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# High-speed X-Ray analysis of spatter formation in laser welding of copper

A. Heider\*, J. Sollinger, F. Abt, M. Boley, R. Weber, T. Graf

*Institut für Strahlwerkzeuge (IFSW), University of Stuttgart, Pfaffenwaldring 43, 70569 Stuttgart, Germany*

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## Abstract

Due to their very good electrical and thermal conductivity copper materials are more and more demanded for industrial applications. For the assembly of copper based parts an effective and reliable welding process is required. At lower feed rates and high penetration depth respectively, welds in copper suffer from many weld defects such as pores and melt ejections. Keyhole instabilities during welding result in most cases in weld defects. In this paper high-speed X-ray imaging of the welding process is used to analyze keyhole instabilities with respect to the formation of weld defects. By means of X-ray observation of the welding process it is shown that bubble formation at the tip of the capillary is one mechanism which causes weld defects such as melt ejections and pores. Furthermore the influence of laser power modulation on bubble formation is discussed.

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*Keywords: Welding Copper, Laser welding, X-ray, Laser power modulation, Process stabilization, Spatters, Pores, Melt Ejections.*

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## 1. Motivation

Due to its very good material properties such as high electrical and thermal conductivity, copper is more and more demanded for industrial applications. Concurrently the latter property makes laser welding of copper a very challenging task. Furthermore since copper shows low absorptivity of a few percent at 1  $\mu\text{m}$  wavelength and possesses high heat conductivity, laser welding of copper often results in defective welds. To

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\* Andreas Heider. Tel.: +49 (0)711 685 69730; Fax: +49 (0)711 685 59730.  
E-mail address: [Andreas.Heider@ifsw.uni-stuttgart.de](mailto:Andreas.Heider@ifsw.uni-stuttgart.de).

achieve welds with penetration depths of several millimeters in copper using commercially available kW-range laser sources relatively low feed rates of less than 10 m/min are needed. Such weld seams suffer from numerous ejections and pores. Furthermore a strong fluctuation of the penetration depth along the weld seam can often be seen.

A typical weld seam of a welded copper sample is shown in Fig. 1. In Fig. 1 (a) and (b) the solidified weld seam surface with a large number of holes can be seen. The corresponding longitudinal cross section is shown in Fig. 1 (c). The numerous holes extend over the whole penetration depth. These holes result, when molten material is ejected out of the melt pool during a weld [1]. Such holes in the weld seam degrade the mechanical and electrical properties of the weld. Hence it is of great importance to avoid or at least minimize such weld imperfections.



Fig. 1. Welded copper sample, Cu-ETP,  $v = 6$  m/min,  $P = 1500$  W,  $d_f = 100$   $\mu\text{m}$ . (a) Weld seam surface with melt ejections; (b) Enlarged image of a melt ejection; (c) Corresponding longitudinal cross section.

Keyhole instabilities are described to be one of the reasons for weld defects [2]. Nowadays, to experimentally analyze the process behavior such as keyhole and melt pool dynamics usually high-speed video observation in the visible wavelength range is applied. With this technique only the sample surface can be observed whereas no information of the behavior inside the material can be obtained. By means of high-speed online X-ray diagnostics while welding, phenomena such as the keyhole dynamics or spatter and pore formation can be analyzed [3], [4]. In this paper the results of X-ray observation of the keyhole behavior in copper welding are shown. The growth of instabilities of the keyhole and the resulting formation of melt ejections and pores will be discussed. In addition laser power modulation at welding copper was used as a method to stabilize the keyhole dynamics as reported in [1]. By means of X-ray observation in combination with high-speed observation in the visible wavelength range the influence of laser power modulation on weld defects is discussed.

## 2. Experimental

For the experiments a continuous wave thin-disk Yb:YAG (TruDisk 5001) laser with a wavelength of 1030 nm and a maximum output power of 5000 W was used. All welds were made with a focus diameter of 100  $\mu\text{m}$ . The laser optics was set to an angle of incidence of  $18^\circ$  to prevent it from damage by the back reflected light. To analyze the influence of heat conduction, a copper alloy (bronze, CuSn6) and a pure copper (Cu-ETP) with high heat conductivity were used for the experiments. The relevant thermo-physical properties are summarized in Table 1

Table 1. Material properties of the copper materials under investigation at ambient temperature [5].

Properties	CuSn6 (bronze)	E-Cu-58 (ETP)
Heat conductivity $k$ [W/(mK)]	75	390
Heat capacity $c_p$ [J/(gK)]	0.377	0.386
Density $r$ [g/cm <sup>3</sup> ]	8.8	8.93
Thermal diffusivity $\kappa=k/(rc_p)$ [cm <sup>2</sup> /s]	0.226	1.131

All welds were 80 mm long bead on plate welds having length, width and thickness of 100 mm, 20 mm and 2.5 mm, respectively. No shielding gas was used. In order to analyze the process dynamics at the sample surface all welds were observed with a high-speed camera at a frame rate of 20 kHz. An additional illumination laser at a wavelength of 808 nm in combination with a band pass filter in front of the camera was used.

The X-ray imaging system is shown in Fig. 2 left. It consists of a micro-focus X-ray tube generating the X-ray radiation and an imaging system converting the X-ray radiation to visible light. The X-ray transmitted sample is visualized by an image intensifier and taken by a high-speed video camera at a frame rate of 2 kHz. The used sample geometry and the directions of laser and X-ray radiation are shown in Fig. 2 in the middle. The sample is arranged vertically and penetrated by X-ray radiation in horizontal direction (see blue arrow in Fig. 2 middle). For welding, the laser beam irradiates the sample from the top and impacts the material at the narrow side of the sample as shown in Fig. 2, [4]. On the right hand side in Fig. 2 one frame of a typical X-ray imaging with the relevant features seen at X-ray observation is depicted. The laser beam (marked with the red area) hits the sample surface and creates a deep and narrow capillary. Due to the lower density of vaporized material inside the capillary, the capillary is visible as a lighter grey area pointed out with the bounded red continuous line (see Fig. 2 right). In addition to the keyhole, pores can be seen on the right hand side of the capillary tip as lighter grey bubbles again due to the lower density of the material (probably ambient gas) inside the pores. The red dashed line above the black area shows the weld seam surface. The welding direction is from the right to the left.

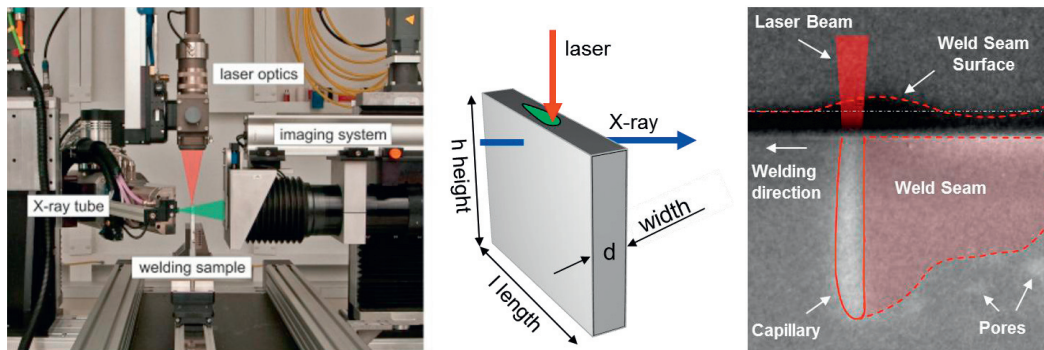


Fig. 2. Left: High speed imaging X-ray system. Middle: Sketch of the welding sample with laser and X-ray directions. Right: Single frame of a high-speed X-ray observation of a weld [4].

### 3. Results and Discussion

To analyze keyhole dynamics and the formation of weld defects X-ray imaging was combined with high-speed imaging of the welding surface in the visible wavelength range, referred to as “vis-high-speed”. Keyhole and melt pool dynamics during welding are discussed with respect to the formation of spatters, pores and melt ejections.

#### 3.1. Bubble formation

Fig. 3 shows a sequence of synchronized X-ray and vis-high-speed recording of a typical formation of a melt ejection at welding copper. Vis-high-speed recording is used to analyze keyhole and melt pool dynamics at the sample surface (top row Fig. 3). The corresponding X-ray images are shown in Fig. 3, lower row to analyze keyhole dynamics inside the material. A narrow and straight capillary can be observed at the initial X-ray image (Fig. 3a, lighter grey area bounded with the red continuous line). After about 17 ms, the tip of the capillary begins to bend against the direction of welding (b) and a “bubble” like structure at the tip of the capillary is formed (c). Within the next 6 ms growing of the bubble occurs (c – e). 35 ms after the initial situation (a) the bubble starts to shrink again (f – h). The observed phenomena such as bubble formation could be explained by an increased absorption due to a bending of the capillary and therefore by an increased vaporization causing growing of the bubble inside the melt pool due to recoil pressure. The bubble pushes the molten material in direction of the sample surface leading to a swelling of the weld seam surface (d). This behavior can be seen in the vis-high-speed image above. The bubble grows as long as the surface tension of the melt pool is larger than the pressure created by the bubble (d).

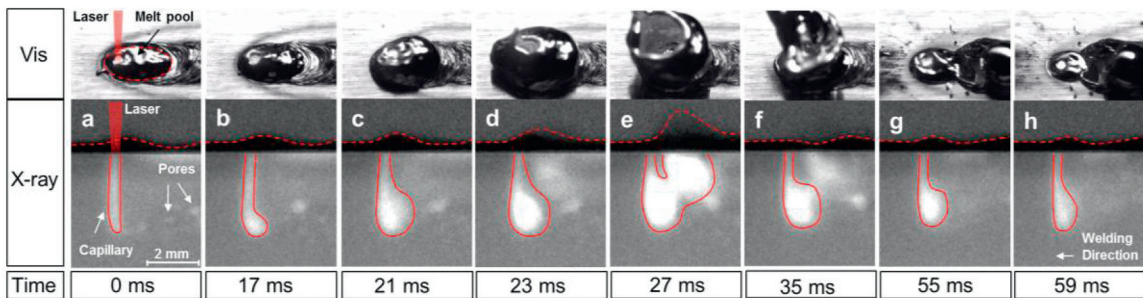


Fig. 3. Bubble formation at welding copper. Synchronized vis-high-speed and X-ray recording. Top: vis-high-speed imaging, bottom: corresponding X-ray imaging at a frame rate of 2 kHz.

After passing a critical state (e) almost the whole molten material is ejected out of the interaction zone and as a consequence a hole remains in the weld seam. After such a melt ejection the reformation of capillary starts (h). From this sequence it can be concluded that if a critical bubble size is exceeded a melt ejection is generated. Therefore the formation of bubbles at the tip of the capillary is one of the reasons for the development of weld defects.

#### 3.2. Laser power modulation

To overcome the mechanism of bubble formation adapted laser power modulation is one effective approach. It prevents the growth of the bubbles and therefore minimizes weld defects such as melt ejection

and pores providing that appropriate laser parameters are chosen [1][6]. For a better understanding of the fundamental process behavior of welding copper during laser power modulation, high-speed X-ray videography of welds with and without power modulation were performed. Particularly keyhole dynamics and the bubble formation at the tip of the capillary were investigated. In Fig. 4 the comparison of a not modulated weld (referred to as “cw”) and welds with different modulation frequencies are shown. The average power was kept constant to  $P_{av} = 3000$  W. All welds were carried out at a feed rate of  $v = 4$  m/min. Power modulation was controlled by a function generator which gave a fast analogue input signal to the laser. All modulated welds were performed with a sinusoidal shape of the laser power modulation.

Three different weld parameters were compared. On the one hand the reference (cw) process without power modulation was analyzed (top row of Fig. 4). On the other hand a modulation frequency of 50 Hz (middle row of Fig. 4) and of 200 Hz (lower row of Fig. 4) respectively, were investigated. At each row single frames of high-speed X-ray observation (grey images an top) and the extracted keyhole shape (lower rows) at a time interval of 2.5 ms are depicted.

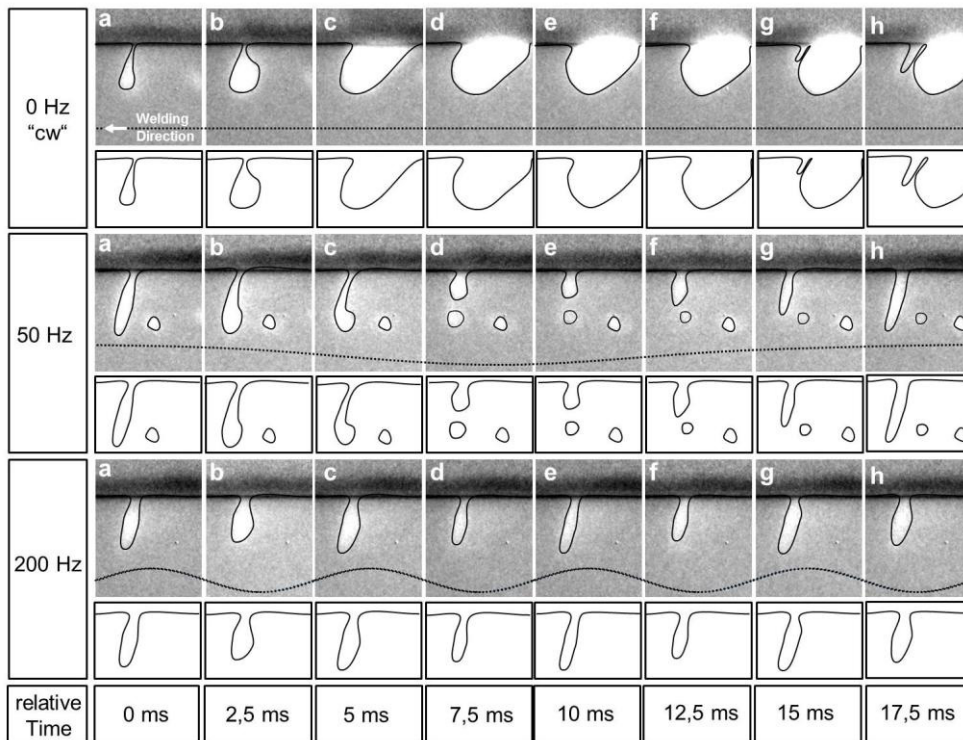


Fig. 4. Single images of high-speed X-ray recording (grey images) of different welds in pure copper (Cu-ETP) and extracted keyhole shapes. All welds were performed with an average laser power of  $P_{av} = 3000$  W at a feed rate of  $v = 4$  m/min. Top row: Without laser power modulation. Middle row: With laser power modulation at a modulation frequency of 50 Hz and amplitude of  $P_{amp.} = \pm 2000$  W. Lower row: With laser power modulation at a modulation frequency of 200 Hz and amplitude of  $P_{amp.} = \pm 2000$  W.

Without power modulation (top row of Fig. 4) bubble formation at the tip of the capillary takes place as described above. Bubble growing occurs and results in melt ejection. The whole molten material is thrown out of the interaction zone. As a consequence a hole in the weld seam remains, visible as a large bright area (see



top row “cw”, c-f). Reformation of the capillary starts at image g. The dashed lines at the X-ray images illustrated the relative laser power at every image.

The middle row of Fig. 4 shows a sequence of a modulated weld at a modulation frequency of 50 Hz. The shown image sequence at 50 Hz corresponds to one period of modulation pointed out with the dashed black line which illustrates the corresponding relative laser power. Starting at the initial situation  $t = 0$  ms (a), laser power is reduced. After about 5 ms (c) the keyhole starts to collapse and a pore remains in the weld seam (see Fig. 4 middle row at 7.5 ms). 10 ms after the initial situation (a) laser power is increased again, visible as an increase in depth of the capillary (e-h). Within this procedure the formed pore moves towards the direction of welding due to the movement of the sample. The frequency of the up and down movement of the capillary is too low to “pick up” the pore again. At every instant of the reduction of the laser power the capillary collapses and a pore is generated. This pore remains at the solidified weld seam. The frequency of pore formation corresponds to the frequency of the power modulation. In addition the penetration depth fluctuates with the sinusoidal shape of the modulation respectively and will be discussed later on.

The lower row of Fig. 4 shows a modulated weld with a modulation frequency of 200 Hz. At half of one modulation period (corresponding to 2.5 ms) the depth of the capillary reaches the lowest value. However no closure or collapse of the capillary is observed and therefore no pore formation occurs. Up to 5 ms after the initial situation (a) bubble formation at the tip of the capillary is visible. A reduction of the laser power due to power modulation prevents growing of the bubble (d-h) and therefore almost no melt ejection occurs. Analyzing the complete X-ray video of the weld a pumping capillary tip is observed. This phenomenon could be explained by a growing and shrinking bubble at the capillary tip.

Following the hypotheses that bubble growing is generated due to an increased vaporization at the tip of the capillary, reducing the laser power leads to a shrinking of the bubble. Hence laser power modulation is a method to prevent bubble growing and thereby minimizing weld defects such as spatters or melt ejection.

In Fig. 5 longitudinal cross sections of welded samples at different weld parameters are shown. Without power modulation a strong irregular fluctuating weld shape occurs (top image Fig. 5). Using laser power modulation at a relatively low modulation frequency of 50 Hz pores were generated in a regular interval at the position of the collapsing keyhole and can be seen in the middle image of Fig. 5. This phenomenon was already reported in [1] and is confirmed due to high-speed X-ray imaging above. The fluctuation in penetration depth is almost 100 % compared to the maximum penetration depth. A homogeneous weld seam with a regular penetration depth is shown in the lower image of Fig. 5. Due to laser power modulation with the used parameter almost no melt ejection can be observed at a modulation frequency of 200 Hz.

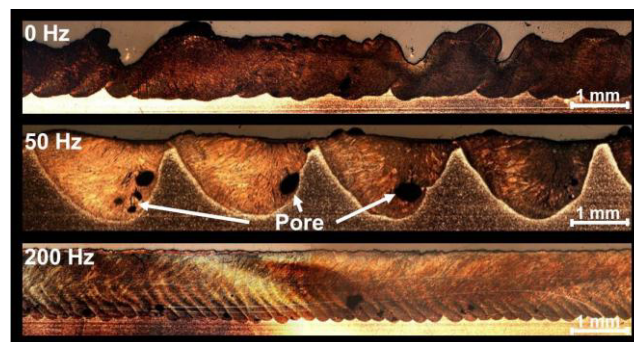


Fig. 5. Longitudinal cross sections of welded CuSn6 samples at different weld parameters. All welds were performed with an average laser power of  $P_{av} = 1000$  W at a feed rate of  $v = 6$  m/min. Top: without power modulation (0 Hz); Middle: with power modulation at a modulation frequency of 50 Hz and an amplitude of  $P_{ampl.} = \pm 750$  W. Right: with power modulation at a modulation frequency of 200 Hz and an amplitude of  $P_{ampl.} = \pm 750$  W.

#### 4. Conclusion

Keyhole dynamics and the resulting formation of weld defects, caused by an instable keyhole was analyzed using high-speed X-ray imaging technology in combination with high-speed imaging in the visible wavelength range to record laser welding of copper. Due to a better understanding of the fundamental process behavior of welding copper it is possible to directly influence the process and therefore to significantly improve the resulting weld seam quality. With the X-ray imaging it was shown that bubble formation at the tip of the capillary leads to melt ejections and pores. In addition high-speed X-ray imaging of laser power modulated welds was used to investigate the keyhole dynamics and bubble formation during power modulation. Due to power modulation bubble growing at the tip of the capillary can be prevented and therefore almost no melt ejections occur provided using appropriate laser parameter.

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