Determination of the geometry of laser-cutting fronts with high spatial and temporal resolution

Michael Sawannia¹, Peter Berger¹, Rudolf Weber¹ and Thomas Graf¹

¹Institut für Strahlwerkzeuge, University of Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany
michael.sawannia@ifsw.uni-stuttgart.de

Abstract. The melt flow velocity and the local surface angles of the cutting front during laser fusion cutting of 10 mm AISI 304 were determined for a laser power of 8 kW and a feed rate of 2 m/min. The cut front was recorded with a polarization goniometer, which uses the polarization of the process emission to determine the local surface angles, allowing to calculate the orientation of the normal vector of the surface. The records in this work were carried out with a frame rate of 75 kHz and a spatial resolution of about 30 µm. This allowed to identify big and small structures moving down the cutting front and to determine their velocities. The approximate velocity of the small structures was 9.1 m/s and for the big structures approx. 2.5 m/s. The information of a usual high-speed video was compared with the additionally obtained geometry information.

1. Introduction
The quality of laser fusion cuts decreases for higher cut depths through dross formation and striations on the cut flanks [1]. These effects also result from the melt flow in the kerf, which in turn depends on the locally absorbed laser power at the cutting front and the kerf flanks [2]. In order to analyze the melt flow, mainly high-speed recordings have been used so far. This technique is used not only in laser beam cutting, but also in laser beam welding. The resulting images typically show bright spots on a dark background moving downward the cutting front or the capillary front during laser beam welding. They are usually interpreted as geometric structures called steps [3], shoulders [4], shelves [5], bumps [6] or humps [7, 8]. For their interpretation a distinction should be made between observation methods that illuminate externally or that record the direct emission from the process. In the case of the external illumination, the brightest spots are created by direct reflections of the illumination source via the front onto the camera. For the case of the direct process emission, the brightness of the spots depends not only on the observation angle but also on the local temperature. The temperature in turn is higher for lower angles of incidence between the surface of the structures and the absorbed laser beam. For both cases the velocity of the bright spots can be determined [1, 6, 8], but exact statements about the structure size and surface inclination of the cutting front are not possible. To determine the real geometry of the cutting front, a new measuring device (polarization goniometer) was used. It uses the polarization information of the thermal process emission to determine the local surface angles, allowing to calculate the orientation of the normal vector of the surface, which is called in the following the surface orientation of the cutting front. With the surface orientation the 3D-surface can be determined, which was already shown in [9, 10]. The primary goal of this work is to determine and describe the actual structures and their resulting velocity.
2. Measurement method
The polarization goniometer records four single images of hot metal surfaces, e.g. cutting fronts, simultaneously for one time step. The single images contain the intensity of the thermal process emission after four linear polarizers. The four polarizers are oriented under 0°, 45°, 90° and 135°. With these recorded intensities the surface angles for each image pixel of each time step can be calculated. Two angles are needed to describe all possible surface orientations of a flat surface element, in our case the angle of inclination $\phi$ and the angle of rotation $\alpha$ are used, see Figure 1.

![Figure 1. Schematic sketch of a camera taking four single images through four different linear polarizers from a thermally emitting surface (the real device is more complex). To describe the orientation of the surface in three-dimensional space, two angles are needed, which can be calculated by the four single images. The first one is the angle of inclination $\phi$ that inclines the surface around $y_L$. The second is the angle of rotation $\alpha$, which rotates the inclined surface around $z_L$. By rotating around both angles, the spatial orientation of the surface element is now fully described.](image)

To describe the angles $\alpha$ and $\phi$, first consider a surface element rotated only about the $y_L$ axis relative to the projection of a surface element on the $x_L y_L$ plane. The tilt angle $\varphi$ is then the angle between the normal vector of this inclined surface element (see Figure 1) and the camera axis $z_L$. This is a positive angle if the rotation was counter clockwise about the positive $y_L$ axis. The angle of rotation $\alpha$ describes the following rotation of the normal vector around $z_L$. For the calculation of the angles only the refractive index $n$ and the extinction coefficient $k$ for the emitting material are needed. The spectral range of the recorded emission is limited by a bandpass filter in front of the camera, to allow the assumption of a constant refractive index over the observed spectral range. A more detailed explanation is given in [10]. For the angle calculation, quotients are calculated from the polarized emission parts. The use of quotients has the further advantage that the temperature influence on the refractive index and on the extinction coefficient is negligible, which is shown in [11]. The two angles already tell a lot over the surface. To detect rising structures, the angle of inclination $\phi$ directly indicates steep regions, whereas the angle $\alpha$ indicates in which direction the structure is inclined. The measurement method was applied to laser beam fusion cutting [9, 10].

3. Experimental Setup
A schematic sketch of the used experimental setup is shown in Figure 2. For the investigations, 10 mm thick stainless steel (AISI 304) was cut with an 8 kW thin-disk laser (Trumpf, TruDisk 8001).
The cutting head was a ProCutterET 100/150 from Precitec. A 100 µm fiber connected the laser with the head. The EdgeTec module of the cutting head was used, which creates a ring shaped intensity distribution of the focused laser beam. With $M^2 = 51$, a beam diameter of 824 µm and a Raleigh length of 9.9 mm was calculated.

![Figure 2](image)

**Figure 2.** Schematic sketch of the experimental setup in a) to define the coordinate systems and pixel position.

A standard cutting nozzle was used with an inner diameter of 2.5 mm. The standoff distance was 1 mm. The nozzle was abraded on the outer contour in Goniometer direction to allow a better view on the cutting front. Nitrogen was used as process gas with a pressure of 12 bar. The sample had a dimension of 150 mm x 6 mm with a thickness of 10 mm. A cut of 40 mm was carried out by moving the sample in feed direction $v$, see Figure 2. The used laser power was 8 kW with a feed rate of 2 m/min. For the experiments, the goniometer was set at 25° to the workpiece surface, as shown in Figure 2. The spectral range of the bandpass filter was 857 nm ± 15 nm. The high-speed camera was a Photron FASTCAM SA5, with a recording frame rate of 75000 frames per second. The spatial resolution was around 30 µm, like for the experiments shown in [9].

4. Results obtained by the goniometer

In the following section, calculation results are shown and explained for the local inclination angle $\phi$ and rotation angle $\alpha$. Furthermore the resulting structures are compared with classic high-speed recordings. Thereafter, corresponding velocities of the structures moving down the front are given.

4.1. Polarization goniometer - measurement and calculation

Figure 3 a) shows the four single images of a time step. Despite different polarizer orientations, they look quite similar. The small differences in the intensity, which are caused by different surface orientations are hardly noticeable, just that the 45° and 135°images are darker, which can be attributed to losses in the corresponding two beam paths that are compensated for the calculation. Before the calculation of the angles, the four single images were filtered with a Gaussian blur filter [12] to reduce the noise impact of the images. For the smoothing the program ImageJ (v1.53i) was used with sigma 1 for the filter. The resulting average image of the four intensities (AVG) and the angles $\phi$ and $\alpha$ are given in Figure 3 b). The average image is identical to the result of a classic high-speed record. The speed of the structures on the front is later evaluated along the three drawn lines. These lines are also used for the $\phi$ and $\alpha$ images. All images are oriented to the camera coordinate system ($x_c$, $y_c$ and $z_c$).
The angles $\phi$ are all positive and are mostly in the range of 15° to 40°. In the $\phi$ image round spots can be discovered, some are marked in Figure 3 c) with purple rectangles. They mostly coincide with the bright spots in the AVG image and indicate that there are significant changes in the surface geometry. The phi and the alpha angle can be used to estimate elevations or dents on the surface, thus obtaining geometry information about the front. The angles $\alpha$ are in the range of -90° to 90°. In the $\alpha$ image almost all $\alpha$’s are positive on the left side and negative on the right side of the cutting front. This would also be the alpha distribution for a hollow half cylinder, which can be thought of as a simplified cutting front. For the middle of the cutting front, all $\alpha$ values vary around $\alpha = 0°$, which is in full agreement with a geometry similar to a hollow half cylinder. In the middle, the angle $\phi$ corresponds to the inclination of the half cylinder, whereby in our case it must still be taken into account that we are looking at the front at an observation angle of 25°, if one wants to make statements about the inclination of the front in the workpiece coordinate system.

In the upper fifth and the lower third of the cut front, $\alpha$ changes its sign from plus to minus on the left side, which can be a result of an undercut or indicates bigger structures on the front.

In Figure 3 c) the angle $\phi$ is shown in four images of consecutive time steps. The time steps are 13.3 $\mu$s, which corresponds to the recording frame rate of 75000 Hz. The red spots can be followed, while they are moving down the front. Two examples are marked with purple squares. The moving spots are probably structural elevations moving down the front due to the cutting gas. The purple arrows show the downward movement of the spots on the front over time. There are also spots that increase or decrease in size over the time steps, which allows the structural evolution to be studied in detail, e.g. the marked spot with the purple rectangles in the upper area. The circles mark positions where the spots do not appear to move for a period much longer than depicted with the four frames in Figure 3. In addition,
the black circles mark a special feature. Above these points, the bright spots from the camera image seem to decrease in their velocity and accumulate. This causes the melt to flow not only downwards, but also over the sides of the kerf.

4.2. Moving structures at the front

To show the dynamics at the cutting front, streak images along a line are a suitable option. The streak images were created for the AVG, φ and α images. The streak images shown in Figure 4 were created along the line on the right side of the cutting front (line 3 in the AVG image in Figure 3). 500 single frames were used, resulting in a displayed time interval of 6.7 ms (time steps of 13.3 µs between each image corresponding to the recording frame rate of 75000 Hz). In the AVG image of Figure 4, orange lines mark small fast moving spots, which occur periodically. The φ and α images also clearly show changes at the same locations. They mainly occur in the marked areas from area 2 to 3. Starting from area 4, most of the structures become larger and slower, which can be seen from the smaller slope over time t and the distance of the structure moved along x_c in the φ-image. In area 1 and 5 the signal is very low, so no statements are made for these areas. Big slow moving structures also occur in the streak images in the upper part (area 2). Three structures are marked in the streak images. The yellow one encloses a big bright spot in the AVG image (in area 2), whereas the red and black one enclose very steep structures in the φ image (in the areas 2 and 4). The markings of the structures were transferred to the respective other image and to the α image. The red marked area in the AVG image is always bright except for the tip at the beginning. In the φ image there is already a steep angle, which suggests, that the structure forms before it becomes really bright (hot). This is a considerable gain of information. The reason for the formation of the slow structures is not yet clear. One presumption for the large structures in the upper area is a pressure rise along the x_c axis in the upper area, whereby the melt is slowed down.

Figure 4. Streak images over 500 single images along line 3 shown in the AVG image in Figure 3. The streak images were carried out for the AVG, φ and α images. The time interval between each time step is 13.3 µs. In the AVG streak image small (orange) and bigger spots (yellow, red, and black) are marked. The larger structures (yellow, red, and black) were also inserted into the φ and α images. The front is divided into five sections, see labels on the left. The contrast of the AVG image is increased, the original image was not overexposed.
Thereby the angle of the surface changes and more laser power can be absorbed. In the following the structure heats up and thus becomes brighter. This applies, for example, to the area marked in yellow. In the lower area, a separation of the gas flow from the front is suspected as the cause. This creates a low pressure, which sucks in ambient air in the lower region of the front and slows down the melt flow (transition from region 4 to 5). This presumption is supported by strong oxidation in the lower region of the cut front. To make the brightness variations in the red and yellow spot easier to see, the contrast for the AVG image was increased. For this reason, it looks like the image was overexposed in area 4, which was not the case. In comparison, the $\varphi$ image has a very even contrast, which is another advantage compared to classic high speed recordings. The angle $\alpha$ implies the rotation of the local surface element accordingly to Figure 1. It varies between -90° and 90° for the structures in area 4 as well as for the two marked in structures area 2, i.e. the structures do not move directly downwards in $x_C$, but also have a lateral movement in $y_C$ direction.

4.3. Velocities of the structures at the front
As mentioned before, the slope of the structures in the streak image correspond to their velocity. The velocity of the small and big structures were evaluated for the left side, the middle and the right side of the cutting front, line 1 - 3 in Figure 3. Ten structures were measured for each area, the error bar is the standard deviation. The results for the laser power of 8 kW and a flow rate of 2 m/min are plotted in Figure 5. For the fast structures, the average velocity in the upper part (area 2) of the front is around 10.6 m/s and in the middle part of the front (area 3) about 10.2 m/s. In the lower part the velocity is about 6.5 m/s. In addition, it is noticeable that the velocity on the centre line is always slightly higher than on the left or right side. The reason for this could be that the melt on the side not only flows directly downwards, but also has a directional component along the cut flank, which means that the observed velocity is lower from the point of view of the goniometer. The slow structures only occurred in the upper and lower part, therefore there are no velocities in the middle (area 3). In the upper part, the average velocity is around 1.8 m/s. In the lower part the structures are nearly twice as fast with 3.2 m/s, but as said before, the structures are also smaller. For the determination of the velocities in Figure 5, the slopes in the respective $\varphi$ images were used. For comparison, the velocities were also determined from the average images. The deviation is not very large with a maximum of 0.72 m/s, which is within the range of the measurement accuracy.

![Figure 5](image_url)

**Figure 5.** Measured velocities for the fast and slow structures in the area 2, 3, and 4. The velocities were measured on the left side, the center and the right side of the front. The error bars correspond to the standard deviation.

5. Conclusion and outlook
This paper presents the actual spatial and temporal resolved surface orientation of the cutting front, calculated by the polarization of the thermal process emission. With these, the bright spots in usual high-speed records get a geometrical orientation, which allows to estimate the shape on the front. Here it is remarkable that the inclination of the structures is already noticeable shortly before the appearance of bright spots. Small and big moving structures can be recognized. The small structures have an average
velocity of 9.1 m/s and the big structures a velocity of 2.5 m/s. The velocity determination over streak images works the same for usual camera images as for the determined angles. 

The next steps in the future are to determine the actual structure sizes and to look more closely at the creation of the structures, with the aim of determining an optimal cutting front and melt flow that will produce high quality cuts.

Acknowledgement
The presented work was funded by the German Research Foundation (DFG) and experiments performed in the context of the project “ELS PoGo” (GR 3172/20-1) and the DFG project “FastShape” (426328417). The responsibility for this paper is taken by the authors.

ORCID iDs
M. Sawannia: https://orcid.org/0000-0003-0972-5975
P. Berger: https://orcid.org/0000-0003-4232-3732
R. Weber: https://orcid.org/0000-0001-8779-2343
T. Graf: https://orcid.org/0000-0002-8466-073X

References
[1] Arntz D, Petring D, Schneider F and Poprawe R 2018 Proceeding of ICALEO
[2] Bocksröcker O, Berger P, Fetzer F, Rominger V and Graf T 2018 Lasers Manuf. Mater. Process. 24 52006
[3] Berger P, Schuster R, Zvyagolskaya M, Hügel H and Schäfer P 2011 Schweissen und Schneiden 20–8
[4] Berger P, Schuster R, Hügel H and Graf T 2010 Proceeding of ICALEO
[5] Golubev V S Laser welding and cutting: recent insights into fluid-dynamics mechanisms Laser Processing of Advanced Materials p 1
[6] Pocorni J, Petring D, Powell J, Deichsel E and Kaplan A FH 2015 Physics Procedia 78 99–109
[7] Matsunawa A and Semak V 1997 J. Phys. D: Appl. Phys. 30 798–809
[8] Hirano K and Fabbro R 2011 J. Phys. D: Appl. Phys. 44 105502
[9] Michael Sawannia, Peter Berger, Michael Jarwitz, Rudolf Weber, Thomas Graf 2019 Lasers in Manufacturing Conference
[10] Sawannia M, Berger P, Jarwitz M, Weber R and Graf T 2018 Proceeding of ICALEO
[11] Weberpals J, Hermann T, Berger P and Singpiel H 2011 Physics Procedia 12 704–11
[12] 2019 ImageJ - Gaussian Blur filter: https://imagejdocu.tudor.lu/gui/process/filters