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Investigation of the influence of beam oscillation on the laser beam cutting process using high-speed X-ray imaging.

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Abstract

Recently, it was shown that oscillating the laser beam during laser beam cutting can increase the maximum cutting feed rate compared to cutting with a static beam. In order to investigate this phenomenon, the geometry of the laser cutting front was observed by means of online high-speed X-ray imaging. Fusion cutting of 10 mm thick samples of stainless steel was recorded with a framerate of 1000 Hz. When the beam was oscillated in longitudinal direction, the maximum cutting feed rate could be increased by 24% compared to cutting with a static laser beam. In addition, the global angle of incidence on the cutting front decreases with an increasing feed rate for both cases. When comparing the global angle of incidence of the two cases at the maximum feed rate for each case, it can be seen that the angle is smaller in case of cutting with an oscillated beam. As a consequence, the absorptivity increases by approximately 20%, which explains an increase of the maximum feed rate due to beam oscillation

Keywords: laser beam cutting, cutting front, beam oscillation, online high-speed X-ray imaging, stainless steel

1. Introduction

The optimization of thick metal sheet cutting with a laser at the wavelength of about 1 µm includes achieving the highest possible cutting feed rate with the lowest possible surface roughness of the cut edge. The surface roughness is determined by the striations, which are a result of the melt flow at the cutting front, which was measured in Lind et al., 2021. The maximum cutting feed rate is given by the maximum amount of molten material per unit time. This is directly related to the absorbed power of the laser beam at the cutting front, which is defined by the angle of incidence on the cutting front. Mahrle and Beyer, 2009 showed, that beam oscillation can influence the cut front angle and therefore the absorptivity and maximum cutting feed rate. Goppold et al., 2020 showed that when the beam was oscillated parallel to the feed direction the maximum feed rate increased and the surface roughness of the cut kerf and the dross height at the bottom of the sample decreased, compared to a static beam.

Since the angle of incidence influences both, surface roughness and maximum cutting feed rate, it is mandatory to know about the dynamic changes of the angle of incidence on the cutting front in case of cutting with beam oscillation. This proceeding presents for the first time a space- and time-resolved experimental determination of angle of incidence on the cutting front during laser beam cutting with beam oscillation by means of high-speed X-ray imaging.

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2. Setup

Cutting of stainless steel 1.4301 was investigated using a TruDisk8001 disk laser with a wavelength of 1.03 µm in combination with a Precitec-LightCutter cutting head. Fig.1 a) sketches the experimental setup. The origin of the coordinate system (x,y,z) was set at the intersection point of the center line of the nozzle and the surface of the sample. The cutting head was connected to a 2D-galvanometer scanner, which enabled a movement of the laser beam in the x-y-plane. The beam-delivery fiber had a core diameter of 100 µm and the beam was focused to a waist diameter of approximately 150 µm to a top hat intensity distribution. The laser power was 6 kW, the focus was positioned 5.3 mm below the sample's surface and nitrogen with a pressure of 12 bar was used as cutting gas. The cutting nozzle with an outlet diameter of 5 mm was positioned 0.7 mm above the 10 mm thick sample (in the direction of the laser beam, z-axis). The feed was achieved by moving the sample. The feed rate was varied between 1.3 m/min and 3.3 m/min. To observe the influence of beam oscillations on the cutting process, cuts with a length of 40 mm were produced with and without beam oscillation. In the following. the static beam is denoted by "scanner off" and the oscillated beam by "scanner on". Fig. 1 b) shows the intensity distribution in the x-y-plane in the case of "scanner off" without beam oscillation. Fig. 1 c) shows the intensity distribution in the x-y-plane in the case of "scanner on" where the laser beam was oscillated parallel to the feed direction with an amplitude of 200 µm and a frequency of 400 Hz.

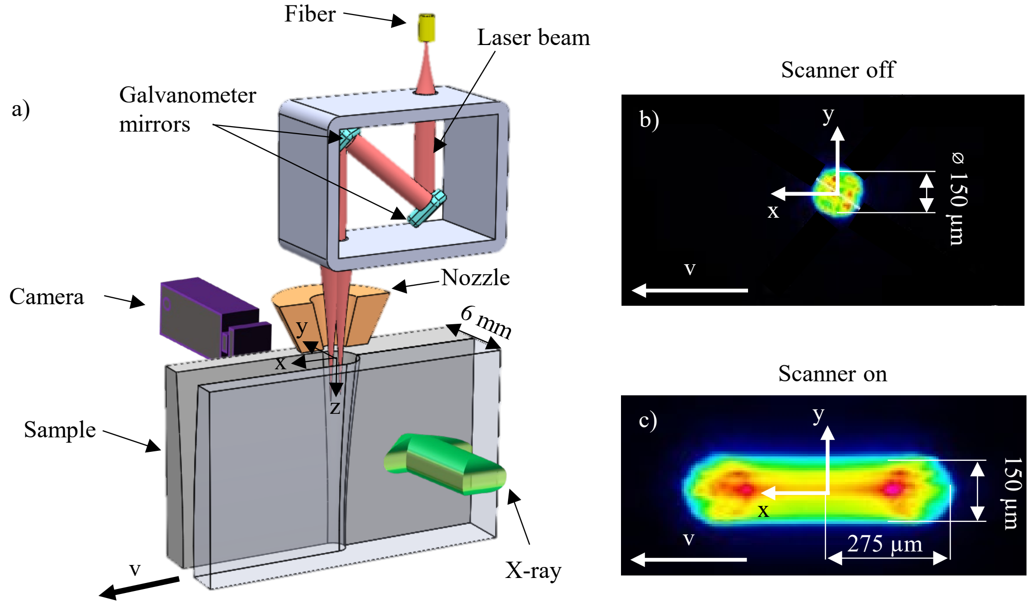

Fig. 1. Sketch of the experimental setup (a) and intensity distributions in case of "scanner off" b) and "scanner on" c) with an amplitude of 200 µm and a frequency of 400 Hz.

The X-ray imaging system consisted of an X-ray tube and a high-speed camera, as described in Abt et al., 2011. In order to be suitable for the X-ray imaging the width of the samples (in the direction of the X-rays, y-axis) was chosen to be 6 mm. The recording by the camera was performed at a frame rate of 1000 fps, with a spatial resolution of 37 pixels/mm. The acceleration voltage of the X-ray tube was set to 140 kV with a tube power of 90 W. The X-ray videos were post-processed with a flat-field correction and Kalman filtering in order to enhance the image contrast and to reduce the noise. The setup is described in detail in Lind et al., 2020, where the system was previously used to study the laser cutting process.

3. Results

Fig. 2 shows two averaged images over 100 frames of an X-ray video showing the cutting process in a 10 mm thick stainless steel sheet in case of "scanner off" (left) and "scanner on" (right). The average images show the cutting process for the two cases ("scanner off" v = 2.5 m/min, "scanner on" v = 3.1 m/min) for the maximum feed rate at which a successful cut was possible.

The images show the gray-scale coded local transmittance of the X-ray radiation through the sample. A clear contrast between the solid sample material (dark, high absorption of X-rays) and the cutting kerf (bright, low absorption of X-rays) is visible in the images. From these images, the geometry of the cutting front (line at the center of the cutting front) was determined, as highlighted by the green dashed line in Fig. 2. The caustic of the laser beam which results from the measured beam characteristics is represented by the white dashed line in Fig.

2 left. In the case of “scanner on”, the caustic is represented by the white dashed line at the maximum positions for x = +/- 0.2 mm.

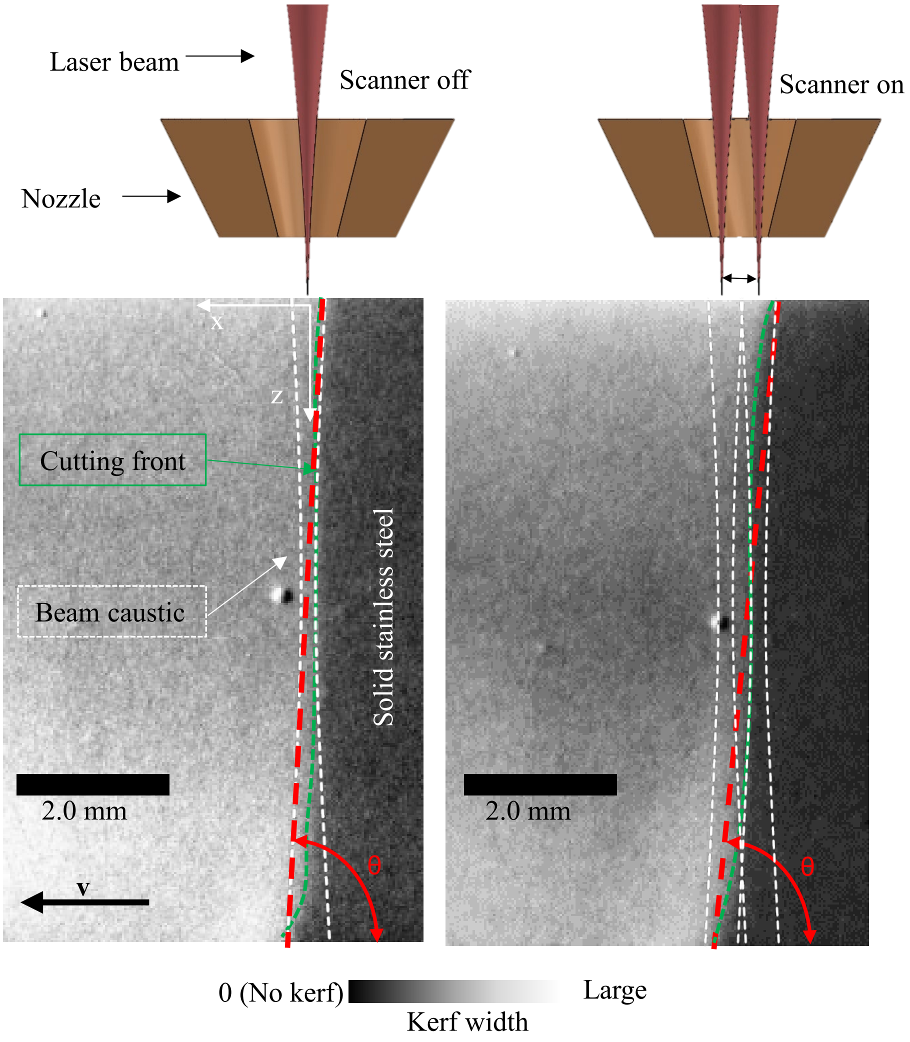

Fig. 2. Average image of 100 frames from an X-ray video showing the cutting process in a 10 mm thick stainless steel sheet in case of “scanner off”at a feed rate of v = 2.5 m/min.and in case of “scanner on” at a feed rate of v = 3.1 m/min at the laser power of P = 6 kW.

The results show, that in case of “scanner on” the maximum feed rate could be increased by 24% compared to cutting in case of “scanner off”. In both cases, the position of the cutting front in x-direction at the lower surface of the sample coincides approximately with the beam diameter at this position. In order to investigate the influence of beam oscillation on the absorptivity, the global angle of incidence on the cutting front was analyzed. The angle between the lower surface of the sample and the line between the position of the cutting front at the upper and lower sheet surface of the sample is denoted by the global angle of incidence θ, as highlighted by the red dashed line in Fig. 2.

Fig. 3 a) shows the global angle of incidence as a function of the feed rate in case of “scanner off” and “scanner on”. The data points represent the average of the global angle of incidence of three repeated experiments. The length of the error bars indicates the range between the minimum and maximum measured values within the three measurements.

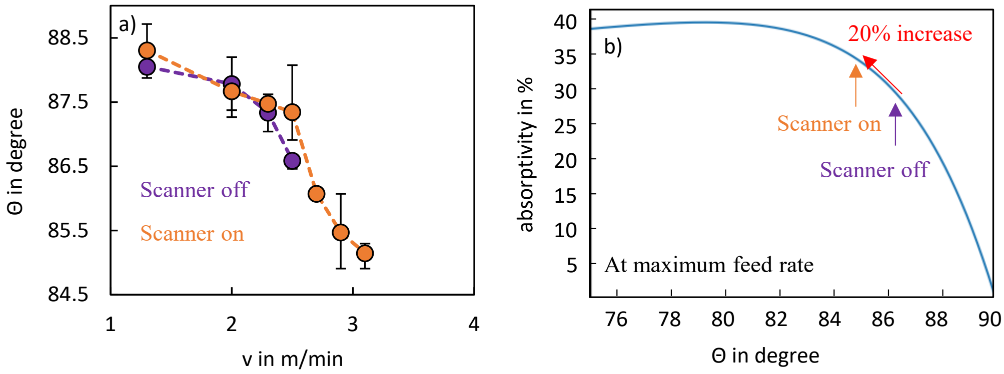

Fig. 3. Global angle of incidence as a function of the feed rate a) and absorptivity as a function of the global angle of incidence b) in case of "scanner off" and "scanner on"; P = 6 kW.

Fig. 3 a) shows that the global angle of incidence on the cutting front decreases with increasing feed rate for both cases. At low feed rates between (1.3 m/min and 2.3 m/min) the global angle of incidence is approximately the same for both cases. At a feed rate of 2.5 m/min at which the "scanner off" case is at its maximum feed rate, the global angle of incidence is smaller in case of "scanner off". When the feed rate is further increased in case of "scanner on" the global angle of incidence decreases further and reaches values below the minimum in case of "scanner off". Fig. 3 b) shows the absorptivity as a function of the global angle of incidence in case of "scanner off" and "scanner on" at the maximum feed rate for each case. The absorptivity was calculated from the Fresnel equations. For this calculation an unpolarised laser beam was assumed, with equal shares of parallel and perpendicular polarization of the laser beam. For this consideration, the complex refractive index $n_c = n - ki$ was chosen for liquid iron, i.e with Re(n_c)=n=3.6 and Im(n_c)=k=5.0. The results show, that in case of "scanner on" the absorptivity is increased by approximately 20% compared to cutting in case of "scanner off". The good agreement between the increase in absorptivity and the maximum feed rate indicates that the influence of beam oscillation on the angle of incidence is mainly responsible for the increased maximum feed rate.

4. Summary

This proceeding presents for the first time a space- and time-resolved experimental determination of the geometry of the cutting front during laser beam cutting with beam oscillation by means of high-speed X-ray imaging.

The results show that, when the beam was oscillated in longitudinal direction, the maximum cutting feed rate could be increased by 24% compared to cutting with a static laser beam. In addition, the global angle of incidence on the cutting front decreases with an increasing feed rate for both cases. When comparing the global angle of incidence of the two cases at the maximum feed rate for each case, it can be seen that the angle is smaller in case of cutting with an oscillated beam. As a consequence, the absorptivity increases by approximately 20%, which explains an increase of the maximum feed rate due to beam oscillation. In order to gain further information about the influence of beam oscillation on the cutting process, future work will focus on the local absorbed irradiance on the cutting front using ray tracing algorithms. This will allow to calculate the overall absorptance considering multiple reflections and the specification of the incident laser beam.

5. References

Abt F., Boley M., Weber R., Graf T., Popko G., Nau S., 2011. Novel X-ray System for in-situ Diagnostics of Laser Based Processes – First Experimental Results. Physics Procedia 2011, pp 761–770. doi: 10.1016/j.phpro.2011.03.095

Goppold C., Pinder T., Schulze S., Herwig P., Lasagni A. F., 2020. Improvement of Laser Beam Fusion Cutting of Mild and Stainless Steel Due to Longitudinal, Linear Beam Oscillation. Applied Sciences 10, p 3052. doi: 10.3390/app10093052

Lind J., Fetzer F., Hagenlocher C., Blazquez-Sanchez D., Weber R., Graf T., 2020. Transition from Stable Laser Fusion Cutting Conditions to Incomplete Cutting Analysed with High-speed X-ray Imaging. Journal of Manufacturing Processes 60, pp 470–480. doi: 10.1016/j.jmapro.2020.10.068

Lind J., Hagenlocher C., Blazquez-Sanchez D., Hummel M., Olowinsky A., Weber R., Graf T., 2021. Influence of the laser cutting front geometry on the striation formation analysed with high-speed synchrotron X-ray imaging. under review, IOP conferene series: Materials Science and Engineering

Mahrle A., Beyer E., 2009. Theoretical aspects of fibre laser cutting. J. Phys. D: Appl. Phys. 42, p 175507. doi: 10.1088/0022-3727/42/17/175507