Analyzing and post-modelling the high speed images of a wavy laser induced boiling front

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Abstract

The boiling front in laser materials processing like remote fusion cutting, keyhole welding or drilling can nowadays be recorded by high speed imaging. It was recently observed that bright waves flow down the front. Several complex physical mechanisms are associated with a stable laser-induced boiling front, like beam absorption, shadowing, heating, ablation pressure, fluid flow, etc. The evidence of dynamic phenomena from high speed imaging is closely linked to these phenomena. As a first step, the directly visible phenomena were classified and analyzed. This has led to the insight that the appearance of steady flow of the bright front peaks is a composition of many short flashing events of 20-50 $\mu$s duration, though composing a rather constant melt film flow downwards. Five geometrical front shapes of bright and dark domains were categorized, for example long inclined dark valleys. In addition, the special top and bottom regions of the front are distinguished. As a second step, a new method of post-modelling based on the greyscale variation of the images was applied, to approximately reconstruct the topology of the wavy front and subsequently to calculate the absorption across the front. Despite certain simplifications this kind of analysis provides a variety of additional information, including statistical analysis. In particular, the model could show the sensitivity of front waves to the formation of shadow domains and the robustness of fiber lasers to keep most of an irradiated steel surface in an absorptivity window between 35 to 43 %.

Keywords: boiling front; high speed imaging; modelling; absorptivity; topology

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1. Introduction

For some techniques of laser materials processing the laser beam interacts with an induced boiling front at grazing angle-of-incidence, like during keyhole mode welding or remote fusion cutting. It is interesting to note that these processes are similar to each other, despite their different goals. The processes are only partially understood owing to the linked complex mechanisms involved, like beam absorption, heat conduction, boiling, recoil pressure and melt flow. The grazing angle-of-inclination of the boiling processing front to the laser beam is typically only 2-8° Kaplan and Matti (2015). From deep penetration laser welding it is well known that the threshold cw-laser beam power density to generate boiling and a keyhole is of the order of magnitude of 10^6 W/cm^2. For several kW of beam power and low travelling speed it was observed that keyhole welding can transfer to remote fusion cutting, RFC. Basically, spatter at the root becomes so extensive until a cut is formed. The important mechanism behind are humps and waves that move down the processing front, which was theoretically predicted, Otto and Schmidt (2010), Zaeh et al. (2010), Matsunawa and Semak (1997). Such waves were recently experimentally observed for lasers with a wavelength of about 1 μm, Eriksson et al. (2011).

The explanation, illustrated in Fig.1(a) is local superheating and boiling at the front, induced by the absorbed laser beam radiation, that accelerates the waves downwards owing to the ablation (recoil) pressure from boiling and the corresponding vertical component of the force. From camera employment as in Fig. 1(a), Fig. 1(b) shows a recorded high speed image of waves moving down the front. If the molten front penetrates through the workpiece, the waves generate drops at the bottom that can detach in case of sufficient momentum that exceeds the surface tension forces, causing root spatter or the RFC-process. Note that in case of partial penetration either the melt flows up again behind the keyhole, causing partial penetration welding or drops are ejected to the top, which would correspond to the remote ablation cutting technique. The direction and stability of the melt flow at the boiling front was studied and discussed by different authors, Otto and Schmidt (2010), Zaeh et al. (2010), Matsunawa and Semak (1997), Wagner et al. (2013).

Fig. 1. Laser-induced wavy boiling front: (a) sketch (side view) of a wavy laser induced boiling front and camera employment, (b) high speed image (180 000 fps, exposure time 1 μs, left: original greyscale, right: enhanced contrast), (c),(d) regular model of a wavy surface, (e) vertical profile of the waves and interaction geometry with incident laser beam rays.

The wavy front pattern observed by Eriksson et al. (2011) by high speed imaging (180 000 fps), see Fig. 1(b), is likely to result from temperature variations because of the absence of an illumination laser. Nevertheless, modelling and image analysis supports the hypothesis that the waves are linked to a wavy surface topology, see Fig. 1(a), in particular to mass flow rather than phase flow (as was confirmed when tracking ejected drops). Analysis of the observed patterns can be found in Matti and Kaplan (2014) and further observations of wavy front patterns were reported by Zhang et al. (2013) and Berger et al. (2010).

The degree of absorption of the laser beam by the processing front strongly depends on the angle of incidence, as described by the Fresnel equations but also by the local projection of the laser beam. The three-dimensional cavity shape of the front in combination with a wavy topology, see Fig. 1, causes a complex absorption behavior, which is here further studied. First theoretical estimations were made for a simplified surface of regular waviness, see Fig. 1(c)-(e), to systematically show the influence of the waviness on the absorptivity Kaplan (2012). The 1 μm wavelength of
fiber and YAG-lasers and their Fresnel-characteristic leads to a very different behavior than for CO₂-lasers with 10 μm wavelength. The calculations also demonstrated that the gracing incidence of the laser rays easily causes shadow domains at the front, already for moderate waviness. The state-of-the-art of the absorption behaviour and of the RFC-technique is described in more detail in Matti et al. (2013 I).

Starting from high speed images of the wavy boiling front, as in Fig. 1(b), deeper image analysis of the wavy front is here presented, followed by post-modelling of the images to reconstruct the three-dimensional wavy front and to calculate the absorption behavior of the laser beam over the front.

2. Methodology

Aim of the present study is improved understanding of the laser induced wavy boiling front, particularly with respect to its topology, melt flow and absorption behavior. The starting point for the study is the 48 high speed imaging videos of the processing front for various parameters (laser power, speed), Eriksson et al. (2011). Selected images are in the first part analyzed with respect to the shape and the dynamic behavior of the waves. In the second part, the greyscale information of the images is applied to reconstruct the three-dimensional wavy processing front for which the absorption behavior is subsequently studied by post-modelling. The interpretation of the results is supported by complementary recent studies, namely modelling of the interaction front for RFC, Matti and Kaplan (2013 II), and modelling of the absorptivity for regular wavy surfaces, see Fig. 1(c)-(e), Kaplan (2012). Detailed information on the methods and on experimental and theoretical data as well as additional results can be found in two core papers on image analysis, Matti and Kaplan (2014), and on post-modelling, Matti and Kaplan (2015).

The high speed images used have mainly recorded laser keyhole welding experiments, both with partial and full penetration, but some parameter combinations have instead led to remote fusion cutting, RFC. Here RFC is preferably studied. The samples welded were 2.4 mm thick stainless steel AISI304. A 15 kW cw Yb:fibre laser was used (wavelength 1070 nm), with fiber core diameter 200 μm. The collimator length, focal length and laser beam inclination angle are 150 μm, 300 μm, 7° respectively. The parameters varied were mainly welding speed and beam power. The laser beam was strongly defocused (9 mm below the sample top surface) to widen the keyhole and in turn to achieve a wider front and image field for recording. Recording was carried out by a high speed camera at 180 000 fps and for an exposure time of 1 μs, arranged as in Fig. 1(a). No illumination laser was applied, while the processing laser wavelength was filtered off, which means that recorded variations in the greyscale can only origin from thermal radiation variations of the process.

In the first part of the study, the analysis of high speed images, the observed shapes of the wave pattern were categorized. Moreover, the time-dependent behavior of the shapes was studied, including greyscale level variations. In the second part of the study, based on the greyscale level distribution selected images were converted to a first two-dimensional topology. Then, based on a semi-analytical mathematical model of RFC, Matti and Kaplan (2013 II), a suitable cavity was calculated, to represent the main front geometry. By superimposing the 2D-topology onto the smooth cavity, a three-dimensional wavy boiling front can be reconstructed from the high speed image, see Fig. 2.

Fig. 2. Combination 3D and 2D of the wavy surface of the front, (a) 3D visualization of the semi cylindrical cavity of the wavy surface of the front, (b) 2D profile of the surface waviness (roughness) from the side showing the irradiated and shadowing regimes, (c) cross-sectional view with details of the 3D wavy front surface.
The grazing angle of incidence of the propagating laser beam can then be derived at any location of the wavy front. From the angle, shadow domains can be derived (the shadow domains are larger, but the part governed by ray-tracing is here not considered, for simplicity), the local absorptivity results from the Fresnel-equations and the local absorption can be calculated by the combination $A \cdot \tan(\theta)$. Multiple reflections are here not considered and would be an additional absorption contribution, even in the shadow domains. Beside the spatial and temporal variation of the topology and absorption, the stochastic variations were quantitatively analyzed by histogram.

**3. Result and discussion**

**3.1. High speed imaging analysis**

During the first step of the study, high speed images of the laser-induced wavy boiling front were analyzed further with respect to categorization of the wave shapes and dynamic behavior of the waves.

**3.1.1. Categorizing the shapes**

Examples of high speed imaging appearances of the laser-induced wavy boiling front are shown in Fig. 3. As can be seen, the 0.7-1 mm wide front shows fine wave patterns and a clear contrast to dark regions. The resolution of the wave pattern can vary. Note that occasionally metal vapor flow appears as a bright area that superimposes (through scattering of the thermal radiation from the melt) the melt surface.

![Fig. 3. Examples of the appearance of high speed images of the laser-induced wavy boiling front for various parameter conditions and time](image)

Figure 4(a,c,e,g) shows typical keyhole front images for four parameter cases. Their wave patterns are categorized in Fig. 4(b,d,f,h), respectively, highlighting the variety of shapes that appear at these images. The shapes are classified into seven categories A-G, representative for most of the videos recorded, see Table 1. Shape category A, comprises bright peaks with almost circular symmetry, can be found quite frequently for all four cases. Category B describes elongated bright shapes that can be oriented either horizontally or about 45° inclined. Closer observation of category B shows that the brightness can vary along the elongated shape which might correspond to a chain of peaks A. Bright irregular shapes are denominated C. Although they can also appear in the central domain of the front, they are very likely and intense in the lower part G of the front where melt is ejected, particularly during remote fusion cutting, see Figs. 4(d,f,h) indicating local superheating and boiling of the melt along with recoil pressure action. Micro-explosions were observed in region G where the melt is driven to the sides, separated and partially ejected as drops. Category D describes elongated dark areas, see Fig. 4(b,d,f,h). They can be oriented horizontally but are often inclined and cross...
each other, creating a mesh-pattern, as in Fig. 4(d). The D-valleys are the contrast to accompanying peaks of A-type. The observed D-valleys can vary between regular or more randomized shapes. Larger dark areas, category E are occasionally observed, as in Fig. 4(h). Category F denominates the top region and its special behavior, almost always in form of interference of two circular waves starting from the top and propagating downwards as fringe patterns. More detailed analysis can be found in Matti and Kaplan (2014). Aim of the categorization is to facilitate in the future the description and discussion of observations and phenomena at the processing front.

![Fig. 4. High speed images of the processing front for four cases: (a) case I, laser power P=10 kW, welding speed v=12 m/min, (c) case II, 10 kW, 6.6 m/min, (e) case III, 13 kW, 6 m/min, (g) case IV, 15 kW, 3 m/min; (b, d, f, h) corresponding highlighting of typical shapes at images (a, c, e, g) respectively, with categories A-G.](image)

Table 1: Categories A-G of the wave shapes observed in high speed imaging of the laser generated processing front

<table>
<thead>
<tr>
<th>Category</th>
<th>Type of shape</th>
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<tbody>
<tr>
<td>A</td>
<td>Bright almost circular islands</td>
</tr>
<tr>
<td>B</td>
<td>Bright elongated shapes, inclined or horizontally</td>
</tr>
<tr>
<td>C</td>
<td>Bright irregular shapes</td>
</tr>
<tr>
<td>D</td>
<td>Dark elongated valleys, inclined, even crossing, or horizontally</td>
</tr>
<tr>
<td>E</td>
<td>Dark wide irregular domains</td>
</tr>
<tr>
<td>F</td>
<td>Top region with circular fringe interaction pattern</td>
</tr>
<tr>
<td>G</td>
<td>Bottom region with bright areas and occasionally melt ejection</td>
</tr>
</tbody>
</table>

From the four cases it is interesting to note that the pattern became finer for higher processing speed. For specific cases the wave pattern became coarser from top to bottom. The largest brightness events can be observed in the G region where the C-shape experiences strong absorption and indicates strong boiling action which is favorable for melt ejection in case of remote fusion cutting but unwanted root spatter in laser keyhole welding.

3.1.2. Dynamic wave behavior

Although the downstreaming flow of the wave pattern at the front appears very continuous and was even measured to keep rather constant velocity (of the order of magnitude of 5-15 m/s) highly dynamic changes take place. Figure 5 shows the wave pattern at the front as a function of time, for eleven time steps. The linear downward movement of visible shapes confirms the rather constant melt flow velocity. Nonetheless, when looking carefully the shapes that move downward change in shape and in greyscale. In other words, shapes, e.g. peaks of type A in Fig. 4, can combine or separate, change their shape (and even category) and vary in their radiating intensity (probably temperature and roughness). In particular, a wave peak will not continuously move down in an unchanged manner but strongly varies...
its greyscale, i.e. flashes. Flashes of the order of magnitude of 20-50 μs can be observed for almost all peaks. The wave flow is composed of many flashes. This flash phenomenon is analyzed, described and discussed in detail in Kaplan (2015). Figure 6 shows another, longer sequence of high speed images where the downward movement as well as the variation in greyscale can be well seen. The interpretation of the flashes is the temporary occurrence of boiling action but also the transfer of momentum to the melt film, to keep a rather constant overall velocity downward the melt film.

Fig. 5. Sequence of eleven high speed images (5.5 μs time steps) showing the transient variation of the wave pattern, case III Fig. 4(e,f).

Fig. 6. Long high speed imaging sequence of part of the boiling front (180 000 fps, 5.5 μs times steps, image height about 1.5 mm)

3.2. Front reconstruction and post-modelling of high speed images

During the second step of the study selected high speed images are post-modelled, to reconstruct the three-dimensional wavy front and to calculate the corresponding absorption conditions over the front. Beside the absorption behavior, the sensitivity on the roughness conversion factor and the time dependency are analyzed. The roughness conversion factor h is used to convert the greyscale levels of the high speed image (here 256 bit camera dynamic range) to the absolute topology roughness levels (in μm).

3.2.1. Reconstruction of the wavy front

The reconstruction sequence of a laser-induced wavy boiling front is shown in Fig. 7.

Fig. 7: Reconstruction of the wavy processing front, case II Fig. 4(c, d). (a) from a high speed image; (b) reconstructed 2D-topology, (c) calculated smooth front cavity, (d) reconstructed three-dimensional wavy processing front, (e) different views on the wavy 3D-front, (f) arrows indicating locations of wave shoulders (blue), peaks (yellow) and shadow domains (red), case III Fig. 4(e, f).

From the greyscale distribution of a selected high speed image, Fig. 7(a), via a roughness conversion factor h a two dimensional topology is derived. Simultaneously, by the aid of a mathematical model on RFC, Matti and Kaplan (2013 II), a smooth cavity is calculated, as the main front geometry, see Fig. 7(c). By superimposing the topology onto the
cavity, finally a three-dimensional wavy processing front results, see Fig. 7(d),(e). Figure 7(f) shows points for part of the front topology on locations of wave shoulders, peaks and shadow domains.

3.2.2. Topology height sensitivity

The roughness conversion factor \( h \) from image greyscale to front topology height (roughness) is an uncertainty that requires an assumption. However, from sensitivity analysis it was possible to limit the range of uncertainty (\( h=0.5 \) was preferred) because the resulting extent of the shadow domain can be compared with the recorded image. Figure 8 compares the topology for three roughness conversion factors, \( h=0.2, 0.5, 0.8 \), in Fig. 8(a-f) by greyscale and black/white view from the bottom (visualizing the shadows) and in Fig. 8(g, h, i) by showing the height profiles in the centerline (aspect ratio distorted here). The sensitivity of the absorptivity distribution over the front for different \( h \) can be found in Matti and Kaplan (2015) along with deeper analysis.

3.2.3. Time dependence

The variation of the calculated three-dimensional wave topology as a function of time (time steps 22 \( \mu s \)) is shown in Fig. 9. As already shown and discussed for Figs.5, 6, the wave shapes can strongly vary as a function of time. However, as presented in Matti and Kaplan (2015), this hardly affects the overall absorption behavior. Despite local modulation of the absorptivity, the absorptivity over the whole front remains more or less independent of time.

3.2.4. Absorption post-modelling

From the reconstructed three-dimensional wavy front, several properties can be derived at any front location by post-modelling, in particular the angle of incidence of the propagating laser beam, the corresponding angle-dependent Fresnel-absorptivity and the absorption \( A \cdot \tan(\theta) \) as a combination of absorptivity and beam projection. The respective distributions across the front are shown in Fig. 10(a)-(c). Not directly radiated shadow domains are colored black. For the absorptivity \( A \), Fig.10(b), a scale ranging from 35 % (normal incidence value) to 43% (Brewster maximum) was
chosen, because most of the irradiated surface domains kept within this range, as will be explained below. Only narrow regions above the shadow domains varied within $A=0$-35%. Nevertheless, the absorption shows stronger variation, because the angle-dependent beam projection shows more influence than the absorptivity. The absorption determines via the laser beam power density the local surface temperature gradient.

Fig. 10. Distribution of post-modelled properties over a reconstructed wavy boiling front, case III Fig. 4(e, f): (a) angle-of-incidence $\theta$ of the laser beam to the surface normal (black: shadow domains), (b) angle-dependent Fresnel-absorptivity $A$ [%], (c) absorption distribution $A \tan(\theta)$.

3.2.5. Statistical analysis

Figure 11 shows a histogram for the calculated absorptivity over the wavy front, corresponding to Fig. 10(b).

Fig.11. Histogram of the absorptivity for case III Fig.4(e, f), which can be divided into the dominant (67% of the front surface) high-absorptivity window and the broad absorptivity range 0-35% for narrow angles, plus the 20% surface domains in shadow.

Surprisingly, 84% of the irradiated surface elements (disregarding the 20% in shadow) experience an absorptivity in the window of 35-43%. The reason will be discussed below. Histograms enable a different statistical view on the data, particularly for complex distributions as in the present study. Although the average value and standard deviation ($A=37.7\pm8.1\%$) provide representative values, they would here not provide the essential information in depth.

3.2.6. Theory of the trends

Usually high speed imaging leads to qualitative analysis and to the identification of certain phenomena. The here presented results have shown that also systematic and quantitative results can be derived, in particular by post-modelling as a powerful tool, despite certain assumptions and simplifications required.
With respect to the reconstruction of the front it can be noted that the greyscale peaks are not expected to be the topology peaks (instead the shoulders, see Fig. 1(a) and Fig. 7(f)), but they can be closely related to them, as explained in Matti and Kaplan (2014). An uncertainty remains, particularly concerning the height level, which asks for more sophisticated imaging, e.g. by two cameras of different angle of view, or by interferometry. The strong absorbing shoulders can be expected to induce temperature peaks and occasionally local boiling accompanied by an ablation pressure that accelerates the melt downwards, as described in more detail in Matti and Kaplan (2014), Kaplan (2015).

Figure 12 illustrates the theory of the main trends of the study, schematically in combination with the Fresnel curve, involving five regimes B, C, D, E, F. The front shows gradual incremental in the wave profile, starting smoothly and becoming more wavy (rough), eventually causing shadow regimes.

Fig.12. Theory part showing the interaction of laser rays with several variations of surface roughness and its three related regimes with the Fresnel absorptivity diagrams (B,C,D) and two shadow regime (E,F) due to wave’s protuberance from surface normal and projection shadow from the ray tracing respectively.

Regimes B, C, D are related to the Fresnel curve. Regime B is a very narrow angle range (0-5°) of the Fresnel curve, however with strongly varying absorptivity (0-35%). These regimes B are very narrow at the wavy front, just above the shadow domains. Moreover, the beam projection is correspondingly low, hence a weakly absorbing regime. Note the definition of 35%, the normal incidence absorptivity, even at the other branch of glancing angles, 5°, since the contributions from the two branches are difficult to distinguish in the analysis. In contrast, all absorptivity below 35% clearly belongs to Regime B. This characteristic is special for lasers of 1 μm wavelength (e.g. fiber and disc lasers) and steel. For other laser-metal combinations this behavior might be not so clear, e.g. for CO2-lasers (10.6 μm) for which the normal incidence-absorptivity becomes quite low. Most of the Fresnel curve (e.g. see Figs. 11 and 10(b)) accordingly keeps within the highly absorbing Regimes C, D.

Regimes E and F are the shadow regimes. In the present study only regime E, defined by any invalid angles of incidence, is considered while regime F of shadow defined by ray tracing borders requires corresponding numerical efforts, which was here neglected. So shadow regimes will be larger than in the here presented results. Nevertheless, this does not change the main trends and findings from the study.

4. Conclusion

(i) Post-modelling of the wavy surface of a laser-induced boiling front was carried out, from the greyscale information of high speed images, which turned out to be a powerful method to reconstruct the front and to carry out absorption analysis and statistics.

(ii) Different categories of wave shapes were distinguished, both for bright peaks (or wave shoulders) and dark shadow valleys; the shapes can separate or combine as a function of time.

(iii) The top and bottom of the front were characterized as domains of special behavior.
(iv) Despite continuous appearance of the waves streaming downwards, detailed analysis has shown pulsating behavior instead, flashing that lasts 20-50 $\mu$s; accordingly, temporary local boiling events can be expected.

(v) The absorptivity widely keeps within a range of 35-43%, because of the stable Fresnel-characteristic for 1 $\mu$m-wavelength lasers and steel; the very sensitive absorptivity branch affects only very limited domains.

(vi) High speed imaging of the waves of a boiling front in combination with post-modelling and statistical analysis enabled significant progress in the understanding and confirmation of key phenomena during laser keyhole welding and laser cutting; the potential for even more sophisticated imaging and modelling is high.

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