

GHz-burst, Gaussian and Vortex Beam, Impact on Surface Morphologies for Melted Layer Generation

Théo Guilberteau^{1,2}, John Lopez¹, Laura Gemini² and Inka Manek-Hönninger^{1*}

¹Université de Bordeaux-CNRS-CEA, CELIA UMR 5107, 33405 Talence, France

²ALPhANOV, Rue François Mitterrand, 33400 Talence, France

*Corresponding author's e-mail: inka.manek-honninger@u-bordeaux.fr

Ultrafast laser polishing in burst mode provides a promising approach for controlling surface morphology through tailored temporal and spatial energy deposition. In this study, ultrashort pulsed laser irradiation in GHz-burst mode is applied to AISI 316L stainless steel to investigate the influence of burst parameters, beam shaping, and spatial overlap on surface modification. Bursts ranging from 50 to 800 pulses per burst with equal energy distribution were employed to explore cumulative thermal regimes. A systematic methodology was adopted, including single-burst interactions as well as variations in spot-to-spot and line-to-line overlaps. The results show that long bursts promote gradual heating, leading to improved process stability and reduced material ejection, while excessive overlap induces overheating, oxidation, and surface degradation. Favorable overlap ranges were identified, enabling the formation of homogeneous molten tracks under visual inspection. A comparison between Gaussian and vortex beam profiles reveals similar global trends, despite differences in their spatial energy distributions. Overall, the study highlights the key role of cumulative thermal effects and parameter interdependence in the melted layer generation with GHz-burst laser irradiation, providing guidelines for optimizing surface finishing processes.

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1. Introduction

Laser surface polishing has emerged as a promising non-contact post-processing technique for improving the surface finish of metallic components while preserving their bulk properties. In particular, stainless steels such as AISI 316L are widely used in biomedical [1], aerospace [2], and industrial applications due to their excellent corrosion resistance and mechanical performance [3-4]. However, manufacturing routes such as additive manufacturing or CNC machining often induce surface roughness and defects that must be mitigated to ensure favorable functional performance. Conventional polishing techniques, although effective, remain time-consuming, difficult to automate, and poorly suited for complex geometries. In this context, ultrafast laser polishing offers a flexible and highly controllable alternative, enabling localized material re-melting and surface smoothing with limited heat-affected zones and minimal thermal damage [5-6].

The interaction of ultrashort pulses with metallic surfaces has been extensively investigated, revealing complex physical mechanisms governed by rapid energy deposition, electron-phonon coupling, and transient melt dynamics [7-8]. Among the various processing strategies, burst-mode operation has recently attracted significant interest thanks to its ability to tailor energy delivery in both space and time. In particular, GHz-burst regimes, where a sequence of pulses is emitted within a short temporal window (0.8 ns), have been shown to enhance heat accumulation while maintaining ultrafast characteristics at the individual pulse level [9-11]. This gradual energy deposition can promote more stable melting conditions and improve surface quality compared to conventional single-pulse or low-repetition-rate regimes [12].

A major challenge in laser polishing lies in achieving a precise balance between sufficient melting for surface smoothing and the prevention of undesirable effects such as ablation, oxidation, or excessive thermal accumulation. This balance is governed by several parameters, whose effects are strongly coupled, including pulse energy, burst duration, repetition rate, beam spot size, and the spatial overlap between consecutive laser impacts [13]. In particular, spot-to-spot and line-to-line overlaps play a critical role in controlling heat accumulation and ensuring uniform energy distribution across the processed surface. As a result, the optimization of laser polishing processes requires a comprehensive understanding of the interplay between temporal and spatial energy deposition.

In addition to these parameters, the spatial intensity distribution of the laser beam is a key factor influencing thermal gradients and melt pool behavior. While Gaussian beams are commonly employed due to their simplicity and widespread availability, alternative beam shaping strategies have been proposed to enhance process control. Among these, vortex beams carrying orbital angular momentum exhibit an annular intensity profile with a central intensity minimum. This specific energy distribution can modify radial heat flow and potentially lead to smoother temperature gradients within the melt pool. Previous studies in laser welding have demonstrated that ring-shaped or vortex beams can improve process stability and reduce defect formation by redistributing energy away from the beam center [14-17]. However, their application to ultrafast laser polishing, particularly in the GHz-burst regime, remains relatively unexplored and requires further investigation.

Therefore, in this work, the influence of GHz-burst ultrafast laser irradiation on the surface modification and

melted layer generation on AISI 316L stainless steel is investigated. The primary goal is to provide a preliminary study of its potential for application for laser polishing, as well as to assess the impact of the different energy distributions of Gaussian and vortex beams on the resulting surface morphology and process stability. A particular emphasis is put on the combined effects of burst parameters, spatial overlap, and beam shaping. The surface morphology and process stability were assessed through visual inspection of microscope images. This methodology does not allow to fully assess the flaws that can be induced during the polishing process but allows for an intuitive understanding of the mechanism at play. A systematic experimental methodology is adopted, starting from single-burst interactions and progressively incorporating spot-to-spot and line-to-line overlaps to reproduce realistic polishing conditions.

By exploring a wide range of pulse-per-burst (ppb) values and processing parameters, this study aims to provide deeper insight into the mechanisms governing heat accumulation and melt dynamics in the GHz-burst regime. The ultimate objective is to identify favorable processing windows enabling controlled surface smoothing while minimizing thermal degradation, and to evaluate the potential benefits of beam shaping strategies for improving the surface morphology of the generated melted layers for potential application in ultrafast laser polishing. The use of long GHz burst could be interesting as every sub-pulse contains energy far below the ablation threshold and could provide a wider process window for surface melting, whereas short burst, for equivalent burst energy, should arise in a more intense rise in heat and reduced process window.

2. Materials and Methods

The laser system used for this experiment was a Tangor 100 from Amplitude (Amplitude Laser Group, Pessac, France), which emits pulses at 1030 nm wavelength with a pulse duration of 505 fs. The output beam is linearly polarized. This laser system can operate in repetitive single-pulse (SP) mode, in MHz-burst mode with up to 32 pulses per burst (ppb) at 40 MHz intra-burst repetition rate, or in GHz-burst mode with up to 800 ppb at an intra-burst repetition rate of 1.28 GHz. The burst repetition rate is adjustable up to 800 kHz and the pulse/burst energy available on the target ranges from 0 to 300 μ J.

For this study, bursts of 50 up to 800 pulses per GHz-burst were selected, with the energy evenly distributed among the pulses, as thoroughly detailed in [12], forming a flat burst in the GHz-burst regime. These two points represent two extremes of the working range: 50 ppb corresponds to a short burst with moderate intensity per pulse, while 800 ppb corresponds to a long burst with much lower intensity per pulse, well below threshold, where the cumulative effects are more pronounced and the heat deposition can occur over a longer timescale. Investigating this wide range allows to explore how burst length and pulse intensity influence the heat accumulation dynamics and material response during laser interaction.

As shown in Figure 1, a beam expander was used to set the diameter of the beam to 5.4 mm at the entrance of the scanner module. The latter included a galvo scanner (LS-Scan XY 20, LASEA, Liège, Belgium) with an f-theta lens of 100 mm focal length, providing a wide field of

60 x 60 mm² and a beam focus of 21.5 μ m. A motorized Z-axis stage (Alio Industries, AI-LM-10000-I-PLT-LP) was used for precise positioning of the Gaussian and vortex beam with respect to the sample surface. Moreover, the station was equipped with a top-view imaging system featuring a long-distance microscope (InfiniMax KX with MX5 objective) coupled with a Basler CMOS camera (Basler acA1440-220uc, resolution 1440 x 1080, pixel size 3.45 μ m x 3.45 μ m, 227 fps, global shutter) in order to precisely set the focus position of the beam. The translation stages, laser gate, laser parameters, image acquisition, and laser power control unit were fully automated and controlled using DMCpro software (v1.0.8, Direct Machining Control, Vilnius, Lithuania), providing precise and repeatable control over all experimental parameters.

While the Gaussian beam configuration serves as the reference setup, additional beam shaping was implemented to generate a vortex beam by inserting a vortex phase mask along the propagation line (with an orbital angular momentum of $m=1$), enabling a hollow core beam and tailored energy deposition.

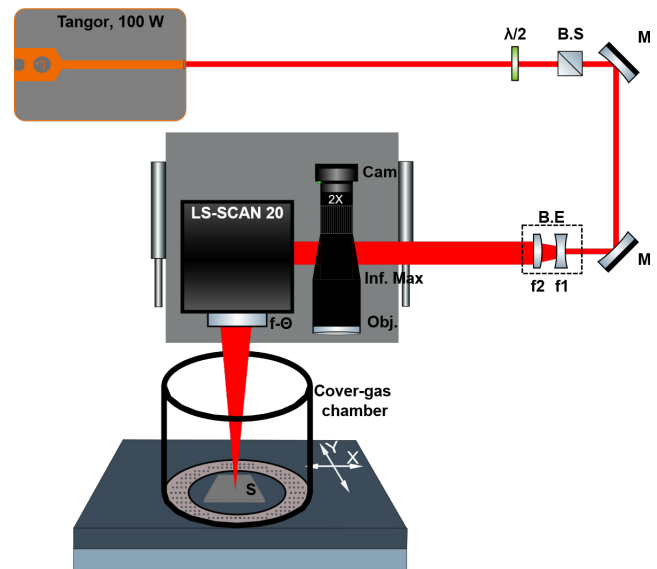


Fig. 1 Schematic view of the experimental setup used for polishing experiments. **B.S.**: Beam Splitter, **B.E.**: Beam Expander, **Cam**: Camera, **Inf.Max**: Infini Max, **Obj**: Objective, **M**: Mirror, **S**: Sample.

An SEM image of the pristine AISI 316L surface is shown in Figure 2. The image was acquired at a magnification of

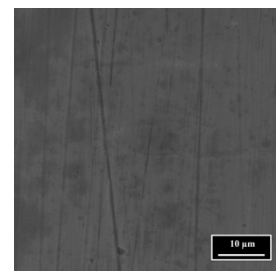


Fig. 2 SEM top view of pristine 316L stainless steel sample surface.

5 000 $\times$, corresponding to a field of view of 556 μm^2 . The surface appears highly smooth and exhibits only minimal defects.

3. Results and Discussion

3.1 Vortex beam

In this section, the results obtained with a laser beam, spatially shaped using a vortex phase mask carrying an orbital angular momentum of $m=1$, are presented. The objective of this section is to identify favorable processing parameters through a systematic, step-by-step experimental investigation based on visual analysis.

3.1.1 Single-burst study

The first step of the study focuses on the impact of a single burst on the sample surface. To this end, several beam spot sizes were investigated by translating the target along the optical axis using the Z-translation stage, thereby defocusing the beam at the surface. For each spot size, the burst energy was varied in steps of 8.5 μJ . In addition, for each parameter set, the number of pulses per burst was investigated from 50 to 800 ppb, using the GHz-burst mode.

The resulting surface modifications were characterized using an optical microscope equipped with a 20 $\times$ objective. Representative results obtained in the GHz-burst configuration are presented in Figure 3. All corresponding fluences given are average fluences, assuming a homogeneous distribution of the burst energy across the entire beam diameter. (i.e., the burst energy divided by the area contained within the beam diameter).

By inspecting the first burst configuration shown in Figure 3(a) several characteristic features can be identified. For the smallest beam spot size (54 μm) corresponding to fluences from 9 to 15 $\text{J} \times \text{cm}^{-2}$ a circular molten region is observed, with a distinct dark feature at its center. This central structure is likely associated with a material protrusion or spike, or may result from a Marangoni effect as well (also called thermo-capillary convection). This arises when a temperature gradient induces a gradient in surface tension (from liquid zone to solid zone), and the matter flows from the cold zone to the hot zone [18]. More detailed SEM images are provided for the evolution of the observed morphology at 340 μJ for several burst durations in Figure 4.

As the burst energy is reduced and thus the fluence, the depth and extent of the molten peripheral ring gradually decrease, and the central feature becomes less pronounced. When increasing the beam spot size and thus reducing the fluence from 8 to 5 J/cm^2 the "thermal pressure", induced by rapid surface heating is reduced due to the lower energy density. At a spot size of 100 μm , the vortex beam primarily melts the outer ring, while the central region remains unaffected.

A similar trend with decreasing extent of the molten peripheral ring and a less pronounced central feature is also observed at an earlier stage when increasing the number of pulses per burst.

3.1.2 Influence of the spot-to-spot overlap

Based on the single-burst study, the 800 ppb configuration was selected, as it provides a more gradual energy deposition, resulting in reduced spatter formation and fewer

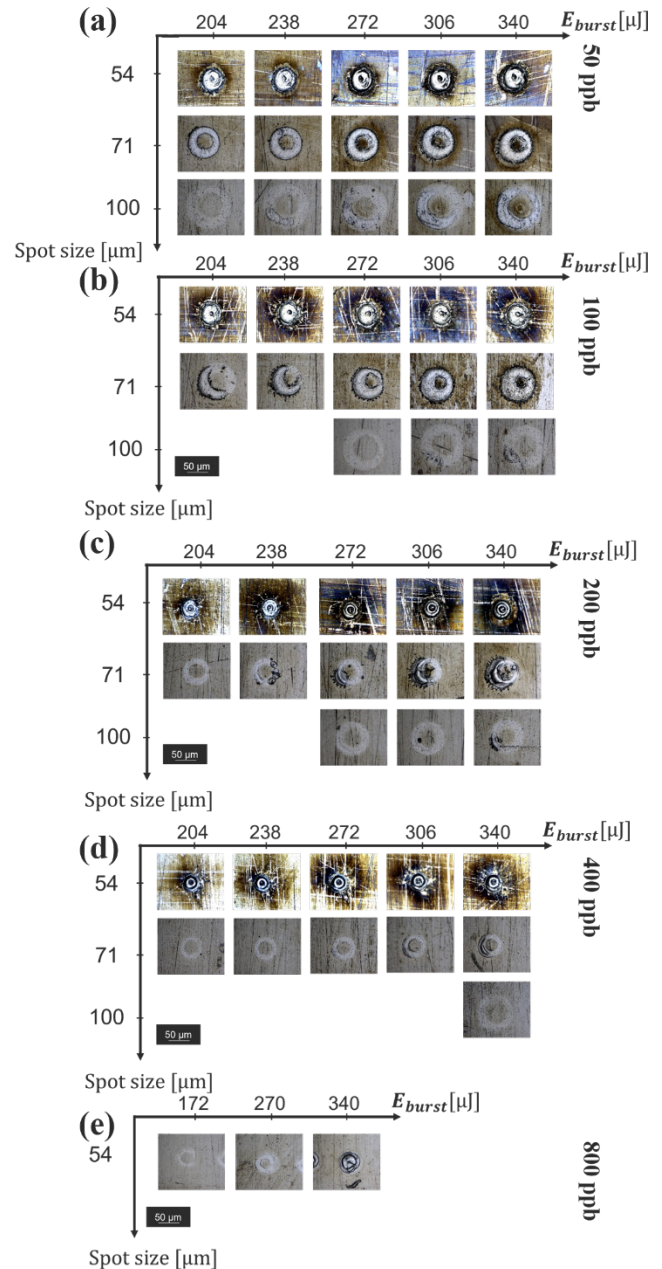


Fig. 3 Optical microscope images of vortex beam surface modifications with increasing number of pulses-per-burst, as a function of energy and spot size. (a) 50 ppb, (b) 100 ppb, (c) 200 ppb, (d) 400 ppb, (e) 800 ppb.

surface protrusions. The influence of burst overlap was therefore investigated using this configuration.

The spot-to-spot overlap (S-2-S) was first studied using a beam spot size of 54 μm and a repetition rate of 20 kHz. The overlap was varied from 0 % to 97 % for three burst energies: 170 μJ , 238 μJ , and 340 μJ . Therefore, any melting at 170 μJ and 238 μJ would be attributed to heat accumulation with spatial overlap, since no melting was observed at these energies in the single-burst study (cf. Figure 3). The corresponding surface morphologies are shown in Figure 5.

For all investigated energies and low overlap values, surface morphologies similar to those obtained in the single-spot configuration (Figure 3) are observed. At the highest burst energy of 340 μJ , increasing the spot-to-spot overlap

rapidly leads to unstable seams. In the range between 32 % and 45 %, the distance between successive spots remains too

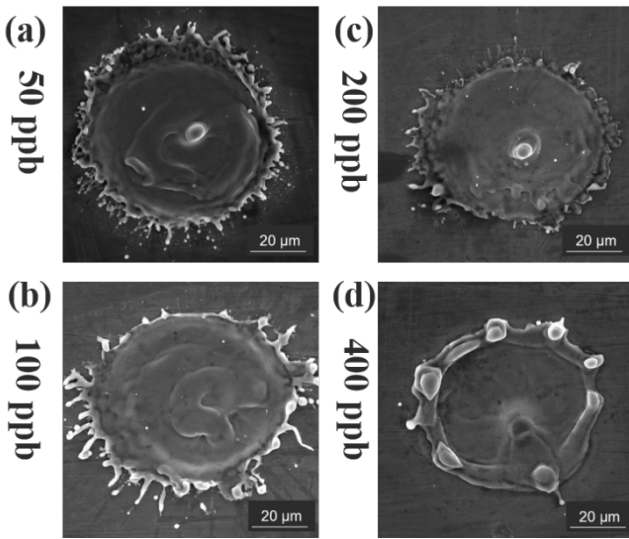


Fig. 4 SEM images of vortex beam surface modifications with increasing number of pulse-per-burst for 92 µm spot size and 340 µJ burst energy. (a) 50 ppb, (b) 100 ppb, (c) 200 ppb, (d) 400 ppb with a magnification of 3 kx.

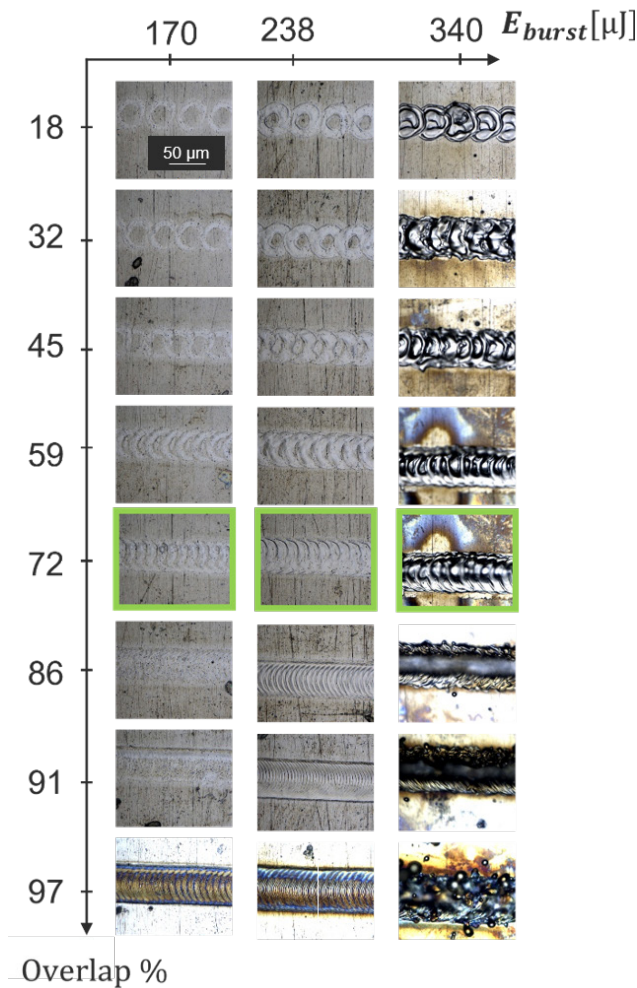


Fig. 5 Optical microscope images of 316L samples showing the influence of spot-to-spot overlap using a vortex beam on the surface appearance for 800 ppb GHz-burst with three burst energies of 170, 238, and 340 µJ, respectively.

large to ensure surface homogenization. A favorable regime is identified at 72 % overlap, where a continuous seam is obtained, although early signs of thermal instabilities are already visible.

For a burst energy of 238 µJ, individual spots remain clearly distinguishable up to 45 % overlap. Between 59 % and 91 %, homogeneous and stable seams are obtained. However, increasing the overlap to 97 % results in excessive heat accumulation, leading to the formation of a heat-affected zone accompanied by strong surface oxidation.

A similar behavior is observed for the lowest burst energy of 170 µJ. Homogeneous seams are obtained for overlaps ranging from 72 % to 91 %, while higher overlap values again lead to overheating and oxidation effects.

An additional observation can be made on the evolution of the track width. Looking at the burst energy of 238 µJ one can measure the evolution of the track width compared to the overlap. The track width is stable at 54 µm until 59 % overlap. After this point the track width gradually increases up to 75 µm for an overlap of 97 %, leading to an increase of 39 % over the investigated overlap. The track widths were measured from the optical microscope images manually using the software ImageJ. The measurement uncertainty was estimated to be approximately ± 2 µm.

Based on these observations, a spot-to-spot overlap of 72 % was selected for subsequent experiments but another interesting working point would have been 238 µJ per burst with 97 % overlap, where a thinner and stable melting layer is also produced.

3.1.3 Influence of the line-to-line overlap

With the spot-to-spot overlap fixed, the influence of the line-to-line (L-2-L) overlap was investigated. Two configurations were considered: a 10 % overlap, and a 75 % overlap. Burst energies of 170 µJ, 238 µJ, and 340 µJ were tested for each configuration. The results are shown in Figure 6.

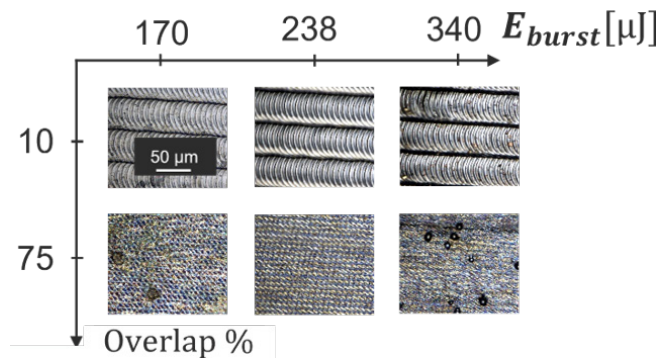


Fig. 6 Optical microscope images of 316L samples showing the line-to-line influence using a vortex beam on the surface appearance for 800 ppb GHz-burst with three burst energies of 170, 238, and 340 µJ, respectively.

It can be directly observed that a 10 % line-to-line overlap produces surface morphologies closely resembling those obtained for a single line. In contrast, a 75 % overlap results in a significantly more structured surface. In this case, the material does not appear to form a smooth molten region for any of the investigated energies; instead, the surface exhibits

a rough morphology, as if each laser spot generated an individual molten pool rather than contributing to a continuous molten track. This behavior leads to a rough visual aspect and heterogeneous-like surface.

These results show that the effect of burst energy, spot-to-spot overlap, and line-to-line overlap are strongly correlated and cannot be considered as independent processing parameters.

Having explored the influence of a vortex beam profile on surface modification, it is interesting to compare these results with those obtained using a classical Gaussian beam. The following section therefore presents the investigations for the same experimental approach using a Gaussian beam profile, which serves as a reference configuration due to its simplicity and widespread use.

3.2 Gaussian beam

In this section, the laser beam is a classical Gaussian beam. The objective of this section is to identify favorable processing parameters through a systematic, step-by-step experimental investigation based on visual analysis.

3.2.1 Single-burst study

The first step of the study focuses on the impact of a single burst on the sample surface. To this end, several beam spot sizes were investigated by translating the target along the optical axis using the Z-translation stage, thereby defocusing the beam at the surface. For each spot size, the burst energy was varied in steps of $8.5 \mu\text{J}$. In addition, the number of pulses per burst was investigated. The corresponding fluences given are again average fluences, as for the vortex beam. (i.e., the burst energy divided by the area contained within the beam diameter).

The resulting surface modifications were characterized using an optical microscope equipped with a $50\times$ objective. Representative results obtained in the GHz-burst configuration are presented in Figure 7.

By inspecting the first burst configuration shown in Figure 7(a) (50 ppb), several characteristic features can be identified. For the smallest beam spot size ($66 \mu\text{m}$), a circular molten region is observed, and no distinct features emerge. As the energy is lowered, the size of the melted zone is reduced (fluence from 6 to $10 \text{ J} \times \text{cm}^{-2}$).

At a spot size of $91 \mu\text{m}$, the Gaussian beam primarily melts the central core, while the external region is heated but not melted. Here also, as the burst energy is reduced, the size of the molten pool is reduced as well (fluence from 3 to $6 \text{ J} \times \text{cm}^{-2}$). A similar behavior is observed for a beam spot size of $104 \mu\text{m}$ (fluence of $2 \text{ J} \times \text{cm}^{-2}$).

Increasing the number of pulses per burst to 100 ppb, Figure 7 (b), leads to comparable trends. For the smallest spot size and highest energy, a re-solidified area with the appearance of a higher reflectivity and smoother re-solidified surface is observed. As the burst energy is reduced, the size of the melted pool is reduced and no trace of melting is obtained at $204 \mu\text{J}$. The overall size of the molten region appears equal compared to the 50 ppb configuration. At a spot size of $91 \mu\text{m}$, the molten region looks more disturbed. Increasing the beam spot size to $104 \mu\text{m}$ results in a very slight molten area for $340 \mu\text{J}$.

This general trend persists as the number of pulses per burst is further increased to 200 ppb and 400 ppb, as shown

in Figure 7 (c) and (d). For small spot sizes, high energy deposition leads to strong melting, while the surrounding remains pristine. For larger spot sizes, melting is shifted toward higher burst energy values with barely any visible at $306 \mu\text{J}$ and $104 \mu\text{m}$.

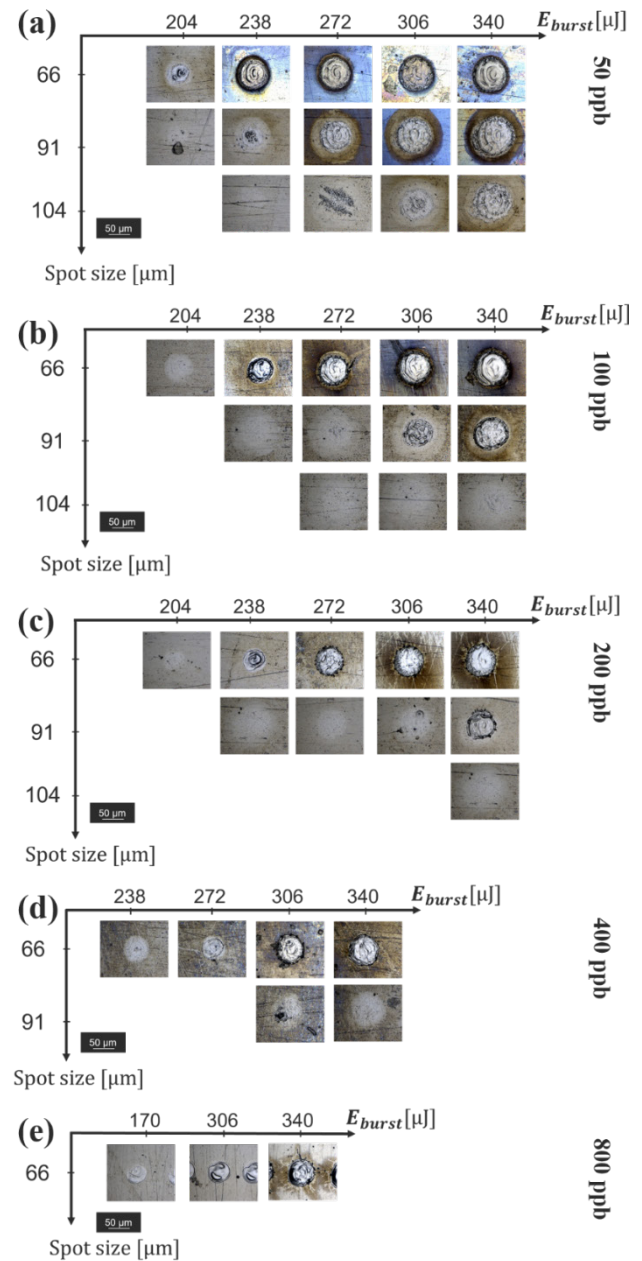


Fig. 7 Optical microscope images of Gaussian beam surface modification with increasing number of pulse-per-burst values as a function of energy and spot size. (a) 50 ppb, (b) 100 ppb, (c) 200 ppb, (d) 400 ppb, (e) 800 ppb.

Based on the single-burst study, the 800 ppb configuration was selected, as it enables a more gradual energy deposition due to the energy being dispensed over a longer time and thus a more gradual heating process. The influence of burst overlap was subsequently investigated.

3.2.2 Influence of the spot-to-spot overlap

The spot-to-spot overlap was studied using a beam spot size of $66 \mu\text{m}$ and a repetition rate of 20 kHz . The overlap

was varied from 0 % to 97 % for four burst energies: 85 μJ , 170 μJ , 238 μJ , and 340 μJ . The corresponding results are shown in Figure 8.

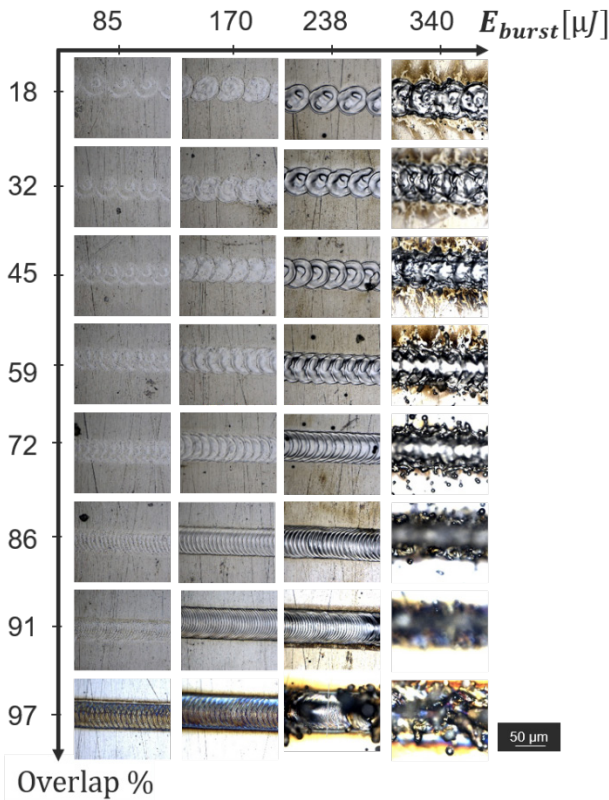


Fig. 8 Optical microscope images of 316L samples showing the spot-to-spot influence on the surface appearance for 800 ppb GHz-burst for four burst energies of 85, 170, 238, and 340 μJ , respectively.

For all energies and low overlap values, surface morphologies similar to those observed in the single-burst configuration (Figure 7(e)) are obtained. At the highest burst energy of 340 μJ , increasing the overlap rapidly leads to unstable seams and localized ablation of the track.

For a burst energy of 238 μJ , individual spots remain clearly distinguishable up to 86 % overlap. Between 86 % and 91 %, the seams appear homogeneous and stable. However, increasing the overlap to 97 % results in excessive heat accumulation, leading to the formation of holes within the track. At a burst energy of 170 μJ , individual spots remain visible up to 86 % overlap, although with a more uniform appearance. Between 86 % and 91 %, stable and smooth seams are obtained. At 97 % overlap, oxidation effects similar to those observed for the vortex beam configuration (Section 3.1) are identified.

Finally, for the lowest burst energy of 85 μJ , for overlaps ranging from 18 % to 59 % a small modified zone is detected but appears discontinuously, as the overlap increases from 72 % to 91 % a thin and smooth molten layer is generated. At 97 % overlap, oxidation effects again become apparent.

An additional observation can be performed on the evolution of the track width. Looking at the burst energy of 238 μJ one can measure the evolution of the track width compared to the overlap. The tracks width is stable at 51 μm

until 86 % overlap. After this point the track width gradually increases up to 86 μm for an overlap of 97 %, leading to an increase of 69 % over the investigated overlap. The track widths were measured from the optical microscope images manually using the software ImageJ. The measurement uncertainty was estimated to be approximately $\pm 2 \mu\text{m}$. Based on these observations, a spot-to-spot overlap of 91 % was selected for the subsequent experiments.

3.2.3 Influence of the line-to-line overlap

With the spot-to-spot overlap fixed, the influence of the line-to-line overlap was investigated. Three configurations were considered: a 10 %, a 50 % and a 75 % overlap. Burst energies of 85 μJ , 170 μJ , 238 μJ , and 340 μJ were tested for a repetition rate of 20 kHz. The results are shown in Figure 9. A 10 % line-to-line overlap produces surface morphologies similar to those obtained for a single line at burst energies of 85 μJ and 221 μJ . At higher energies, surface degradation becomes apparent. A 50 % overlap leads to comparable results for the two lowest energies.

Increasing the line-to-line overlap to 75 % results in a significantly more structured surface. In this regime, each individual molten line seems to overlap entirely with the previous one, thus leaving only the edges of the previous melted line, and therefore, leading to a rough and heterogeneous surface. A potential strategy to mitigate this effect would be to increase the inter-burst repetition rate in order to enhance thermal accumulation, although this would increase the risk of overheating.

As observed for the vortex beam configuration, these results confirm that the effect of burst energy, spot-to-spot overlap, and line-to-line overlap are strongly correlated and cannot be considered as independent processing parameters.

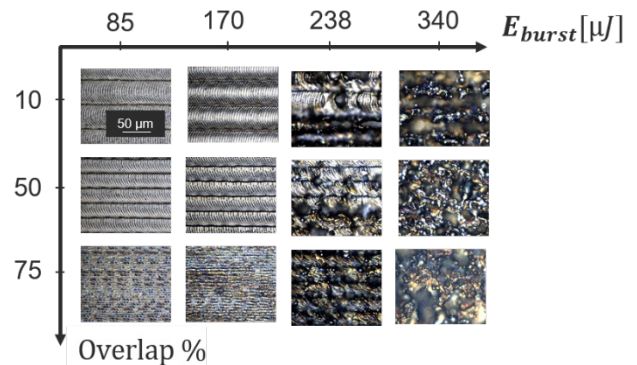


Fig. 9 Optical microscope images of 316L samples showing the line-to-line influence on the surface appearance for 800 ppb GHz-burst for four burst energies of 85, 170, 238, and 340 μJ , respectively.

Overall, the observations performed in this section provided valuable insight on the correlation between the induced effect of each parameter, such as S-2-S, L-2-L, burst duration, beam spot size, and beam shape. The two beam shapes investigated, vortex and Gaussian, showed only small differences in their respective behavior based on this simple visual analysis.

Additionally, the polishing process has been identified as a cumulative process where burst-to-burst irradiation results

in a heat accumulation but can be detrimental if this heat accumulation is too pronounced.

4. Conclusion

In conclusion, this study provides a comprehensive investigation of the melted layer generation on AISI 316L stainless steel with GHz-burst ultrafast laser irradiation and the resulting surface morphologies, highlighting the strong interplay between burst configuration, beam shaping, and spatial overlap parameters. The use of long bursts (up to 800 pulses per burst) was shown to promote a more gradual energy deposition, and more control than short GHz burst leading to improved process stability and reduced spatter formation at the burst energy investigated, although excessive heat accumulation can induce oxidation and surface degradation. Both vortex and Gaussian beam profiles enabled controlled surface melting, demonstrating their potential for application in laser polishing, with the vortex beam offering a more distributed energy deposition due to its hollow intensity profile but with the presence of a protrusion, while the Gaussian beam exhibited more homogenous melting behavior based on the visual analysis. While these differences in the results produced with the two intensity distributions could be observed in the single-burst study, they could not be observed anymore in the case of a spot-to-spot and line-to-line overlap, where the resulting molten surfaces had a very similar appearance.

The systematic analysis of the spot-to-spot and line-to-line overlaps demonstrated that favorable layer melting conditions rather arise from a delicate balance between sufficient thermal accumulation for homogenization and the avoidance of overheating effects than from the intensity distribution. In particular, overlap values around 72–91 % were identified as critical regimes for achieving continuous and stable molten tracks, depending on the beam profile and energy input. The results also confirm that processing parameters cannot be treated independently, as their combined effects govern the final surface morphology.

Overall, despite slight differences between vortex and Gaussian beams, both configurations yielded comparable trends under visual inspection which indicates that the process is primarily governed by cumulative thermal effects rather than by the intensity distribution itself. The practical implication of this is that Gaussian beams can be preferred for polishing applications due to their simplicity but further investigations should be performed to investigate the thickness of the melted layer with both configurations. Finally, this work emphasizes that the melted layer generation with GHz-burst laser irradiation is inherently a cumulative thermal process, where precise control of energy distribution in space and time is essential to optimize surface appearance while minimizing undesired thermal effects.

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