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Process Stabilization at welding Copper by Laser Power Modulation

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Abstract

Due to their material properties such as high electrical and thermal conductivity, copper materials are more and more demanded for industrial applications. The same material properties make laser welding of copper a challenging task. Laser welds often suffer from defective weld seams with ejections, pores and a large fluctuation in the penetration depth.
In this paper the influence of laser power modulation during copper welding on weld imperfections is discussed. It is shown that a sinusoidal power modulation leads to a strong reduction of melt ejections and also to an increase in penetration depth.

Keywords: Laser Welding; Copper Welding; Power Modulation; Process Stabilization; CW; Spatter; Ejection

1. Introduction

The current efforts in the electrification of automobiles significantly increase the need for a reliable and effective copper welding process. Due to the low absorptivity at 1 µm wavelength and the high heat conductivity, laser welding of copper materials often results in defective welds. Such weld seams suffer from many ejections and pores. Furthermore a strong fluctuation of the penetration depth along the weld seam can often be seen. For industrial applications primarily the cross sectional area of the welds are of interest to achieve the highest efficiency of electrical and thermal conductivity. Hence it is of great importance to minimize or even avoid such weld imperfections. Figure 1(a) shows the appearance of a melt ejection from a high-speed video observation of a welding process. In Figure 1 (b) and (c) the solidified weld seam of a welded sample with a lot of holes can be seen. These holes result, when molten material is ejected out of the melt pool during a weld.

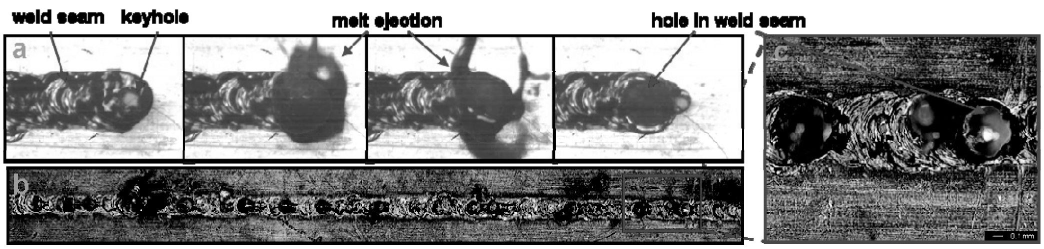

Figure 1: Welded copper sample, Cu-ETP, v = 6 m/min, P = 1500 W. (a) Formation of a melt ejection out of high-speed-video; (b) Weld seam with melt ejections; (c) Enlarged image of a melt ejection.

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A weld for industrial applications has to fulfil several specifications. One of the most critical requirements is the strength of a weld depending on the connected area. Furthermore the electrical and thermal resistance defined by the uniformity of material is especially important for the use of copper materials. Melt ejections lead to a hole in the weld seam and degrade the mechanical and electrical properties of the weld.

In general the laser welding process has two distinct regimes, heat-conduction welding and deep-penetration welding. The latter is characterized by the formation of a capillary which forms a deep and narrow weld. It is known that ejections out of the melt pool and the building of pores may result from the oscillation of the keyhole as a result from the collapse of the keyhole [1]. The formation of a capillary starts at the threshold from heat-conduction to deep-penetration welding. In the vicinity of the threshold it is possible to influence the formation of the capillary by changing the laser power. Thereby the keyhole dynamics can also be influenced in order to stabilize the process. In this paper the effect of laser power modulation around the deep-penetration threshold will be discussed regarding ejections and the formation of pores. Furthermore the change in penetration depth due to the modulation of the laser power will be discussed.

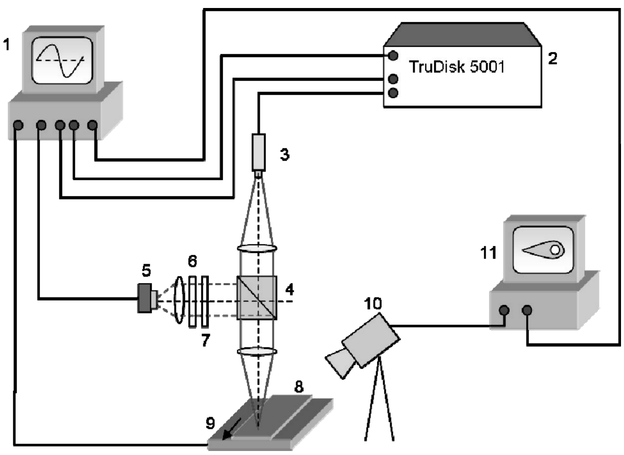
2. Experimental Setup

All experiments were made with a TruDisk 5001 laser with a fibre delivery with 100 µm core diameter. The laser has a maximum output power of 5000 W at a wavelength of 1030 nm. All welds were made with a focus diameter of 100 µm. The laser optics was set to an angle of incidence of 18° 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 higher heat conductivity were used for the experiments. The relevant thermo-physical properties are summarized in Table 1. All welds were 80 mm long bead on plate welds in 2.5 mm thick samples. No shielding gas was used.

Table 1: Material properties of the copper materials under investigation at ambient temperature [2].

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/cm³]	8.8	8.93
Thermal diffusivity κ=k/(rc$_p$) [cm²/s]	0.226	1.131

Figure 2 shows the experimental setup. Power modulation is done by a function generator (1) which gives a fast analogue input signal to the laser (2), setting the actual laser power. With the fibre delivery (3) the laserlight is transported from the laser to the optics (4) which focuses it onto the workpiece (8).



(1) Control and Measurement PC and Function Generator,
(2) Laser TruDisk 5001,
(3) Light Conducting Cable,
(4) Beam-Splitter,
(5) Photodiode, for the Back-Reflection Signal,
(6) Interference Filter (1030 nm), (7) Neutral Gray Filter,
(8) Workpiece,
(9) Moved Axis,
(10) High-Speed-Camera,
(11) PC for High-Speed-Images.

Figure 2: Experimental setup of the processing system.

In order to analyze the process dynamics all welds were observed with a high-speed camera at a frame rate up to 10 kHz. Furthermore the back-reflected laser light form the workpiece was observed using a photodiode.
The welded samples were analyzed with respect to the number of melt ejections, the number of pores, the penetration depth and the fluctuation of the penetration depth. The melt ejections were counted from the weld seam surface. The number of pores and the penetration depth were measured from the longitudinal and cross-sections.

3. Results and Discussion

3.1. Melt Ejections

Figure 3 shows a longitudinal cross-section of a welded sample (Cu-ETP, v = 6 m/min, P = 1500 W). In the majority of cases melt ejections extend over the complete penetration depth as seen in Figure 3 and therefore they turn out to be the most critical weld imperfection.

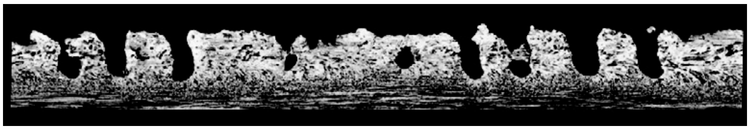


Figure 3: Longitudinal cross-section of a weld with many melt ejections.

The susceptibility to weld imperfections strongly depends on the feed rate. At low feed rates (v < 8 m/min) the amount of ejections increases with decreasing velocity as shown in Figure 4. To investigate this effect the laser power was kept constant while increasing the feed rate and the number of ejections was counted. The diagram shows, that pure copper (Cu-ETP) suffers from about a factor of two more ejections than bronze (CuSn6). This behaviour is confirmed by the high-speed images that show stronger fluctuations of the melt pool.

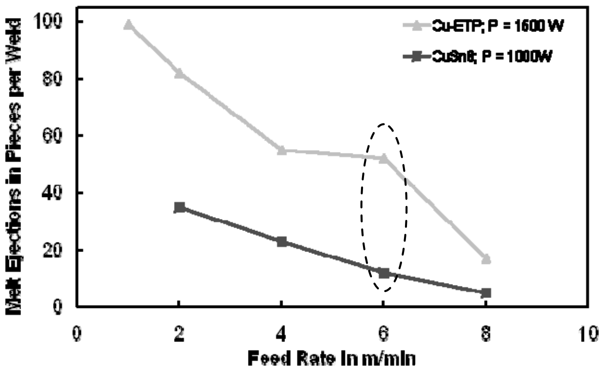


Figure 4: Correlation between melt ejections and feed rate at a constant laser power for two different copper materials.

The following analysis was performed at a feed rate of 6 m/min due to the welding depth of several mm which can be reached with this parameter. The laser power was sinusoidally modulated with an average power of 1000 W for CuSn6 and 1500 W for Cu-ETP. The average power chosen corresponds to the threshold power for deep penetration welding [4]. Welds were performed with different modulation frequencies at constant modulation amplitude of $\pm$ 750 W.

Figure 5 (left) shows the penetration depth and the number of ejections depending as a function of the modulation frequency. The penetration depth increases at all modulated welds in comparison to the welds with constant laser power (modulation frequency = 0 Hz). The best results regarding the melt ejections are achieved at a frequency between 400 - 600 Hz at Cu-ETP. The corresponding longitudinal cross-sections and weld seam surface can be seen in the Figure 5 (right).

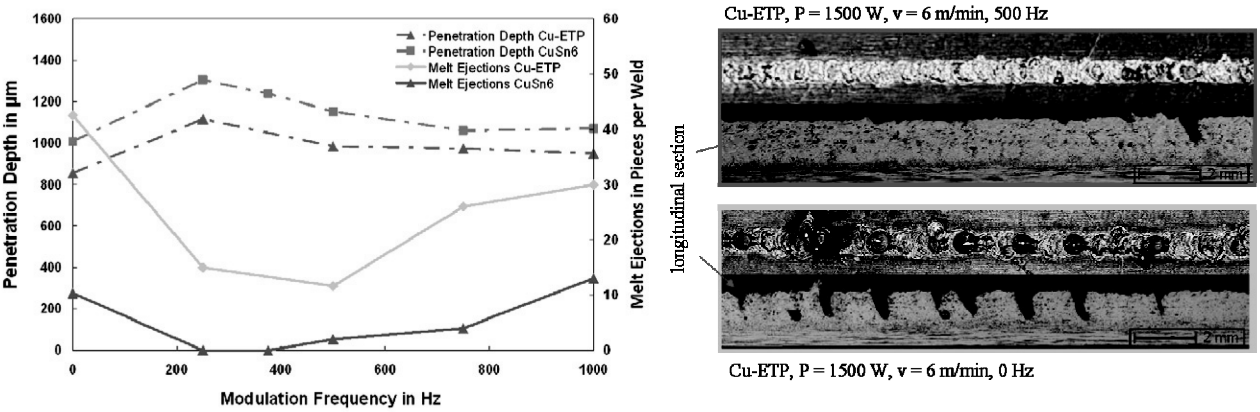


Figure 5: Left: Penetration depth and melt ejections as a function of the modulation frequency. Right: Longitudinal cross-sections and weld surface of pure copper (Cu-ETP); top: modulated welding at 500 Hz; bottom: unmodulated.

For the bronze material it is possible to produce a weld with few or even without any ejections at a frequency of about 350 Hz. The higher heat conductivity of Cu-ETP leads to a smaller penetration depth and a larger number of ejections caused by a stronger oscillation of the keyhole as can be seen in the high-speed videos.

An explanation for the instability of the welding process at low feed rates has been illustrated by a model of R. Fabbro [3] which can be applied and extended for the present case: The welding process becomes instable at lower feed rates as a consequence of a small angle of the keyhole front wall. The evaporation pressure decreases with decreasing angle of the keyhole front wall relative to the incident beam and also decreases with decreasing absorbed intensity. As soon as the closing pressure of the keyhole - resulting from the local surface tension - overbalances the evaporation pressure the keyhole collapses. As a result of the collapse of the keyhole melt ejections occur.

Following this model the keyhole stability is influenced by a varying incident intensity. This effect is considered to be very pronounced if the intensity is periodically modulated across the deep penetration threshold. The evaporation pressure in this case strongly changes with the intensity directly influencing the balance between evaporation pressure and surface tension. In addition, as the evaporation pressure is dependent to material properties different behavior is expected for the used materials under consideration as seen in Figure 5.

3.2. Stability of welding depth

For almost all welds the molten area is one of the most important criteria. The quality of a weld seam is significantly affected by the solidified including the thermal and electrical resistance. Therefore a critical weld characteristic is the fluctuation in penetration depth. Figure 6 left shows two longitudinal cross-sections with the fluctuation in welding depth for the bronze material (CuSn6). The fluctuation is the peak-to-peak variation of the welding depth represented by the dashed lines. The largest penetration depth measured in the longitudinal cross-section is defined as 100 % penetration depth. The difference between the highest and lowest penetration depth neglecting the melt ejections is defined as the fluctuation in penetration depth.

The diagram in Figure 6 right shows the measured fluctuation in penetration depth for the two investigated copper alloys. The fluctuation at the bronze material is larger than at pure copper as can be seen from Figure 6 (right). With a modulated laser power it is possible to reduce the fluctuation up to 60 % (Figure 6 right). These results were confirmed by repeating the experiments several times.

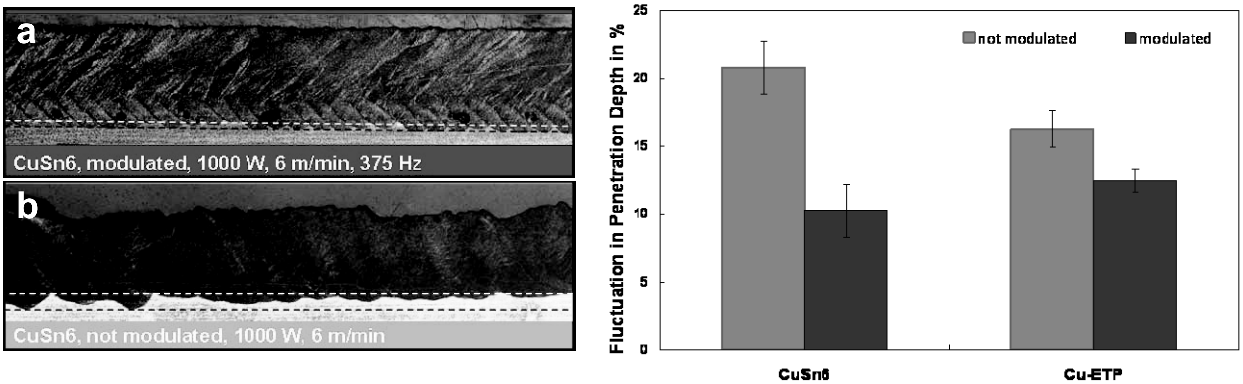


Figure 6: Left: Longitudinal cross-sections of modulated (top) and not modulated (bottom) weld. Right: Fluctuation in penetration depth for CuSn6 and Cu-ETP with modulated and not modulated laser power.

3.3. Formation of pores

The formation of pores was investigated at the sinusoidal modulation of the laser power. Figure 7 shows two longitudinal cross-sections. The upper image shows a modulated weld with a lot of pores. The pores are mostly situated at the lower part of the solidified weld seam. In contrast the unmodulated weld (lower image of Figure 7) on the one hand shows less pores but on the other hand the complete weld is much more inhomogeneous regarding the welding surface and the penetration depth.

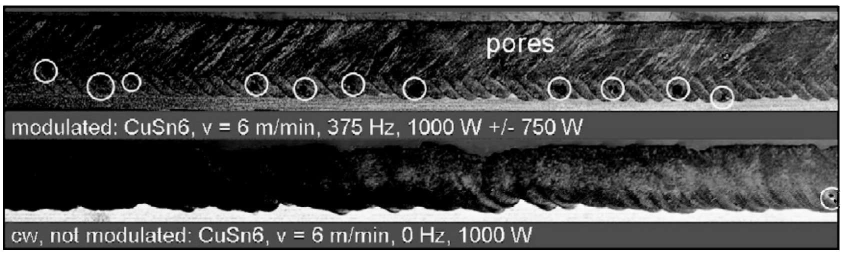


Figure 7: Top: Modulated weld with many pores; CuSn6, f = 375 Hz, Paver = 1000 W, Pampl = +/- 750 W, v = 6 m/min. Bottom: Not modulated weld; CuSn6, f = 0 Hz, Paver = 1000 W, v = 6 m/min.

An analysis of the location of the pores shows that the pores arise frequently at the trailing edge of the laser power. One can clearly see this behaviour at a modulation frequency of 40 Hz (Figure 8 left). The green curve shows the laser power and the red signal shows the normalized back-reflection. The longitudinal cross-section is aligned to the laser power. If the capillary is closed most of the laser power is reflected back to the optics and can be detected as a rise in the observed back-reflection signal. This correlation is usually seen when passing the threshold from heat conduction welding to deep penetration welding [5]. The rise in the back-reflection signal at decreasing laser power as seen in Figure 8 is a clear indication for a closing capillary. At this point the capillary collapses and a pore can form.

A closer look to the geometry of the solidified weld seam shows two different angles (α and β in Figure 8 right) that can be observed at the trailing and rising slope. As the opening and closing processes of the capillary are dominated by different physical phenomena [6] the angles of the two slopes indicated by the red and the blue dashed line in Figure 8 (right) are unequal as well. A specific analysis of the opening and closing behaviour of the capillary is reported in [6].

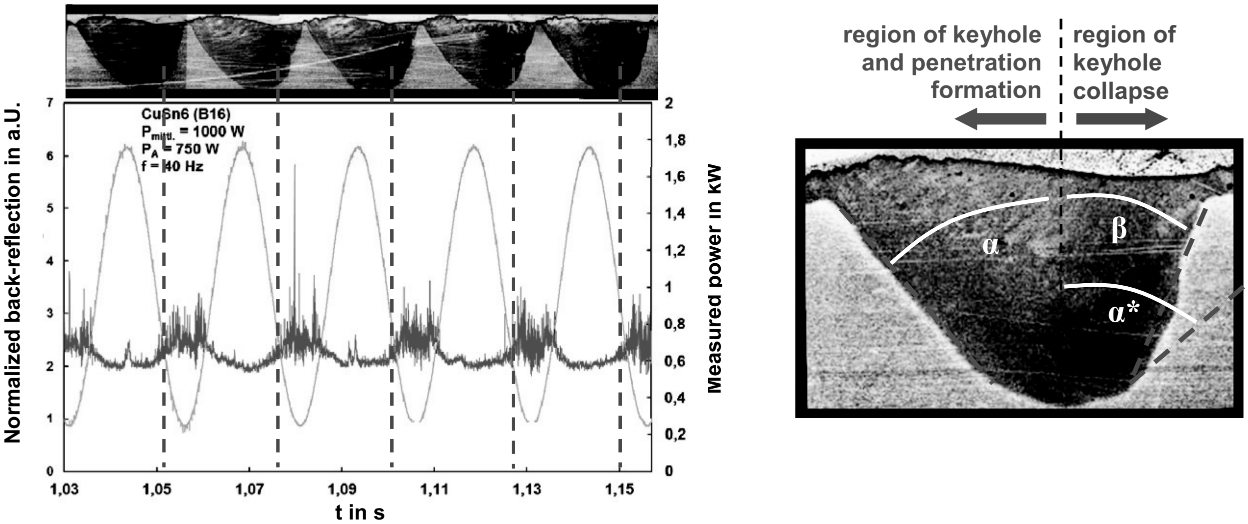


Figure 8: Left: Top: Longitudinal cross-section of a weld, f = 40 Hz, CuSn6, P = 1000 W, v = 6 m/min; bottom: Normalized back-reflection and measured power. Right: Longitudinal cross-section with different angles of the trailing and rising slope of solidified weld seam.

3.4 Surface quality

Another criterion to evaluate a weld is the subjective surface quality of the weld. Melt ejections lead to the loss of heat and the collapse of the keyhole and not only cause a fluctuation in penetration depth but also a variation in the weld seam width. Due to the effect of stabilization of the keyhole by modulating the laser power the weld seam width is almost constant and the weld surface shows good uniformity. Figure 9 shows the improvement of the weld seam surface by modulating the laser power. In comparison to the welds without modulation a significantly more regular surface can clearly be seen at the modulated welds.

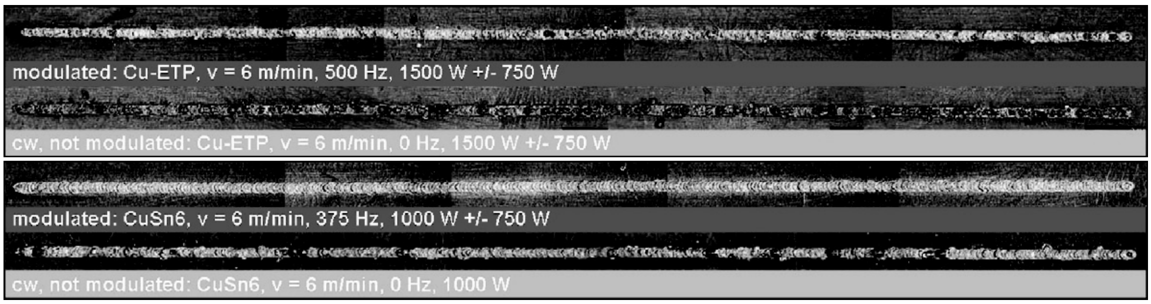


Figure 9: Top: Weld seam surface of Cu-ETP, modulated and not modulated. Bottom: Weld seam surface of CuSn6, modulated and not modulated.

4. Conclusion

The presented experimental results clearly show that the modulation of laser power has a mostly positive influence on the weld quality in copper. On the one hand, an increased formation of pores was observed using this method. Pore formation was observed mostly at the trailing edge of the modulated laser power during the collapse of the keyhole. This might be overcome by using optimized shape of the modulation signal as was reported [7].

On the other hand it is shown that it is possible to significantly reduce the melt ejections with a sinusoidal modulation of the laser power across the deep penetration threshold. The power modulation causes a stabilization of the keyhole and reduces the fluctuation of penetration depth. Furthermore the penetration depth could be increased by the modulation. In addition, smooth weld seam surfaces and a constant weld seam width could be obtained.

5. Acknowledgment

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