of the powder accumulated around the treated zone reaches a critical angle, it induces an avalanche-like reaction, starts to slide back towards the cleaned area and brings down more particles. A dynamic flowability test in a rotary drum was performed for the powder used in this study. The average observed repose angle was $31.1^\circ \pm 4.5^\circ$, and the critical avalanche angle was $36.5^\circ \pm 2.9^\circ$. In the case of powder moved by laser-induced shock waves, the powder is not rotating but rather

pushed with each scan in a wave-like movement, visible by naked eye. Nevertheless, an avalanche angle in a similar range as in the dynamic flowability test is to be expected also during the powder relocation using shock waves.

The powder removal instabilities are also influenced by the gas flow. As shown in Fig. 5b, there is a difference of the cleaned area shape as a function of the sample distance to the gas flow origin (detailed view provided in Fig. 10). The cleaned area of the samples in the back row has a V-shape (Fig. 10a), sign of a dominating powder collapsing by sliding. However the cleaned area of the samples in the front row have rather an Ω -shape (Fig. 10b) which might be explained by the interaction of the shock waves with a gas flow, leading to possible turbulences. As the effect of the gas flow is stronger in the front row, a larger powder volume can be lifted at a considerable height, especially during deep scanning. This can increase the removal efficiency, but the powder can be also entrained in the turbulent flow, and redeposited on the already cleaned surface.

4.2. Effect of the process parameters on the powder removal efficiency

The powder removal efficiency depends on many factors, one of the most evident ones is the number of scans N . The cleaned area is increasing with N , nevertheless, it is expected not to increase infinitely. In the case presented in Fig. 7a, the maximum efficiency will be probably slightly above 80%. With the first few scans, a large amount of powder is blown away, leading to a strong increase of the cleaned area and depth. However, due to the nonlinear energy and speed distribution, the shock wave appears to be weaker with distance from the origin. According to the Sedov-Taylor point strong explosion theory (Sedov, 1946, and Taylor, 1950), the speed of a shock wave v_{shock} starts at a maximum value and decreases with time following Eq. (2) with E_0 released energy, ρ_0 unperturbed gas density and $K(\gamma)$ constant depending on the adiabatic coefficient of the gas. Therefore, at a given combination of process parameters, a maximal distance where powder can be blown away can be experimentally determined, and further scans do not lead to a significant improvement.

$$v_{shock}(t) = \frac{2}{5} \left(\frac{E_0}{K(\gamma) \cdot \rho_0} \right)^{1/5} \cdot t^{-3/5} \quad (2)$$

The effect of the defocusing Δf is less straightforward compared to the number of scans. By moving the focal plane below the top horizontal surface, the efficiency increases as the laser beam waist moves to the zone of a deeper powder volume (Fig. 7b). Smaller spot size results in higher intensities and possibly larger plasma plumes, leading to stronger shock waves. When shifting the focal plane further downwards, the strong shock waves might blow the deep powder back on the already cleaned surface, via the effect of the turbulent gas flow explained above. In the extreme case of an overly large focal plane offset, the intensity in the upper region can even get insufficient to induce strong shock waves. The defocusing limitations could be overcome by using a dynamic focusing unit instead of a static focal plane setup, in order to keep the laser beam permanently in focus. Moreover, defocusing by manually moving the

Figure 10: Detail on the parts from the repeatability study (position 6 from Fig. 5b): (a) V-shaped (position 3 from Fig. 5b) and (b) Ω -shaped cleaned area.

build platform is not a suitable solution for an industrial application. In addition, a large shift of the platform upwards can also create a shadow for the gas flow.

Hatch spacing has also a considerable effect, by changing it from $h=343\text{ }\mu\text{m}$ to $40\text{ }\mu\text{m}$ the efficiency could be almost doubled. By decreasing hatch spacing, the total number of pulses increases, as does the number of induced shock waves. Metelkova et al. (2020) also observed that the hatch spacing has a significant influence for disturbing powder around a horizontal surface. The authors noted that for $h < 40\text{ }\mu\text{m}$ a plateau was reached and the disturbance was not further increasing. However in case of inclined surfaces, this plateau might not be valid anymore. In the future research, further optimization of parameters such as h might thus lead to even higher efficiency.

Besides the distance to the gas flow origin, number of scans, focal plane offset and hatch spacing, other parameters investigated by Metelkova et al. (2020) were proved to have a significant impact on the powder removal efficiency, such as pulse energy E_p , pulse-to-pulse distance d_p or pulse duration τ .

4.3. Ablation of powder or bulk material

Fig. 6a shows that upstairs or downstairs scanning direction with respect to the surface inclination has a considerable impact on the cleaning efficiency. Scanning downstairs involves starting on the sample surface. It was observed that ablation of bulk material leads to stronger shock waves compared to starting scanning in loose powder. It seems that bulk ablation is accompanied by higher process temperatures, as can be witnessed by a higher intensity white-blue light in Fig. 11a compared to the yellow-orange light in Fig. 11b. This might be related to the presence of voids between powder particles, but also to their unconstrained movement.

The voids between the particles lead to less material available for ablation, plasma formation and shock wave generation in the beam interaction zone. Sinico et al. (2019) reported an apparent density of $52.3\% \pm 0.3\%$ compared to the bulk material density, analyzing the same material and particle size distribution. In addition, the argon gas present in the voids can reduce the heat transfer to the surrounding particles and the heat can be partially removed with the gas flow. In contrast, the solid substrate can more easily accumulate heat, acting as a pre-heating for the following pulses.

Fig. 11b shows that due to the unconstrained particle movement, they can be easily ejected by the shock waves in form of spatters during the interaction with the laser beam or even before the interaction itself. Also, the mechanisms of shock wave propagation might be different. The solid part surface acts probably as a confinement, therefore the shock waves can not propagate spherically but hemispherically. Instead of propagating downwards, half of the shock wave slides along the solid surface, steering the motion of the particles previously lying on the surface or surrounding the interaction zone. On the other hand, loose powder particles can be moved in all directions and the energy of the shock wave can be dampened out by radial motion of the powder particles. Moreover, the powder can be compacted in the vertical direction instead of a lateral movement promoting an efficient powder removal.

The difference in efficiency when ablating bulk or powder material can also explain the difference between parallel and perpendicular scanning. In parallel scanning, first only a small amount of powder needs to be removed, leading to an efficient bulk ablation. But as the powder volume is gradually increasing, the powder depth can become too large as the removed powder is moved on top of the initial powder volume (Fig. 11c). On the other hand, with perpendicular scanning, if the first scans in the deep powder can open the way to the solid substrate, an efficient ablation can occur in the deep powder, enabling a better cleaning (Fig. 11d). However, if the powder is not removed even after multiple scans, melting can occur instead of ablation. This undesired case has a strong negative impact on the surface quality and geometrical precision of the final product.

Figure 11: Difference in ablation of (a) bulk and (b) powder material and illustration of (c) parallel and (d) perpendicular removal strategy with respect to the involved powder volume.

4.4. Proof of concept: application to various geometries

In the last step of the study, the powder removal technique was applied to various sample geometries (Fig. 2), such as V-shaped prisms with inclination $\alpha=15^\circ$, 30° or 45° ($d=2-4$ mm), samples with a 45° V-groove ($d=2$ mm), or a sinusoidal sample with a 4 mm height step and continuous angle variation $\alpha=0^\circ-40^\circ$. The powder was removed using the scanning strategy D with $h=40\mu\text{m}$, $\Delta f=-2$ mm and $N=5$. After selective powder removal, all the samples were remelted with four CW passes, leading to a significant increase in quality of many investigated samples (Fig. 12). Some samples could be cleaned entirely, such as 15° V-shaped prisms (Fig. 12b) or samples with V-shaped grooves (Fig. 12a). Especially the sinusoidal sample with a height step of 4 mm was unexpectedly well processed. Its surface quality was significantly improved, except for a small quantity of unremoved powder in the corner, which was welded to the surface by remelting (Fig. 12b). Similarly, a small quantity of powder attached on the surface was observed also for the 15° block (Fig. 12c), despite a lower depth ($d=3.1$ mm) and lower powder volume (about 44% compared to the sinusoidal sample). In this case the removal efficiency might be affected by an increased avalanche effect due to the steep slope in the middle area of the sinusoidal surface ($\alpha_{\text{max}} = 40^\circ$). On the other hand, the 45° prisms showed only a limited improvement of the surface texture, surface roughness was visibly improved but a waviness appeared on the surface (Fig. 12c). This may be related to the steep slope angle and a high initial roughness. These observations might insinuate that not only depth, inclination and volume have a strong influence on the powder removal efficiency and process limits, but also the overall sample geometry.

Surface texture of all samples up to 45° could be improved. However, when crossing the process limitations, undesired features can be created by melting the powder covering the lower areas of the treated surface (Fig. 8c,d). This effect can be more or less pronounced, depending on the amount of powder remaining on the surface. Therefore the process should be first properly optimized to ensure a complete powder removal before proceeding to the remelting step. Increasing the number of powder removal scans or combining scanning strategies might be a suitable solution.

Regarding the processing time, a single ablation pass takes about 5.6 s, a single remelting pass takes about 7.8 s and the switching time between the two lasers takes about 10 s. The additional processing time caused by this methodology depends strongly on the part size and inclination: a simple 5° inclined part which can be cleaned using a single powder removal pass and remelted once, results in +33 s. Cleaning the 15° sample with five scans followed by four remelting passes takes about 79 s. The additional time is thus comparable to the scanning time for a single layer in the build job. As the entire build job takes typically several hours, this additional processing time seems almost negligible considering the surface quality gain. Either way, any post-processing would take a much longer time.

Using a static focal plane setup implies that at a high degree of defocusing the XY coordinates of the laser spot do not correspond anymore to the intended locations. As a matter of fact, the calibration is made for the in-focus position, so by defocusing the real position is offsetted as a function of the incident angle of the laser beam and distance to the center of the scanning field. In case of the present optical system, in the corners of the 90×90 mm base plate, a compensation about $55\mu\text{m}$ per millimeter of defocusing is needed. In order to achieve remelting of a precise shape, the CAD model dimensions should be adapted accordingly.

Figure 12: Application of the method on various sample geometries: (a) overview of the base plate with inclined blocks, V-shaped prisms, V-shaped grooves and a sinusoidal surface, (b) detail on a sinusoidal surface and $15-30^\circ$ V-shaped prisms, (c) detail on a 15° inclined block and prisms with higher inclination and depth, beyond the limits of the applied strategy, (d) detail on the powder remaining after the cleaning process and welded to the bottom of the inclined surface.

5. Conclusions

This work shows the potential of using shock waves induced by a nanosecond pulsed laser in order to in-situ improve the quality of inclined surfaces produced by LPBF. The proposed method consists in powder removal by shock waves and subsequent in-situ remelting of the inclined powder-free surfaces. This allows reducing the number of post-processing steps necessary to achieve the desired surfaces quality, within a time comparable to a single layer scanning. After four remelting passes, the arithmetic mean height of the unfiltered primary profile P_a could be reduced in average by 55%, from 15.0 μm in the as-built state to 6.8 μm after remelting.

The study investigates the efficiency of removing powder from selected areas of various sample geometries. Multiple scanning strategies were considered, including part and scan vector orientation with respect to the gas flow, number of scans and focal plane offset. Especially the latter showed a strong effect on the powder removal efficiency, as it allows reducing the number of scans, which limits the processing time and the impact on the surface quality.

It was shown that for a 5° inclined surface the number of ablation passes does not have a strong influence on the final surface quality after remelting. Even after 20 ablation passes leading to an increase of P_a from 15.0 μm to 27.4 μm , by four remelting passes it could be decreased to 6.4 μm .

The powder removal limits depend mainly on the depth, inclination angle, powder volume to be removed and sample shape. If the powder is not fully removed, it can be melted into a freeform structure and remain attached to the surface. This significantly deteriorates product quality.

The scanning strategy leading to the highest powder removal efficiency turned out to be scanning perpendicular to the stair edge. As a result, a part with a 15° inclination angle and maximal depth of 2 mm could be entirely cleaned and remelted. Also for example a part with a sinusoidal shape (maximal depth of 4 mm) involving a large powder volume could be cleaned almost entirely.

In order to further improve the powder removal efficiency, a dynamic focusing unit can be used instead of a static focal plane setup. This would also help overcome the imprecision of scan vector positioning due to the offset between the calibrated position with no focal offset and the actual location of laser-matter interaction.

This study is only a first step in investigating this technique, future research will focus on its application to other materials and part geometries, including further parameters optimization. Moreover, the approach will be studied with respect to mechanical properties such as fatigue behavior, which is highly sensitive to the surface quality.

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