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Procedia CIRP 124 (2024) 653–656

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13th CIRP Conference on Photonic Technologies [LANE 2024], 15-19 September 2024, Fürth, Germany

High-Speed Synchrotron X-ray Imaging of Micro-hole Formation during the Ablation of Grooves by Ultrashort Laser Pulses

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Abstract

The formation of slits with very high aspect ratios is critical for the production of additively manufactured parts for advanced electric drives. In this work, high-speed synchrotron X-ray imaging is utilized to observe slit/groove formation in stainless steel using ultrashort laser pulses. The results reveal that, under the pulse conditions employed here, a narrow, deep slit or groove can be created by the eventual consolidation of micro-holes which are generated in the early stages of the laser-material interaction. The success or otherwise of this micro-hole consolidation has a complex relationship to the process parameters.

Peer-review under responsibility of the international review committee of the 13th CIRP Conference on Photonic Technologies [LANE 2024]

Keywords: ultrafast laser ablation, ultrashort laser pulses, microstructures, grooves, highspeed synchrotron x-ray imaging

1. Introduction

Laser-based powder bed fusion of metals (PBF-LB/M) is an additive manufacturing process, creating complex components by melting successive layers of metal powder.

The potential of combining additive and subtractive laser processes has been shown in previous research where ablative post-processing of printed parts with ultrashort pulses has been demonstrated [1, 2].

Based on these results, a novel manufacturing approach, integrating PBF-LB/M and ultrafast laser processing at the layer level was developed. This new approach not only exceeds the accuracy limits of conventional PBF-LB/M, but also the achievable aspect ratios for e.g. micro-holes or grooves compared to conventional micromachining with ultrashort pulses [3, 4].

In the subtractive part of the process, material is locally removed by a multitude of scanning passes to produce structures with dimensions significantly below 100 µm in width. This results in the creation of a v-shaped groove. When repeated over several additive layers, these grooves can be connected to each other and form a thin slit spanning several layers. However, this process is very time-consuming due to the high number of scan passes required. Increasing the scanning velocities and pulse repetition rates would increase the productivity of the process.

It has been noted that, when processing metals and semiconductors with ultrashort pulses, an inhomogeneous groove bottom is formed after just a few scanning passes. This was first shown by Fornaroli et al. [5] in silicon. The semi-periodic appearance of the depth of the groove can also be described as a series of micro-holes.

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10.1016/j.procir.2024.08.194

This behaviour can also be seen in stainless steel. The formation of a series of micro-holes during the ablation of grooves with an increasing number of scans has been observed as shown in Fig. 1. The presence of melt is recognizable after a few tens of passes. Individual micro-holes are formed after around 100 passes. The spacing of these micro-holes appears to be self-organized.

Recent studies focusing on laser welding, cutting, and drilling have underscored the efficacy of high-speed X-ray imaging as an invaluable asset for visualizing laser materials processing [6-8]. The exceptional beam quality of X-rays from a synchrotron enables the real-time observation of micro-hole formation during drilling. This research showcases how this method facilitates a comprehensive examination of the formation of micro-holes during the ablation of a groove while scanning along a straight line, providing valuable insights into the intricacies of the cutting process.

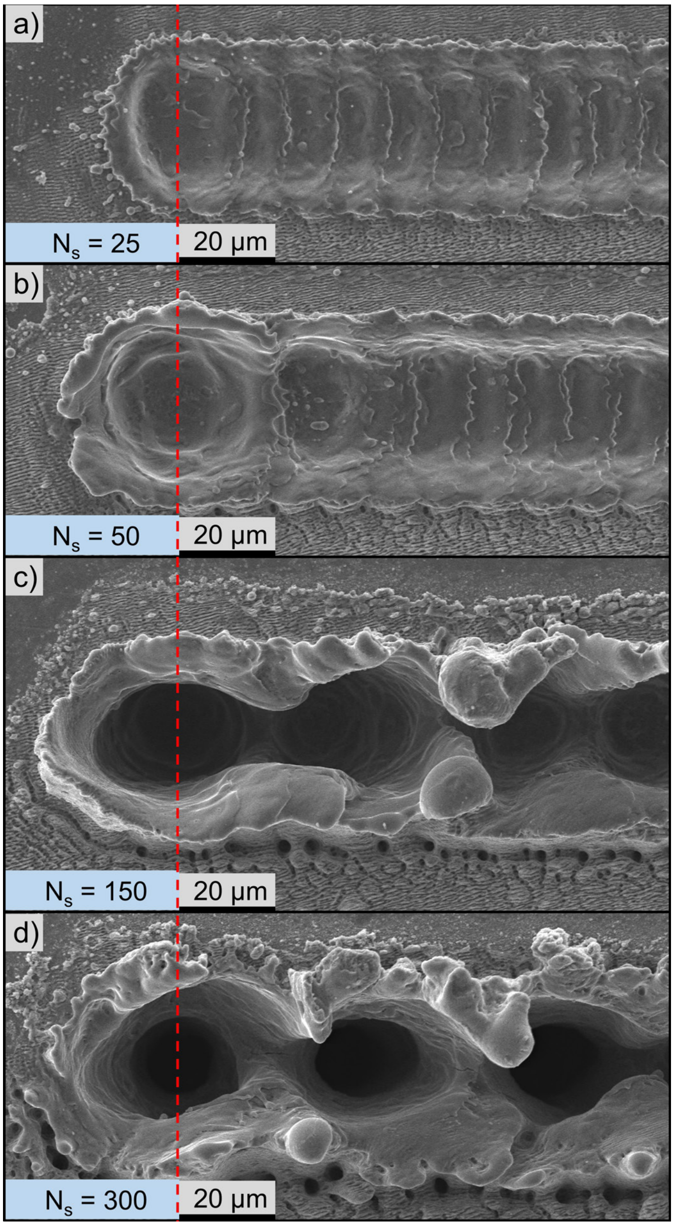

Fig. 1. SEM images of grooves manufactured in stainless steel. The individual images show the top view on the grooves after increasing number of scanning passes.

2. Experimental setup

The experiments were carried out at the DESY (Deutsches Elektronen-Synchrotron, Hamburg, Germany) [9]. The relevant experimental setup employed for investigating laser material processing has been extensively explained by Wagner et al. [7]. A variant of this setup is shown in Fig. 2. Experimental Setup. An ultrafast Yb:YAG laser (Carbide CB3-80) from Light Conversion (Vilnius, Lithuania) was used. The circularly polarized laser beam was guided into a galvanometer-scanner, through a f-theta lens with a focal length of 160 mm and focused on the surface of the sample, resulting in a focal diameter of $d_f = 50$ µm. The laser beam parameters are provided in Table 1.

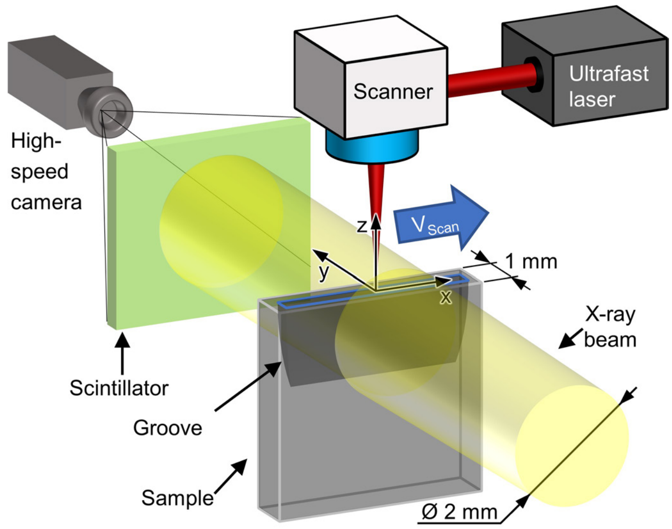

Fig. 2. Experimental Setup (not to scale).

The energy of the monochromatic X-ray beam was set to 89 keV. The investigated sample material was stainless steel (AISI 304) with a width of 1 mm. The X-ray image sequence underwent post-processing in two steps following the methodology outlined by Wagner et al. [7]. A flat field correction was initially applied to the sequence to avoid misinterpretations due to the intensity profile of the X-ray beam. A Kalman filter was then applied for further refinement [10].

Table 1. Laser beam parameters and optical setup.

Dimension	Unit	Carbide CB3-80
Wavelength (λ)	*nm*	1035
Laser Power (P)	*W*	15; 30; 60
Pulse energy (E_p)	*µJ*	100; 200
Repetition rate (f_{rep})	*kHz*	150; 300
Pulse duration (τ_p)	*ps*	8
Beam Quality (M^2)	-	< 1.1
Beam diameter (D_r)	*mm*	4.6
Polarization	-	circular
Focal length (f)	*mm*	160
Focus diameter (d_f)	*µm*	50

The parameters detailed in Table 1 yield peak fluences of approximately 10.2 J/cm² and 20.4 J/cm² in the focal plane. Lines of 4 mm length were ablated along the x-direction for a total of 1600 scans, using a repetition rate of 150 kHz as well as 300 kHz. The scan speed was adjusted to 1.5 m/s and 3 m/s respectively, which resulted in a pulse overlap of approx. 80 % in each case.

The high-speed camera was set to a framerate of 3 kHz. The achievable camera resolution was 1500 x 800 pixels with a scale of 1.17 µm/pixel.

3. Results

Fig. 3 shows different chronological sequences of micro-hole formation during the scanning of a groove in the x-direction. The processing parameters are listed above each group of images. To obtain images with a higher signal-to-noise ratio, each image is the average of 100 captured frames selected over the respective duration of 25 scans just before the actual number of scanning passes Ns is reached, which is indicated below each image.

The following points can be determined from an analysis of Fig. 3:

In each case micro-holes have begun to form before 100 scans have been completed. These micro-holes initially have a periodicity of approximately 50 µm, with sides which extend up to the top surface of the sample until approximately 200 scans have been completed.

By the time 400 scans have taken place, the hole entrances have started to be ablated away from the top surface of the sample and this recession results in a partially successful groove with a fluctuating penetration depth.

After 1600 scans the success of the grooving operation can be measured by comparing the penetration of the grooves from the top surface of the sample to the top of the highest micro-hole entrance. For the parameters used here, this ‘groove depth’ hierarchy is;

Fig. 3a (240 µm), Fig. 3b (220 µm), Fig. 3c (130 µm), Fig. 3d (60 µm).

The parameters given in Fig. 3a clearly give the deepest groove results. In the case of Fig. 3b both the scan speed and the pulse frequency have been doubled (and the process time halved), and this has given similar results to Fig. 3a but with a slightly reduced ablation efficiency.

In the cases of Fig. 3c and Fig. 3d the individual pulse energy has been doubled compared to Fig. 3a and Fig. 3b. These higher energy pulses remove more material per scan but this process makes the micro-holes larger and more resilient to conversion into an overall groove. Although the micro-holes seem to combine to some extent, their entrances remain relatively close to the top surface of the sample, frustrating the generation of an overall groove.

It should be borne in mind that, although the deepest groove depth (240 µm), was achieved by the parameters given for Fig. 3a, the parameters used for Fig. 3b achieved 92% of this result (220 µm), in half the process time (2.13s rather than 4.26s). Therefore, the Fig. 3b parameters would be preferred from a production engineering point of view.

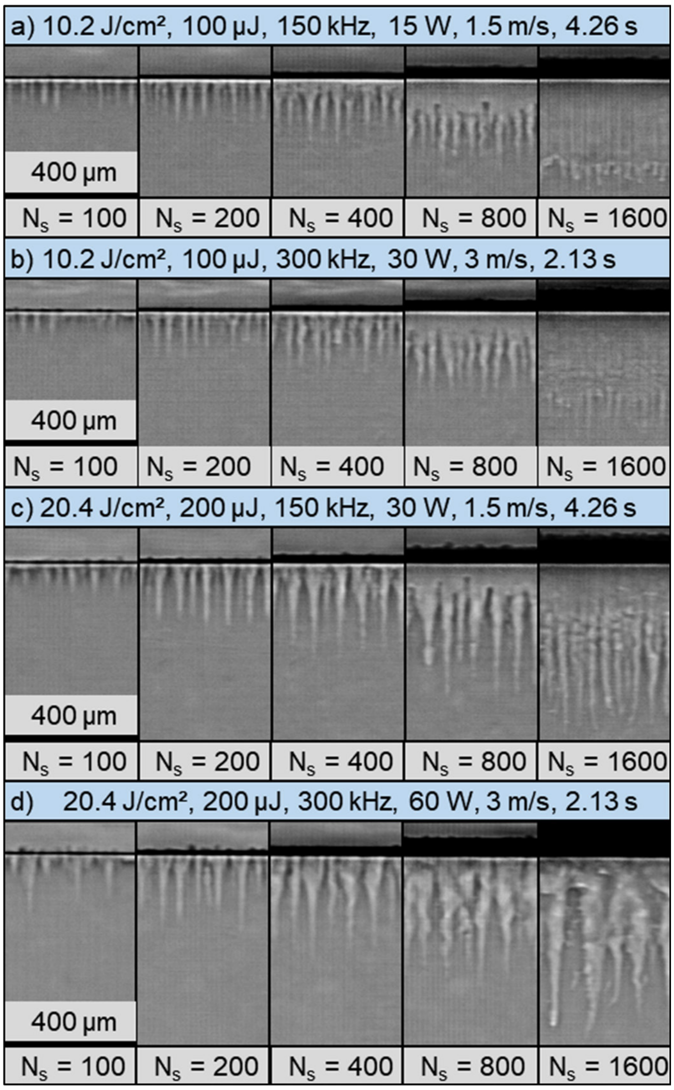

Fig. 3: Chronological sequences of micro-hole formation during the scanning of a groove in the x-direction. The number of scanning passes N_s already applied for each position is indicated below each image. The processing parameters are listed above each group of images. Each tile spans a width of 400 µm is only a section of the original frame.

It is clear from the above results that fine groove cutting is possible in stainless steel but the mechanisms involved are complex and results are not linearly related to process parameters. A considerable amount of future work needs to be carried out to establish optimum process parameters.

4. Conclusions

The following conclusions can be drawn from this work;

a. Grooves or slits with very large aspect ratios can be created in stainless steel using ultrashort laser pulses.
b. The grooves created in the parameter range employed here are generated by the consolidation of a line of micro-holes which are drilled into the material in the early stages of the laser-material interaction.
c. The relationship between the process parameters and the resulting groove/slit is complex and requires further investigation.

Acknowledgements

This research was funded by the Ministry of Science, Research and Arts of the Federal State of Baden-Württemberg within the InnovationsCampus Mobilität der Zukunft.

Thanks to Light Conversion (Vilnius, Lithuania) for providing the ultrashort pulsed laser (Carbide CB3 80). The presented investigations were carried out in cooperation with DESY in Hamburg and with RWTH Aachen University within the framework of the Collaborative Research Centre SFB1120 - 236616214 " Bauteilpräzision durch Beherrschung von Schmelze und Erstarrung in Produktionsprozessen " and funded by the Deutsche Forschungsgemeinschaft e.V. (DFG, German Research Foundation). We acknowledge DESY (Hamburg, Germany), a member of the Helmholtz Association HGF, for the provision of experimental facilities. Parts of this research were carried out at PETRA III and we would like to thank F. Beckmann and J. Moosmann for assistance in using P07 EH4. Beamtime was allocated for proposal I-20210713. The sponsorship and support are gratefully acknowledged.

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