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# Local flashing events at the keyhole front in laser welding

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ABSTRACT

For sufficiently high power density, high power lasers induce a vertical boiling front that enables keyhole welding. Waves streaming down the keyhole front were recently observed by ultra-high speed imaging. Although the wave flow appears continuous, deeper analysis has revealed that it is composed of flashing events. The evaluation of eleven events for five parameter cases confirms a strong modulation of the recorded grayscale of bright peaks, achieving up to 50% higher brightness. The flash can even end 50% darker than initially, probably in the shadow of the laser beam. The flashing events took place every 5-15 μs, lasted for typically 10–70 μs and moved at a speed of 10–15 m/s. The flashing events are of fundamental significance to understand the keyhole front. They are associated with temperature peaks and with temporary local boiling action, accompanied by ablation pressure that accelerates the melt.


## 1. Introduction

The interaction of a high power laser beam with a metal induces surface boiling when the power exceeds a threshold value, typically of the order of $MW/cm^2$. During surface boiling, the offstreaming atoms transfer through the equivalent ablation pressure (also called recoil pressure) a strong momentum to the melt. Even for moderate boiling the pressure achieves values that easily accelerate the melt, which not only generates melt flow but often very violate events such as spatter ejection. A laser-induced boiling front [1–3] at glazing inclination to the laser beam governs processes such as keyhole (vapor capillary) mode laser welding, [4–7] see Fig. 1(a),(b), laser drilling, laser ablation and laser remote cutting [8,9]. While drop ejection needs to be avoided in laser welding, for the other mentioned processes it becomes the major material removal mechanism determining a sound process and product quality. The geometry of the concave-shaped processing front is complex but essential for stable process conditions. The ablation pressure governs the development of the shape of the processing front, globally and as a collective of local events. The interaction involves mechanisms such as laser beam propagation, absorption, heat conduction, boiling, melt and vapor flow, phase changes (e.g. the formation of nano-particles in the vapor), scattering and absorption of the laser beam by the metal vapor, etc. Despite manifold experimental and numerical efforts, this complex interaction mechanism between the laser beam and the processing front is only partially understood. Nonetheless, the above mentioned techniques such as keyhole mode laser welding, laser drilling or laser ablation are often properly working and well established techniques, provided the process quality can be ensured for a certain application. To reduce empirical optimization, improved understanding is strongly desirable.

Laser-induced boiling action and the accompanied ablation or recoil pressure accelerating the melt was calculated either by kinetic gas dynamics, solving the Boltzmann equation, or by introducing discontinuity equations for the so-called Knudsen layer.[10] High speed imaging is frequently applied to observe many valuable phenomena at the melt surface, see Fig. 1(a), or in the vapor flow, [4,11] usually at frame rates between 1000 and 20 000 fps, and by filtering the backscattered radiation from an illumination laser. A complementary technique, available only at two research groups, is x-ray transmission imaging, where tracer particles or a contrast liquid in the melt can be observed from the side, however, at lower resolution in space and time [4].

However, only recently [12] it became possible by ultra-high speed imaging to observe a wavy capillary surface at the keyhole front, which shows a complex structure (or pattern), see Fig. 1(c), that moves downwards and indicates sub-surface turbulences. The images were recorded at 180 000 fps with a shutter time of 1 μs but no illumination laser, hence merely observing the thermal emissions. Eriksson et al.[6] postulate that bright areas observed correspond to local temperature peaks resulting from hot wave shoulders where high absorption and a strong evaporation has taken place. Dark areas show less hot domains, probably in shadow. Although the observed waves do not directly correspond to the melt surface topology, they are strongly related to it. 48 observations for a wide range of energy parameters (however

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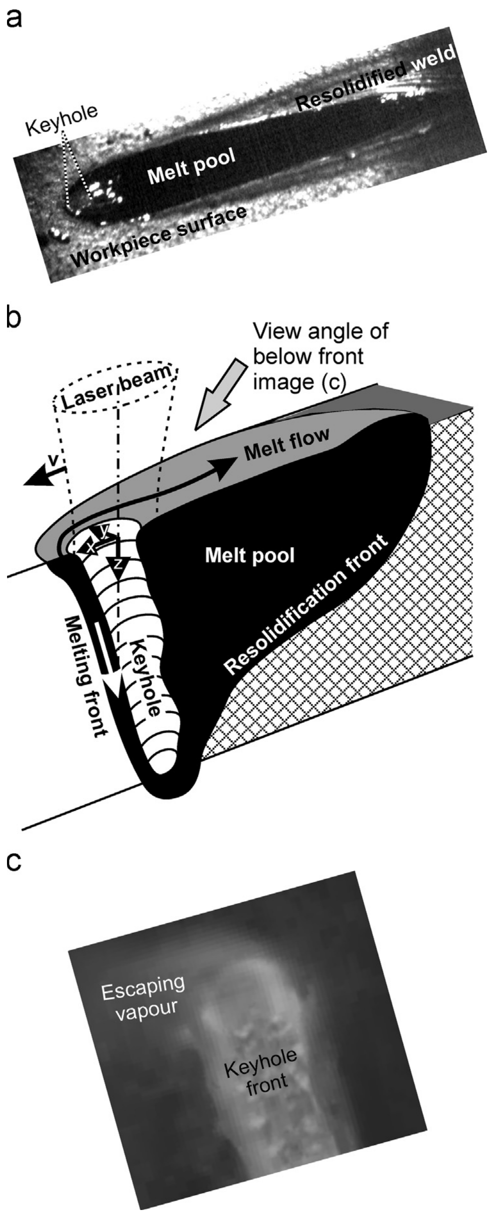


**Fig. 1.** High speed imaging of the keyhole front in laser welding: (a) high speed image of the weld pool top surface and keyhole opening, (b) illustration of the keyhole and melt pool, and camera view, (c) image downstreaming waves observed at the boiling keyhole front, recorded from the rear side.

only for the Yb:fiber laser wavelength of 1070 nm, hence not for 10.6 μm $CO_2$-lasers yet) were carried out which all agree that the boiling front surface is not smooth but shows topography of wavy oscillations (humps). The observations aid to improve the understanding of the fundamental physical mechanisms involved.

Zhang et al. [13] observed liquid shelves (humps) on the front of the keyhole in laser welding, with typical Gauffer structures. For laser interaction with ice, Berger et al. [14] identified humps (shoulders) that are accompanied by the generation of larger pockets at the rear capillary wall, associated with strong evaporation taking place at the shoulder. Instabilities of hump formations at the front were predicted numerically for the condition that the horizontal component of the melt front/keyhole wall velocity propagates opposite to the welding direction. [15] Under certain processing parameters the momentum of the oscillations at the keyhole humps are strong enough to vertically eject spatter, finally changing the process from keyhole welding to remote fusion cutting [1,8]. The velocity distribution of the melt film flow observed by Eriksson et al [16]. was expanded into an empirical equation to model the front geometry and absorption conditions for laser remote fusion cutting.[9] Numerical simulation of the fluid flow in laser materials processing, including the boiling action and ablation pressure, has confirmed that the induction of downstreaming waves at the keyhole front are likely to take place [1–3].

To estimate the consequences, the Fresnel absorption at a wavy processing front was systematically calculated, [7,17] for glazing incidence of the laser beam. Strong local Fresnel-absorptivity modulation was predicted across a growingly wavy metal front, accompanied by increasing shadowing. Owing to very different Brewster angles, $CO_2$-lasers show a very different behavior compared to 1 μm wavelength lasers. The absorbed laser power density distribution on humps in a keyhole was calculated in dependency of the laser wavelength, beam quality and polarization [14]. The power contributions of the thermal emission from the keyhole, melt pool and solid surface domains during laser welding were calculated in comparison with high speed imaging and photodiode sensor signals. The results demonstrated that the combination of a large and hot melt pool dominates the detected radiation intensity [11] while the time dependency is governed by scattering through the fluctuating vapor plume [18].

The quantitative measurement of the vertical fluid flow and its direction from top to bottom of the keyhole developed by streak photography visualizes time-dependent events [6]. In many cases a nearly vertical downward flow was observed. In particular, evidence was found that the waviness is not merely phase but mass flow. For high line energy $P_L/v$, i.e. high laser power $P_L$ and low welding speed v the downward thrust is so strong that laser remote fusion cutting takes place, as an ultimate trend from increasing root spatter in full penetration welding. Another observation was ejected micro-droplets dwelling to the rear of the keyhole, causing vapor burst [13]. The melt ejection velocity distribution shows sharp maxima in the hump areas and the hump formation frequency is directly proportional to the translation speed [15].

A recently conducted deeper analysis on the patterns of the observed boiling front discovered that the brightness of the wave peaks is not continuous but strongly fluctuates. The brightness dynamics is here studied for eleven typical strong flashing events. The findings partially explain the fundamental mechanisms of the whole process and are accordingly discussed.

## 2. Methodology

From 48 recently recorded high speed imaging videos for different laser power and processing speed, [6,16] five cases I-V were selected for deeper analysis, see Table 1. Basically, increasing line energy from 50 to 300 was selected, for systematic comparison. For $E=150$ kJ/m, a second case was added to compare two cases of almost identical line energy but different power and speeds. From each video two events of brightness flashes were arbitrarily selected, plus a third one for Case IV, denominated Ia,Ib,

**Table 1**
Selected 5 videos and 11 boiling events studied, and corresponding laser parameters.

| Case and event no. | P [kW] | v [m/min] | E=P/v [kJ/m] |
|---|---|---|---|
| Ia,Ib | 10 | 12 | 50 |
| IIa,IIb | 10 | 6 | 100 |
| IIIa,IIIb | 7 | 3 | 140 |
| IVa,IVb,IVc | 15 | 6 | 150 |
| Va,Vb | 15 | 3 | 300 |