Sustainable Production through Advanced Manufacturing, Intelligent Automation and Work Integrated Learning, J. Andersson et al. (Eds.)

doi:10.3233/ATDE240154

Drop Detachment Under Intense Laser Irradiation

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Abstract. During laser processing, complex effects can occur regarding the laser-material interactions. A high laser energy input leads to surface melting and even boiling. The resulting recoil pressure can create the so-called keyhole, a vapor channel existing during welding and called cut front during laser cutting. On the keyhole front wall, the induced recoil pressure pushes the melt downwards and can ejects melt drops. Usually, those melt ejections are seen as undesired spattering or necessary waste to enable the cutting. However, outflow characteristics can tell more about the complex process behavior. Therefore, this work aimed to relate melt ejection formation effects to keyhole behavior in order to get a better understanding of the complex laser-matter-interactions and fluid flows. Axial beam shaping was used to create different energy inputs into the keyhole front walls. Beam shaping was done with an optic that can superposition up to four laser beams in axial direction, leading to varying intensity distributions on the inclined keyhole front walls. Based on high-speed image analysis, it was seen that different outflow characteristics occur depending on the beam shapes. A high intensity on the front keyhole wall could be related to high temperatures on the keyhole wall. The outflow mechanism was shown to be able to move from corrugating to atomizing drop generation at increasing temperature due to temperature-dependent material properties. The main influencing factors are assumed to be the vapor speed and the keyhole/drop diameters that define the outflow mechanism.

Keywords. Laser-matter interaction; melt ejections; metal vapor; keyhole

1. Introduction

Laser beam processing is a long-established technology used for many industrial applications like welding or cutting. The laser energy input into the material defines, which process can be achieved. At low energy input using low laser powers, large laser spots and/or fast processing speeds, e.g. hardening or marking can be performed. When reaching melting temperature, remelting, heat conduction welding or additive processes are possible. However, a special feature when using high-intensity laser beams is the creation of a deep energy input into the material, which is of particularly interest for increasing the process efficiency and enable thick sheet joining or cutting.
When overcoming the deep penetration threshold, a so-called keyhole, a vapor channel inside the melt pool, is created, in which the laser beam is reflected and absorbed multiple times (e.g. [Kaw11]). High-power laser systems can provide increasing intensities

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(power per illuminated area) by higher laser output power at smaller focal spot diameters. This enables welding and cutting of thick materials [Fro15]. On the one hand, the increased depth of the keyholes leads to the efficient thick-sheet processing possibilities. On the other hand, the diverging laser beam leads to typically decreasing energy input in the lower keyhole front areas.
When welding through the material, the melt pool has two surfaces, one on the laser side and one on the root side of the material. During welding, imperfections can occur based on the melt pool creation and flows. Undercuts, underfills, dropouts [Fro15] or even spatter ejections [Sal10] can occur. In welding, melt ejections are not desired since they denote material losses for the melt pool and the particles might attach to surfaces of the part. However, in cutting processes, the material ejections are desired. In fact, drop ejections enable the separation of the parts, which are either induced by a focused gas flow pushing the melt from the cut front or inducing the recoil pressure using the high-intensity laser beam during remote cutting. In both cases, the material flow needs to be controlled either to maintain the material in the melt pool or guide the material from the cut front and avoid e.g. dross formation.
Controlling melt flows of liquid metals can be challenging due to the high temperatures and the typically low surface tension and viscosity values. In particular, the root part of a melt pool can show dynamic behavior. In addition, the keyhole is typically inclining when the input energy is not sufficient to push the melt on the keyhole wall away by the induced recoil pressure, which can induce additional dynamic features in the melt flow.
Drop ejections from liquid flows were examined in many works. The derived parameters that help describing those phenomena are the Ohnesorge number Oh

$$Oh = \frac{\eta}{\sqrt{\sigma \cdot \rho \cdot d}} \quad (1)$$

with the viscosity η, surface tension σ, density ρ, drop/keyhole diameter d denoting the relation between viscous to inertia and surface tension forces and the Reynolds number Re

$$Re = \frac{v \cdot d \cdot \rho}{\eta} \quad (2)$$

with the geometrical dimension of the drops denoting the relation between inertia and viscous forces.

Most of the factors in equations 1 and 2 are temperature dependent. Therefore, the Ohnesorge and Reynolds number will change with increasing temperature.

One possibility to alter the energy input and thereby the temperature distribution inside the keyhole is beam shaping. Beam shaping has a long tradition in laser beam processing. For hardening, rectangular or line laser beams were already used when laser beam processing just started. However, most material processing techniques still run with the laser beam provided by the laser machines. Typically, the laser beams transferred through an optical fiber show a tophat profile in the focal plane projecting the fiber end distribution into the focal spot. Further away from the focal plane, the spatial intensity distribution typically turns more into bell-shaped profiles. Single-mode fibers offer the possibility to also derive Gaussian-like distributions in the focal plane.

During the last years, beam shaping possibilities increased rapidly for applications in the high-power range. Dynamic beam shaping solutions were developed. A typical beam shaping solution is the use of oscillating mirrors to rapidly guide and scan the laser beam (e.g. [Sch14]). Oscillating beams or vibrating membranes can be used to alter the beam shape in certain patterns (e.g. [Ai22]). Rapidly switching the laser beam through a pattern offers the quasi-static application of a huge variety of beam shapes with the possibility of switching between patterns (e.g. [Pri20]). It could be shown that keyholes can be converted into more stable buttonholes using oscillating beams (e.g. [Vol21b]).

Diffractive optical elements were further developed to also withstand high local intensities and form high-power laser beams. A huge variety of beam shapes can be created. However, the desired pattern is usually only available in the calculated plane due to the pattern creation mechanism using interference.

Refractive optical elements provide the possibility to create one specific static beam profile in a robust way. Often, the beam shape is still visible also within the Rayleigh length of the beam around the focal position. Typically, refractive beam shaping is used to form donut or ring patterns (e.g. [Vol16]), but also more complex intensity distributions are possible.

Some advantages of beam shaping during laser beam processing are already known. The redistribution of energy input helps to avoid temperature peaks and local melting during hardening (e.g. [Qiu12]). Donut-shaped beams were shown to influence the energy absorption inside the keyhole during laser beam welding [Vol17]. Splitting the laser beam into several spots can support the stability of keyholes as well. Four-spot or even nine-spot welding was seen to improve the vapor outflow conditions, less shear forces on the keyhole wall and thereby reduced spatter ejection [Vol22]. The melt flows were shown to be changed. The wider melt pools offered the melt pool to flow towards the melt pool center line, which enabled an increased gap bridgability.

Another possibility of refractive beam shaping is to superposition several laser beams along the optical axis and create a kind of elongated volume of higher intensities. Initial tests could show that the spatter occurrence can be decreased using such an axial beam shaping [Vol19, Vol21].

The possibilities of beam shaping are not fully understood yet, but increasing research on applications of beam shaping in various tasks increase the knowledge about laser beam shape impacts. Since several aspects need to be considered in the complex system, other processes like cladding, drilling, Directed Energy Deposition or Powder Bed Fusion can benefit from an increased understanding of process physics. Liquid flow understanding can even support related processes that use different heat sources, like electron beams or plasma sources in the future.

This work used the axial beam shaping method to superposition up to four laser beams and vary the energy input on the keyhole front wall. The aim is to relate keyhole characteristics to drop formation effects in order to get a better understanding of the complex laser-matter-interactions.

2. Methods

A laser remote cutting setup was installed using a gantry CNC system that moves the laser optics relative to the sheet. A titanium sheet of 1 mm thickness was used to perform the laser processing experiments creating a track of 45 mm length. Shielding gas Argon was used at 19 L/min. The laser beam was angled by 20° against the moving direction to avoid back reflections into the laser optic. A fibre of 100 µm diameter combined with a 200 mm focal distance of the focussing lens created a focal spot diameter of 100 µm in the beam waists. The laser power was set to 5 kW (IPG fibre laser) and the processing speed to 7.5 m/min. A beam shaping optic (Adloptica, foXXus) was used to create different axial beam shapes (Figure 1). The axial beam shaping utilizes the axial superposition of up to four separate laser beams.

A keyhole was created during processing that was going through the whole sheet. High-speed recording was performed at 4000 fps from the side to observe the drop outflow from the processing zone. The keyhole front inclination was observed and the drop sizes ejected from the bottom opening of the keyhole were measured and averaged.

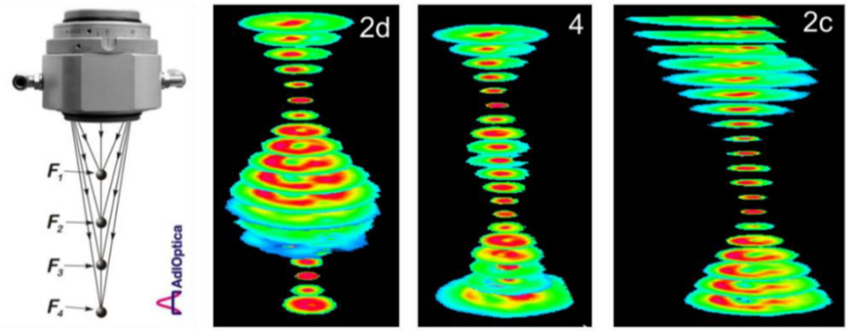

Figure 1. Axial beam shaping optic and beam measurements of used beam shapes [Vol21a]

The resulting intensity distributions on the front wall was calculated. For that, the laser beam was split in sections. Each section received one intensity value depending on the intensity absorbed in this section. The ray was then projected on the keyhole wall, while the keyhole dimensions were estimated from the high-speed images. The absorption percentage was derived using Fresnel equations, depending on the incident angle of the ray, assuming unpolarized laser light.

Cutting of the sheets was performed using the three different axial beam shapes. The resulting drop ejection characteristics were compared to the keyhole front wall energy distributions. The influence of surface tension, viscosity, processing speed and drop diameter on the drop formation mechanisms were evaluated and categorized for the different cases.

3. Results

The processing of the material with the different axial beam shapes lead to different keyhole and process behaviours. At 2c-configuration, the keyhole was seen to be inclined following the angled laser beam, while at 2d-configuration, the keyhole is nearly straight inside the sheet. The 4-configuration shows a keyhole that switches between partial and full penetration. This indicates that the energy input into the keyhole is changed when using the different beam profiles.

The high local intensity at the lower part of the sheet at 2c-configuration leads to an atomizing drop ejection, while the wider spread intensity distribution at 2d-configuration shows corrugation with later drop formation of a regular size of ~0.1 mm diameter.

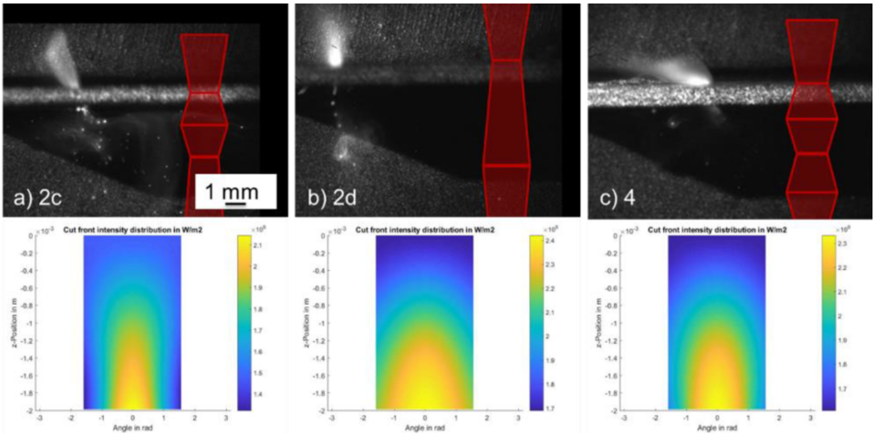

Figure 2. High-speed images of laser processing of a 1 mm titanium sheet (laser beam movement from left to right) at different beam shapes including calculation of front intensity distributions (projection of the rounded keyhole front)

4. Discussion

The main purpose of the investigation was to understand the melt physics under intense laser irradiation better. The ejections on the lower part of the keyhole are usually seen as waste material and are typically not of high interest regarding cut or weld quality in the sheets. However, it is possible that the outflow gives indications about the process behaviour. Therefore, the hypothesis of this work is that the metal vapour is the main driving force to define melt drop formation and not the melt surface tension.

General tendencies are known for laser cutting. A higher inclination angle and a higher temperature at the cut front are typically created at increased cutting speed [Mas03]. This means that the melt can be overheated and even vaporizes (e.g. seen in remote cutting). Simulations show that heating above 3000 K is possible [Ott12]. Since the energy input by the laser beam can alter the keyhole front inclination angle [Sch12], the melt flow and also the drop formation and appearance should be affected.

In this work, it was seen that for a higher keyhole front inclination angle that follows the laser beam at 2c-configuration, the keyhole front should be comparably hot due to the local high intensity values. The 2d-configuration seems to be less heated.

In order to get a better understanding of the relations between keyhole and drop formation, the Ohnesorge diagram was plotted at increasing parameter values (arrow direction) of the main influencing factors (Figure 3). The transition zone from corrugating to atomizing was added based on literature experience (e.g. [Hug13]).

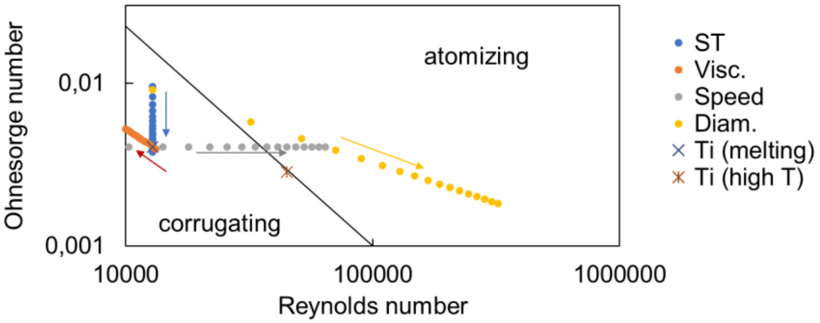

Figure 3. Tendencies of Ohnesorge vs Reynolds numbers at varied surface tension (ST), viscosity (Visc.), vapor speed (Speed) and drop/keyhole diameter (Diam.) including arrows indicating increasing values of the parameter and examples of titanium at melting temperature and at increased temperature (see Table 1)

The drawn parameters were varied keeping the respective other parameters constant at melting temperature values (Table 1). Surface tension and viscosity show comparably small changes in the ranges of possible values. However, the vapor speed and the ejecting drop/keyhole diameter can change the ejection mode from corrugating to atomizing according to Figure 3. The data points of this work at melting and at high temperature (2500 K) were inserted as examples to show the tendencies (Figure 3, Table 1). In general, a higher temperature changes the parameters to move from corrugation to atomization.

Table 1. Material parameters of titanium and calculated Ohnesorge and Reynolds numbers

	Unit	**Ti (melting)**	**Ti (2500 K)**
Density	kg/m3	4500	4500
Dynamic viscosity	Pa*s	0.0035	0.002
Vapor speed	m/s	100	200
Average drop diameter	m	0.0001	0.00013
Surface tension	N/m	1.64	1.1
Ohnesorge number		**4.07E-03**	**2.84E-03**
Reynolds number		**1.29E+04**	**4.50E+04**

This tendency seems confirmed in the actual experiments. The high temperatures of the keyhole front wall at 2c-configuration shows the tendency to atomizing, while the lower temperatures of the 2d-configuration tend to show corrugation.

5. Conclusion

In laser processing experiments of titanium sheets, high-speed imaging and intensity calculations could show that the temperature-dependent parameters can shift the drop ejection from corrugation to atomization, while the vapor speed and drop size are the main factors to define the ejection mode. Furthermore, it was shown that a high intensity on the keyhole front wall leads to higher temperatures and in turn to the tendency to atomizing ejections.

Acknowledgements

The authors acknowledge the funding of PoSAddive – Powder Sheet Additive Manufacturing (EIT raw materials, No. 22021) and SMART - Surface tension of Metals Above vapoRization Temperature (Vetenskapsrådet, No. 2020-04250).

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