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# Transient interaction of a boiling melt with a pulsed Nd:YAG-laser

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ABSTRACT

The boiling front induced by a pulsed Nd:YAG-laser at very slow translation speed was studied. The purpose is to understand fundamental melt movement mechanisms. The melt was observed by high speed imaging, with and without illumination. When switching on the laser beam a hole is drilled through a bulk of melt. The hole expands and the boiling pressure gradually opens the melt bridge, instead developing an interaction front similar to cutting. These conditions remain in quasi-steady state during the pulse. The ablation pressure from boiling shears waves down the front and keeps the melt downwards in a stable position. When switching off, the waves smoothen and in absence of boiling the surface tension drags the melt back upwards, to semi-torus-like Catenoid shape. Evidence on the large melt pool and its shape was achieved by three-dimensional reconstruction from cross section macrographs. The basic findings how melt can move with and without ablation pressure can enable controlled melt dynamics for various laser processing techniques, like remote cutting, ablation, keyhole welding or drilling.



**Contents**



## 1. Introduction

During laser materials processing, such as welding, cutting, additive manufacturing, cladding or drilling with laser beams, the melt flows in a highly complex manner that is essential for the resulting product quality, after resolidification. Though very important, the melt flow is only partially understood and not fully under control, which can generate imperfections in the product. Here a specific geometrical situation of the interaction of a pulsed laser beam with the melt was created to enable extended observation of the melt flow by a high speed imaging camera. The findings contribute to an enhanced fundamental understanding of melt flow phenomena that are relevant for laser materials processing in general.

Although much is unexplored yet, many studies have addressed the melt flow in laser materials processing, as will be described in the following.

Computational Fluid Dynamics (CFD) was applied for calculation of the melt flow and its manifold accompanying mechanisms

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in laser materials processing, including beam absorption, evaporation, plasma formation, hydrodynamic instabilities or gas dynamics [1–6]. For techniques like keyhole laser welding, remote laser cutting or laser drilling a direct driving mechanism of the melt is generated from the laser beam by achieving the boiling temperature at the interaction front. The off-streaming vapour generates an ablation pressure (also called recoil pressure) that can strongly accelerate the melt. Melt removal via the laser-induced ablation pressure is applied in laser drilling [3,7] and in remote laser cutting techniques. There, a thin molten layer forms that is accelerated by the induced pressure gradients. The vector component of the melt film momentum normal to the surface then needs to exceed the surface tension forces to enable melt ejection.

During cw-mode (continuous wave) laser keyhole welding mechanisms like Marangoni convection and melt flow around the keyhole take place. In case of pulsed laser processing it was shown that the interaction from optimum pulsing can withstand mechanisms that generate weld imperfections, like keyhole collapse and porosity.

Switching the laser pulse off and in turn the boiling action can rapidly alter the mechanisms from hydrostatic pressure, surface tension forces, squeezed melt or shear stress. The duration of pulse-low can then govern the solidification behaviour [8].

For longer pulse durations of the order of milliseconds, simulations [9] have shown a transition from hydrodynamic expulsion to explosive expulsion of the melt, which increased the average velocity of the expelled droplets. Similarly, in full penetration keyhole laser welding, spatter ejection at the root can take place. Apart from the above mechanism, the drag force from a strong metal vapour jet escaping the keyhole bottom opening can accelerate and eject the melt [10].

While usually during keyhole welding the surface tension forces are directed against the ablation pressure, for very thin sheets a peculiar phenomenon was observed, which was then called donut laser welding. [11] The keyhole developed a Catenoid-shape (similar to a torus) where the vertical positive curvature balances the negative horizontal curvature with respect to surface tension (Young-Laplace equation) at any location. For a pulsed laser beam, the hole was periodically moved further, by slight boiling action.

Particularly in larger melt pools, Marangoni convection, driven by temperature and in turn surface tension gradients, causes vortices along with heat convection, often in a complex manner [12]. Several flow patterns in the weld pool during laser welding, including inner vortex flow behind the bottom part of a blind keyhole, were predicted by modelling and observed in x-ray transmission imaging experiments [13]. Similarities in the melt flow behaviour of metals can also be found in very different techniques, like vortices in a basic oxygen furnace during steelmaking [14] that may cause surface instabilities and in turn affect the generation of metal droplets and their size distribution. In the same context, longer pulse durations in laser drilling generate eddies beneath the melted layer, which might cause a wavy topology at the walls of the hole [9].

A wavy surface flowing downwards was observed at the keyhole front during laser welding, by ultra high speed imaging (180 000 fps) of the non-illuminated thermal radiations [15]. The effects from recoil pressure and surface tension forces periodically drive the humps downwards and can cause collapse of the keyhole [13].The wave behaviour and its statistical consequences on the laser beam absorption were deeper analysed, by categorizing the patterns and by their evaluation as a function of time [16] as well as by reconstruction of the wavy front and post-modelling of the resulting absorption behaviour.[17].

Beside observation of the melt flow by high speed imaging, a highly valuable method for deeper analysis is mathematical modelling of the physical mechanisms, owing to the complexity particularly by numerical simulation. The mechanisms addressed comprise boiling, mass and heat transfer, phase transitions, Marangoni (thermocapillary) flow, ablation (recoil) pressure, shear stress, surface tension (pressure from the curvature), gas dynamics (including the Knudsen layer), spatter ejection, humping, absorption, beam scattering, multiple reflections, recondensation, and in particular the geometrical interaction conditions (e.g. the absorption front and its topology) [1,3–9,12–14,17–23].

During gas assisted laser cutting an instability of the side regions of the front kerf causes a periodical initiation of the resulting striation topology. Hirano and Fabbro [24] explained the combined instability (thermal and hydrodynamic) due to surface tension in the central and side region of the front kerf by a physical model. Yilbas et al. [25] observed a pulsating nature of the molten metal along the cut. The striation formation of the resulting cut for pulsed lasers was associated with melt film instabilities, particularly determined by the geometrical relations. A linear stability analysis addressing the formation of striations was also carried out by Vossen et al. [6].

The melt of several laser techniques (namely keyhole welding, remote cutting, drilling and ablation) is mainly driven by the ablation pressure from boiling, which is achieved for laser power densities in the range of 0.1-100 MW/cm$^2$ [21]. For iron a temperature of about 3250 K was measured for which the boiling pressure starts to affect the melt, accompanied by a high level of recondensation. Melt ejection can take place initially when developing a keyhole or front [8], followed by stabilisation.

The ambient pressure was found and demonstrated to have great influence on a laser-induced evaporation process [21–23], as was considered by a modified recoil pressure model [22,23]. Pang et al. [22] have shown that the observed increase in penetration depth during laser welding under vacuum (1–2 orders of magnitude below atmospheric pressure) is, apart from other phenomena, caused by temperature differences at the keyhole wall.

During laser drilling, for increasing depth the variation of the absorption can modulate the ablation pressure and in turn the piston effect such that the molten material can retain at the wall of the hole [26]. Therefore forces from evaporation can change their direction and magnitude dramatically depending on the temperature, position and slope of the irradiated liquid surface [2]. A systematic experimental study to identify the initiation of melt surface deformation from the recoil pressure was carried out by Hirano et al. for iron [21]. For cw-laser cutting, high speed imaging enabled to observe the hydrodynamics of the melt layer on the kerf front at frame rates of 20 000 fps [24] and to quantify the cut front properties with respect to measuring the position of the operating (melting) point at frame rates of 4000 fps [5]. For laser drilling, the dynamic behaviour of the melt and vapour was observed at 4500 fps [7] and at 100,000 fps [27]. Berger et al. [28] recorded the generated capillary behaviour of the laser interaction in water and ice, enabling the clear observation of local capillary collapses.

The thermal radiation level was measured with a CMOS camera sensor at 20 000 fps, to determine the threshold surface temperature [21]. Other observations were made in combination with x-ray transmission imaging from the side, which also enabled reconstruction of the three-dimensional melt pool and capillary in laser welding [29]. Gatzen et al. [30] recorded the melt flow behaviour in laser welding, at 500 fps, which revealed that the flow becomes deflected under an external alternating magnetic field. Kaplan et al. [19] performed analysis of the keyhole collapse along with bubble formation for pulsed lasers, X-ray recorded at 1000 fps and accompanied by a mathematical model. The typical time constants of the respective mechanisms were identified, in particular collapsing within milliseconds.