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The Impact of Dynamic Burst Mode and Intraburst Separation Time on Volume Removal and Surface Quality in Laser Ablation of Stainless Steels Using Ultrashort Pulsed Lasers

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Abstract

Stainless steel alloys are an essential material in industrial applications due to their excellent corrosion resistance and mechanical properties. However, variations in chemical composition, thermal diffusivity, and microstructure can significantly influence laser processing performance. This study focuses on the impact of the energy distribution within burst trains of pulses on the ablation efficiency and surface quality of three stainless steel grades, being AISI 304, AISI 420, and AISI 316Ti. Using an ultrashort pulsed laser operation at at pulse duration of 250, rectangular cavities are produced at various fluence levels and different burst configurations, using different intraburst energy distributions. Burst mode operation, particularly with varied intraburst energy profiles, enhanced both material removal and surface finish. For example at a fluence of 9 J/cm² and a burst frequency of 5 MHz, using positive and negative intraburst slopes, ablation rates of 1.1 and 1.8 mm³/min were reached, with roughness values (Sa) values of 4.5 and 2.9 µm, respectively.

Keywords: burst mode, ultra short pulsed lasers; dynamic burst

1. Introduction

Stainless steel alloys are widely used in medical, food, and tooling industries due to their excellent biocompatibility, corrosion resistance, and mechanical strength, as reported for instance by Narayan et al. In particular, tailored chemical compositions and microstructures enhance performance factors such as bacterial adhesion, hardness, and machinability. Laser-based methods, particularly ultrashort-pulsed (USP) lasers, are gaining popularity for precision processing, offering advantages like minimal thermal damage and high accuracy. While continuous wave lasers dominate in welding and cutting applications, USP lasers are preferred for material removal and marking. Achieving high removal rates without compromising surface quality remains a key challenge. Using higher laser power can enhance ablation but also it can degrade surface quality due to overheating. Optimal ablation typically occurs at fluences between 3 to 15 times the ablation threshold, as shown by Gruner et al and Neuenschwander et al, highlighting the need for precise fluence control.

Burst-mode processing, in which the laser energy is divided into multiple sub-pulses, offers a promising approach to balancing ablation rate and surface quality, as shown by Žemaitis et al. For instance, varying the number of pulses per burst redistributes the laser energy while minimizing excessive thermal effects. MHz bursts (with nanosecond time-spacings) enhance ablation through heat accumulation, while GHz bursts (with temporal spacing of picoseconds between to consecutive pulses) can reduce surface roughness through remelting, although plasma shielding may reduce efficiency. Combined MHz-GHz (Bi-burst) modes can leverage the benefits of both regimes depending on the ratio of MHz and GHz burst, as sown for instance by Obergfell et al and Förster et al.

Despite these advances, few studies have examined the impact of intraburst energy distribution, often referred to as dynamic burst shaping, on laser-material interaction. This study focuses on how the slope of the bursts energy distribution influences both ablation rate and surface quality in AISI 420, AISI 304, and AISI 316Ti stainless steels, which were selected due to their different thermal properties, microstructure as well as chemical composition. By varying fluence while keeping pulse duration constant, the effects of burst characteristics are isolated. Surface morphology, roughness, and defect formation are evaluated using confocal and optical microscopy to assess the influence of burst slope.

2. Materials and Methods

2.1. Materials

For the laser structuring experiments, 1 mm thick stainless steel samples (HSM Stahl- und Metallhandel, Germany) of AISI 304 (X5CrNi18-10), AISI 420 (X46Cr13), and AISI 316Ti (X6CrNiMoTi1) alloys were used.

2.2. Laser ablation experiments

The laser ablation process was carried out using a five-axis laser machine (GFMS LP400u, Switzerland). The system was equipped with a solid-state ultra-short-pulsed laser source (LightConversion Carbide CB-3, Lithuania), emitting a fundamental wavelength of 1030 nm with a pulse duration of 250 fs. The used laser source permits to use burst of pulses, splitting the main pulse up into 10 sub-pulses. The laser has a maximum average power of 40 W, with a maximal pulse energy (Ep) of 200 µJ. The laser beam was deflected on the surface using a galvanometer scanner (Scanlab Excelliscan, Germany) equipped with an f-theta lens having a focal distance of 160 mm. This optical setup leads to a beam diameter (ω_0) of approximately 36 µm. The optical setup was kept the same for all conducted experiments in order to make all used parameters comparable. To investigate the influence of the burst-mode, the number of bursts was varied between 3 to 10 bursts with GHz repetition rate and 3 to 10 bursts with MHz repetition rate. Oscilloscope measurements of exemplary burst configurations are depicted in Fig 1. Furthermore, the slope of the burst was varied between -1 and 1, which is indicated for each individual case in Figure 1. The intraburst pulse separation time was 450 ps and 17 ns for GHz and MHz bursts, respectively.

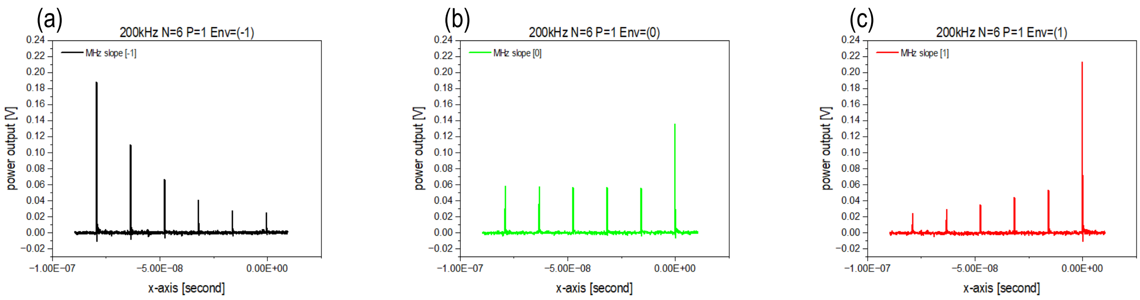

Fig. 1.Oscilloscope measurements of MHz burst pulse with slopes of (a) -1, (b) 0 and +1.

2.3. Surface characterization

The depth, volume and surface roughness of the laser-generated trenches was measured using a confocal microscope (Keyence VK-3000, Japan). In addition, an optical microscope (Keyence VHX-7000, Japan) was used to analyze the surface morphology of the laser treated volumes.

3. Results and discussion

Various burst modes were systematically evaluated to investigate their influence on the ablation behavior of the three stainless steel alloys mentioned above. For each parameter set, a 2 mm × 2 mm cavity was ablated on a 100 mm × 100 mm stainless steel plate for each alloy.

The results demonstrate a clear influence of the burst slope on both ablation rate and surface quality. Notably, it was found that the laser fluence plays a critical role as higher fluences amplify the effects of the burst slope on ablation rate and surface characteristics.

Using 10 MHz bursts with zero slope, the highest ablation rate was achieved, being approximately 5.1 mm^3/min at a fluence of 17 J/cm^2 on AISI 304. This nearly doubles the rate achieved without burst mode (2.9 mm^3/min) for the same steel. The enhancement is primarily attributed due to inter-pulse heat accumulation, which lowers the ablation threshold and facilitates more efficient material removal. Applying a negative slope (-1), where the initial pulses in the burst carry higher energy, reduced the removal rate to 3.2 mm^3/min. Furthermore, a positive slope (+1), showed the lowest rate of 1.9 mm^3/min. In the GHz burst regime, ablation rates decreased significantly below 1.0 mm^3/min. Interestingly, a positive slope (+1) in this regime slightly improved ablation from 0.6 mm^3/min at zero slope to 0.9 mm^3/min.

In the bi-burst regime, which is characterized by combining MHz and GHz bursts, the ablation rate was strongly influenced by both the ratio of the MHz and GHz components as well as the slope within the GHz burst. A positive slope (+1) for the GHz component generally resulted in higher ablation rates. For example, a configuration combining a 10 MHz burst with a 3–10 GHz burst yielded rates up to 3.5 mm^3/min.

Regarding surface roughness, nearly all burst configurations resulted in smoother surfaces compared to the non-burst reference (Sa ≈ 20 µm). Notably, GHz bursts produced consistently smooth surfaces, however at lower ablation rates. This is attributed to the short inter-pulse spacing and low single-pulse energy, which leads to high heat accumulation. A thin melt layer forms and re-solidifies, resulting in a smoother surface. Negative burst slopes in the GHz regime significantly reduced roughness to below 0.5 µm Sa. In contrast, positive slopes led to increased roughness. In the MHz regime, a surface roughness reduction was also observed, though not as pronounced. Values around 2 µm Sa were attainable while still maintaining high ablation rates.

Material-specific differences in surface defect formation were also evident. Figure 2 shows digital microscope images comparing the steels AISI 304 and AISI 316Ti under identical laser process parameters. The influence of the burst slope, ranging from –1 to 1, is clearly observed in the resulting changes in surface morphology. For example, at negative slopes, the surface shows a polished, bright, and reflective appearance. As the slope approaches zero, the surface gradually darkens. With further increase toward positive slopes, it becomes increasingly darker, reaching an almost black appearance. This general trend is observed in both materials. In case of negative burst slopes, AISI 316Ti showed clear microhole formation, which becomes noticeable as pits across the entire surface at slope -1, unlike AISI 304, which remained unaffected at identical settings.

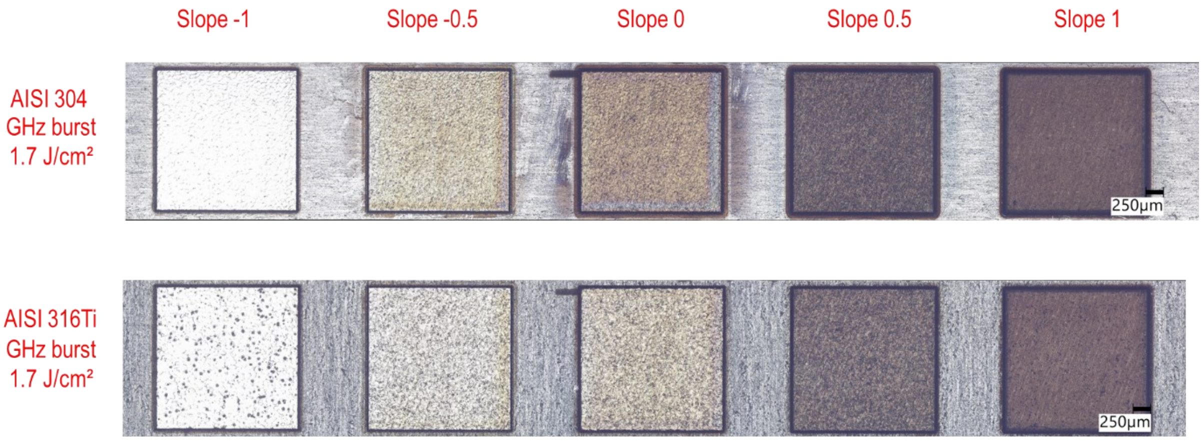

Fig. 2. Digital microscope images of GHz burst with different slope from -1 to 1. Material AISI 304 and AISI 316Ti.

4. Conclusion

In this study, the effects of MHz and GHz burst slopes on the laser ablation behavior of three stainless steel alloys (AISI 420, AISI 304, and AISI 316Ti) were examined. The results demonstrated that the burst slope in the MHz regime had a significant influence on both material removal rate and surface quality, with steeper positive and negative slope generally reducing the ablation rate. In the GHz regime, the influence of the slope characteristics on material removal rate was less pronounced, but the effect on the surface quality was important. Despite their different material properties, all three alloys exhibited comparable ablation rates. In terms of surface quality, microhole formation was observed only in AISI 316Ti under a specific energy distribution, indicating a dependency on both alloy type and the temporal distribution of pulse energy.

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References

Narayan, Roger J. 2012, Materials for medical devices. ASM International. Materials Park, Ohio: ASM International, pp. 199–210.

Gruner, Andreas; Schille, Joerg; Loeschner, Udo, Joerg Schille, and Udo Loeschner (2024): Ultrashort Pulse Laser Surface Texturing for Injection Mold Functionalization.JLMN, pp. 20–26.

Neuenschwander, Beat; Jaeggi, Beat; Schmid, M.; Hennig, G. 2014, Surface Structuring with Ultra-short Laser Pulses: Basics, Limitations and Needs for High Throughput. Physics Procedia, pp. 1047–1058.

Žemaitis, Andrius; Gečys, Paulius; Barkauskas, Martynas; Račiukaitis, Gediminas; Gedvilas, Mindaugas 2019, Highly-efficient laser ablation of copper by bursts of ultrashort tuneable (fs-ps) pulses. In Scientific reports 9 (1), Article 12280, pp. 1–8.

Obergfell, Dirk; Azarhoushang, Bahman; Lasagni, Andrés Fabián 2024, Comparison of ablation rate on stainless steel using pulsed lasers in different burst modes. Materials Letters, pp. 1–4.

Jaeggi, Beat; Förster, Daniel J.; Weber, Rudolf; Neuenschwander, Beat,2018, Residual heat during laser ablation of metals with bursts of ultra-short pulses. Advanced Optical Technologies, pp. 175–182.