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3D simulation of spatial and temporal modulation in laser beam fusion cutting

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Abstract

Mean profile height and perpendicularity are, along with adherence of dross, the main quality features in laser fusion cutting of sheet metals. Research indicates that the dynamics of the thin melt film and the beam shape have a strong effect on these quality features. Recent measures to reduce the mean profile height include spatial and temporal modulation of the laser beam. A 3D simulation of the melt film dynamics is used to analyze the effect of these measures on the mean profile height and the perpendicularity of the cut surface. Insight into the temperature distribution inside the solid material allows a deeper understanding of how spatial and temporal modulation of the laser beam act on the cut surface. Furthermore, the effect of artificial additional beam sources can be analyzed. The most positive effect on the cut surface was created by a homogenous illumination of the side of the cutting front.

Keywords: Laser Fusion Cutting; Melt Film Dynamics; Simulation

1. Introduction

High-performance laser fusion cutting of stainless steel is well established in industry. Modern energy-efficient solid-state laser systems provide inferior cut quality compared to energy-intensive CO_2 laser systems (Stelzer et al., 2013). Deepening the understanding and developing measures to enhance the quality of the cut for modern laser systems with a wavelength of $\lambda = 1\ \mathrm{\mu m}$ is subject to current research. Besides differing absorption properties of solid state and CO_2 generated laser light (Brügmann and Feurer, 2015), both systems show dissimilar beam shapes caused by beam generation and guiding and an optimization of the beam shape

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for perpendicularity and mean profile height. (Hirano and Fabbro, 2013) analyzed the correlation between the inclination of the cutting front and the mean profile height for a fiber laser with a mediocre beam quality of $M^2 = 14.7$ and found a reduced cut quality for inclinations $\alpha \leq 3°$. As a possible explanation the increased shadowing of the laser light for smaller inclinations was given. Theoretical works using linear stability analysis of the governing equations of the melt film show that the absorption properties of CO_2 lasers lead to a much less pronounced excitation of melt waves compared to $1\ \mu\text{m}$ lasers (Poprawe et al., 2010). (Vossen et al., 2015) suggest to prevent the growth of melt waves by fast closed loop control of the laser power. (Pocorni et al., 2017) show that fiber lasers tend to generate melt humps that are moving downwards the melting front with a group velocity that is smaller than the velocity of the melt itself. X-ray observation of the melt front during laser fusion cutting of stainless steel sheets of $10\ \text{mm}$ thickness indicate that with increasing feed velocity the lower two thirds of cutting front get inclined, while the upper third keeps its steep inclination (Lind et al., 2020).

The approach analyzed in this paper is the spatial and temporal modulation of the laser beam, especially the oscillation of the laser beam axis in feed direction. (Wetzig et al., 2020) demonstrate a setup utilizing high power fiber lasers along with two fast galvanometer and piezo-driven scanning mirrors. Linear beam oscillation in feed direction was able to reduce the occurrence of dross and to increase the maximum possible cutting speed, while the mean profile height was increased (Goppold et al., 2020). The increased mean profile height leads to a reduced quality of the cut. To understand how linear beam oscillation increases the mean profile height, temperature profiles of the cutting front are recorded coaxially during the process and analyzed. (Pinder and Goppold, 2021) developed an explanatory model that includes the volatility of the surface temperature.

To understand why the cut quality is reduced for some oscillation configurations, a deeper insight into the temperature profiles of the cutting front is required. A simulation of the cutting process for longitudinal oscillation is performed for the parameters given in Table 1.

Table 1. Seed point parameters for longitudinal oscillation from (Hirano and Fabbro, 2011).

Parameter	Symbol	Value
Material	$-$	$EN\ 1.4301$
Sheet thickness	a	$3\ \text{mm}$
Laser power	P_L	$8\ kW$
Cutting speed	v_0	$1\ \text{m}\ \text{min}^{-1}$
Focal layer position rel. to top surface	z_0	0
Rayleigh length	z_R	$30\ \text{mm}$
Beam radius	w_0	$850\ \mu\text{m}$

2. Methodology

A reduced 3D model of the laser fusion cutting model is extended to simulate the periodic motion of the laser beam axis. A detailed overview of the mathematical task of the model and assumptions made is given by (Halm et al., 2021). The methodology to analyze the temperature profiles on the cutting front is presented by (Halm et al., 2019). To estimate the quality of a cut, two criteria are evaluated for each simulation: the perpendicularity u and the mean profile height R_{z5} as defined by the (International Organization for Standardization, 2009). Both measures require a high-resolution recording of the cut surface. The granularity of the computational mesh to solve the time-dependent temperature behind the laser beam axis is not sufficient for this purpose. However, the motion of the geometry with respect to the frame of reference of the laser beam axis within one time step of the calculation is below $\Delta x \leq 1\ \mu\mathrm{m}$, so that high-resolution recordings of the cut surface can be created, that show a much finer resolution in feed direction than the computational mesh. Fig. 1 shows the computational domain with an overlay of this recording. The cut surface behind the laser beam axis is resolved sufficiently to evaluate the mean profile height and perpendicularity.

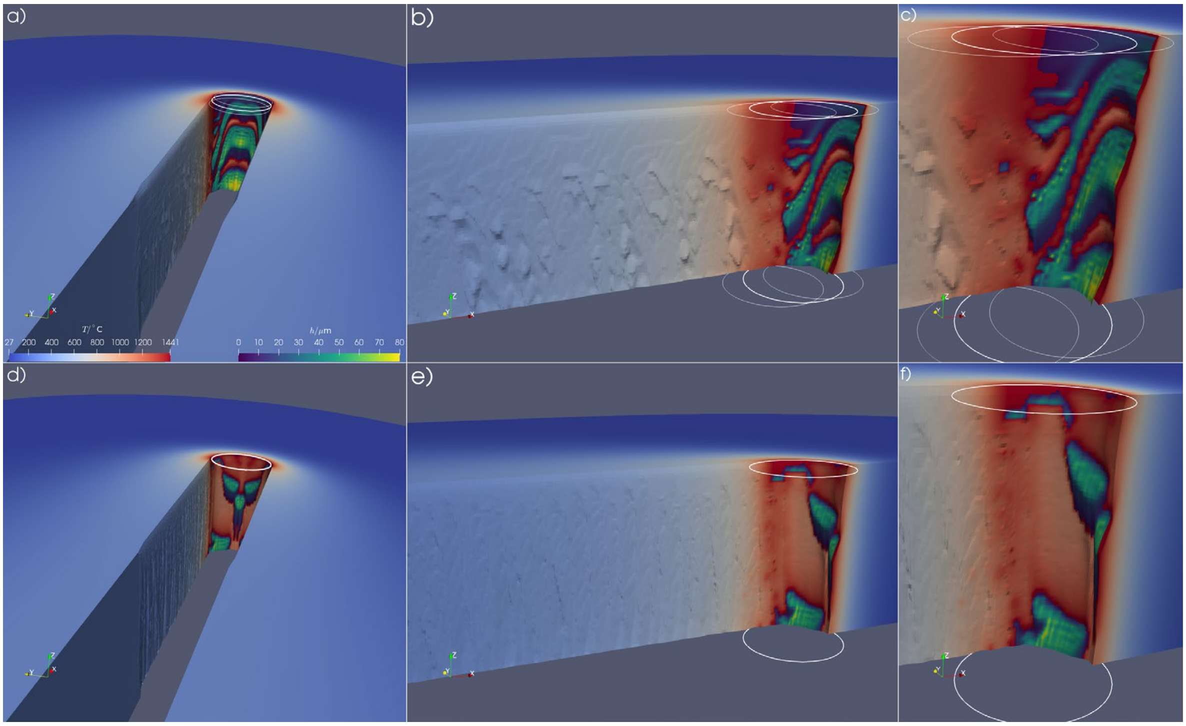

Fig. 1. Simulation of laser fusion cutting. (a) Computational domain with color-coded temperature *T* and melt film thickness h at the cutting front. (b) and (c) zoom of the cut surface and the cutting front. (a)-(c) show the process for a longitudinal oscillation of the laser beam with $\Delta x = 400\ \mu\mathrm{m}$. (d)-(f) show the reference process without oscillation. The thick white circles indicate the laser beam diameter at its central position. The thin circles in the upper row indicate the laser beam positions at its maximum deviation.

The measurement distance of the simulated cut surface is $L = 5\ mm$. To suppress effects of the relaxation of the cutting front at the start of the cut, the total simulation length is set to $7.5\ mm$. ISO 9013 defines the angular tolerance or perpendicularity as difference of the minimum and maximum values of the surface profile at a constant position x along the cut. The topmost and lowermost 10% of the cut are excluded to avoid errors due to rounding at top and adherent dross at bottom. The perpendicularity *u* is given as mean of the local perpendicularity u_x along the measurement distance L. The mean profile height R_{z5} is defined as the arithmetic mean of the maximum and minimum values of five bordering horizontal measurement distances of length $L/5$ at a fixed height z of the cut.

3. Results

A reference cut is simulated using constant parameters given in Table 1. An exponential Gaussian profile with exponent $n = 10$ is used as beam distribution. The total cut length is $7.5\ mm$, while the least $L = 5\ mm$

are used to evaluate perpendicularity u and mean profile height R_{z5}. For the longitudinal oscillation the beam axis x-position is moved by

$$p_x = \Delta_x \, sin(2\pi f \; t) \tag{1}$$

with modulation frequency f and amplitude Δ_x. The simulated frequencies are $f = [500, 750, 1000]\,Hz$, the amplitudes $\Delta_x = [200, 400]$ µm. Fig. 1 (d-f) shows the simulation result for the reference cut and Fig. 1 (a-c) the result for $f = 1000\,Hz$ and $\Delta_x = 400$ µm. Mayor qualitative differences include:

- Volume of molten material is greater for oscillation.
- Shape of the melt waves changes significantly: stairwise to hoof-shaped.
- The inclination of the melting front is increased. The apex position at top matches the beam radius at maximum deviation $p_x = +\Delta_x$.
- The apex position at bottom is not changed significantly.

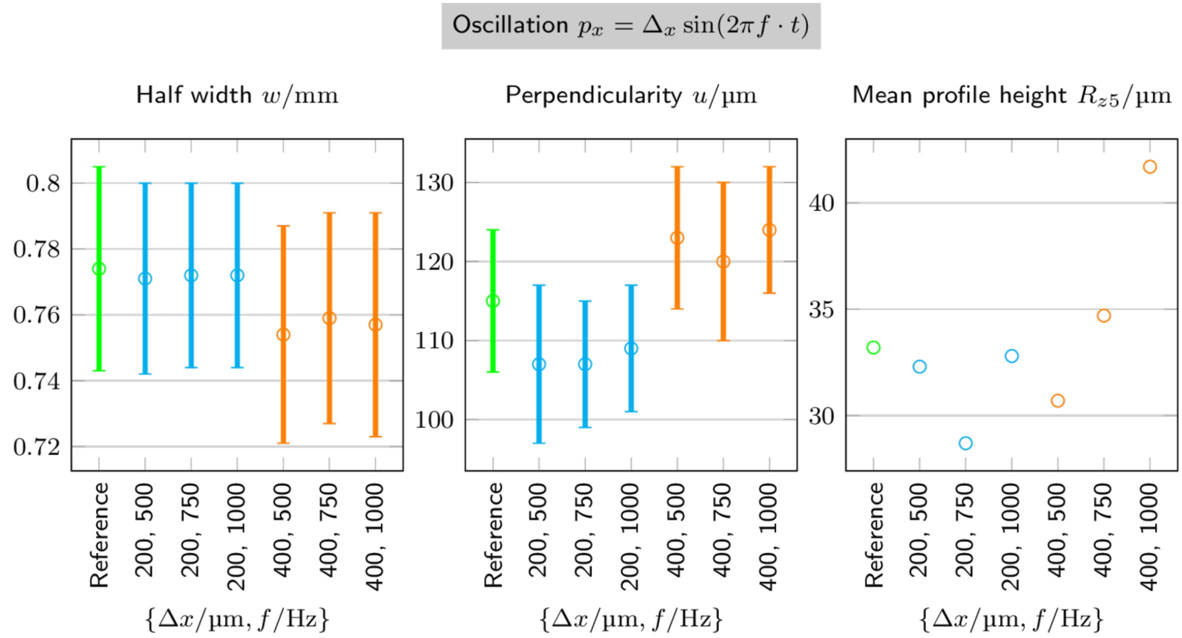

Fig. 2. Kerf width, perpendicularity and mean profile height for different longitudinal oscillation configurations.

Fig. 2 shows the results for kerf width $2w$, perpendicularity u and mean profile height R_{z5}. Conclusions are:

- Kerf width is only slightly changed for oscillation amplitude $\Delta_x = 200$ µm. For $\Delta_x = 400$ µm the kerf width is decreased by $2\Delta w \approx 40$ µm.
- Perpendicularity is enhanced for small oscillation amplitude $\Delta_x = 200$ µm and worsened for $\Delta_x = 400$ µm.
- Mean profile height is enhanced for small oscillation amplitude $\Delta_x = 200$ µm with a distinct minimum at $f = 750\,Hz$.
- Mean profile height is not enhanced for large oscillation amplitude $\Delta_x = 400$ µm with a clear trend to become worse with increasing oscillation frequency.

The simulation results show that no significant quality enhancement can be found for longitudinal oscillation in general, while small enhancements can be found for one distinct parameter set $\Delta_x = 400\ \mu m$, $f = 750\ Hz$ for the cutting configuration given. One possible explanation could be, that the longitudinal oscillation shows a huge impact on the expression of the process at the apex of cutting front, but the essential processes that determine the shape of the cut surface happen on the side of the cutting front. To demonstrate the importance of a homogenous heat input at the side, an artificial power source is added, that illuminates the whole cutting front with incident into +*y* direction. On the cutting front Fresnel absorption formulars are used, so that the additional heat flux is zero at the apex of the cutting front. The additional power source is not raytraced, only the first absorption contributes to the absorbed heat flux.

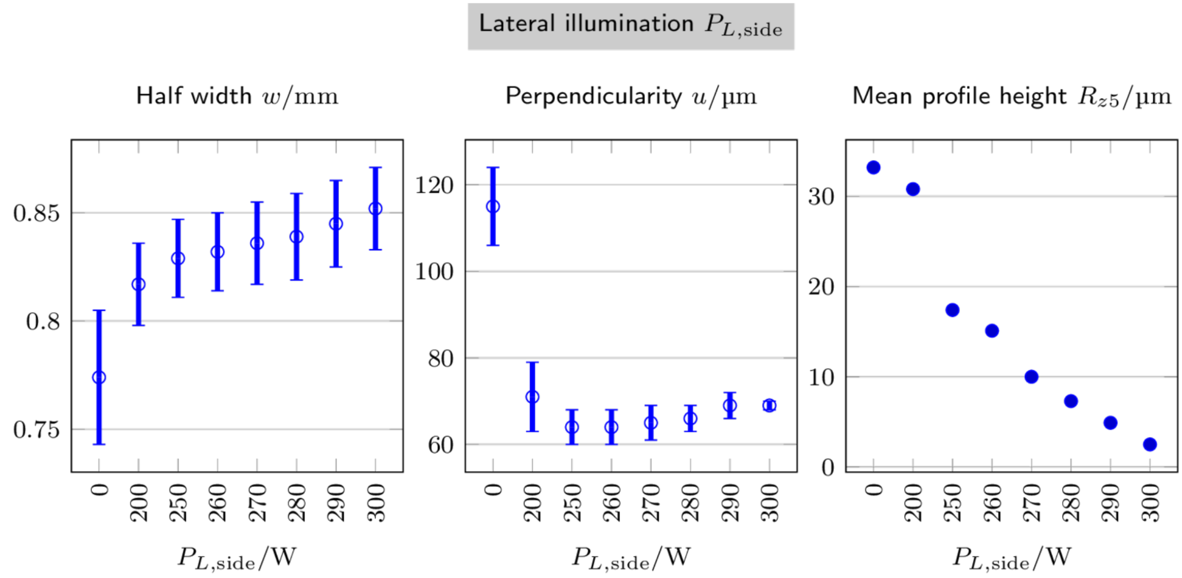

Fig. 3. Kerf width, perpendicularity and mean profile height for artificial lateral illumination.

Fig. 3 shows this effect for an illumination power between 200 W and 300 W. The kerf width is increased with increasing lateral illumination and the perpendicularity is significantly enhanced for all illumination powers. The mean profile height is slightly enhanced for a small lateral illumination of 200 W and drops drastically between 200 W and 250 W. With increasing lateral illumination, the mean profile height is reduced further. This theoretical example shows that measures to enhance the quality in laser fusion cutting should focus on the homogenization of the heat input at the side of the cutting front.

4. Conclusion

In the presented work the effect of longitudinal oscillation on the quality criteria in laser fusion cutting is analyzed by means of simulation. It is shown that for a given cutting configuration slight improvements of the quality can be expected for distinct oscillation amplitudes and frequencies, while most configurations do not lead to a better quality of the cut. A possible explanation could be that the longitudinal oscillation increases the inclination and the volume of the melt film at the apex of the cutting front but does not homogenize the heat input on the side. To demonstrate the effect of a homogenized heat input on the side, an artificial beam source is added that pointed at into +*y* direction. This additional heat input drastically increases the simulated quality of the cut. However the effect of this artificial beam source is hard to apply into a real cutting process. Measures to enhance the quality should focus on the homogenization of the temperature and heat flux distribution on the side of cutting front.

Future research should focus on other modulation patterns and on the homogenization of the temperature profile at the side of the cut. A closer look should be taken at the single parameter set that reduces angular tolerance and mean profile height.

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