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Enhanced process understanding for laser welding of copper and aluminum alloys with dynamic beam oscillation

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Abstract

The increasing electrification of automotive application require high quality and efficient joining processes for copper and aluminum alloys. Dynamic beam oscillation is suitable to cover the wide range of joining application for copper (thin to thick sheets) through the possibility of adapted energy distribution by one optical setup. However, amount of welding parameters increases strongly, which results in higher complexity of influencing factors.
Deeper process understanding and the identification of crucial process factors is necessary to overcome existing limitations in joint quality such as formation of blowouts, spatters and pores. Therefore, comprehensive insights in the welding process by X-ray imaging, high-speed video-recordings are combined with metallographic analysis. In this paper, the impact of the beam path speed on the process regime and the weld seam quality will be presented. Moreover, the transferability to applications and other difficult to weld materials like aluminum die-cast will be illustrated.

Keywords: laser beam welding; copper; beam oscillation; beam path speed; expanded keyhole; X-ray

1. Introduction

In the ongoing engagement against climate change, alternative propulsion systems such as e-mobility need to be further improved and the manufacturing process for components made more efficient. In e-mobility, there is a large field of different applications and a wide range of geometries as well. Processing of materials like copper and aluminum for those application within serial production is essential.

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For reliable and flexible joining processes, laser beam welding shows high potential to face these challenges. Due to low stability of conventional welding processes with regard to blowouts, spatters and pores (see Fig. 1. (a)), there is a need of adapted joining technologies.

Besides approaches like laser beam welding with wavelengths in the range of 515 nm or 450 nm (Dittrich et al., 2018, Pricking et al., 2019 and Zediker et al., 2019) or laser power modulation (Heider et al., 2011) beam oscillation seems to be an efficient way to enable stable welding processes (Liebl et al., 2014 and Franco, 2017). Beam oscillation – as a superimposed movement of the beam to the feed motion – increases the flexibility and enables an adaption of the energy distribution in the process zone. The number of process parameters increases too. Moreover, to achieve high quality weld seams, it is essential to know how different parameters influence the welding process and how irregularities develop during the process (Fig. 1. (b+c)).

Fig. 1. Comparison of copper weld seam surfaces for same energy per unit length with (a) typical failures during static beam guidance; (b) unsuitable oscillation parameters; (c) adapted oscillation parameters

The goal of the paper is to present the influence of the beam path speed v_B on the quality of the weld seam. It is a function of the welding speed v_W and the velocity of the circular oscillating beam $v_{Osc,x;}$ in x-direction and $v_{Osc,y}$ in y-direction.

$$v_B(t) = \sqrt{(v_W + v_{Osc.x})^2 + (v_{Osc.y})^2} \qquad (1)$$

The velocity of the circular oscillating beam can calculated by the following term and depends on time t, the oscillation amplitude $a_{x,y}$ as well as the oscillation frequency $f_{x,y}$ in x- and y-direction.

$$v_{Osc.}(t) = \begin{bmatrix} v_{Osc.x}(t) \\ v_{Osc.y}(t) \end{bmatrix} = \begin{bmatrix} a * 2\pi * f * cos(2\pi f t) \\ a * 2\pi * f * cos(2\pi f t + \frac{\pi}{2}) \end{bmatrix} \qquad (2)$$

2. Experimental setup and methods

2.1. Optical setup and experimental plan

The welding trials were carried out using a 5000 W single mode fiber laser (YLS-5000-SM, IPG Photonics) combined with a galvanometric scanning optics (welDYNA, Scanlab) with a maximum oscillation frequency of 4000 Hz. With a core fiber diameter of 30 µm and a magnification of 1.25 the focal diameter was set to approx. 37 µm and the focal position on the surface of the samples. The samples were made out of Cu-OF with dimensions of 60 mm x 20 mm in different thicknesses up to 4 mm.

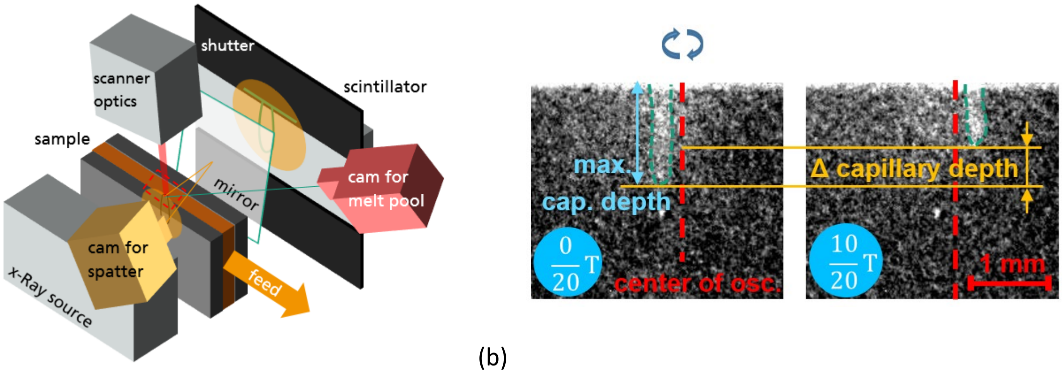
The boundaries of the experimental plan including different parameter variations is shown in Table 1. To sort the effects of different parameters such as variation of frequency, amplitude as well as welding speed and laser power for circular oscillation towards the welding quality out, serval experimental trials were carried out.

Table 1. Experimental plan and variation range of parameter

Parameter	Laser power	Welding speed v_W	Amplitude $a_{x,y}$	Frequency $f_{x,y}$
Minimum	1000 W	1.5 m/min	0.05 mm	250 Hz
Maximum	3000 W	6 m/min	0.4 mm	4000 Hz

2.2. Methods and quality assessment

To identify the physical interactions of the dynamic beam oscillation with respect to the geometry of the interaction zone, complex process diagnostics using measurement methods with high spatial and temporal resolution were carried out. To determine the geometry of the vapor capillary and flow fields, the experimental approach was on X-ray analysis with an acquisition rate of up to 10 kHz. For the determination of the melt pool, a high speed camera was used. For the detection of spatters and melt ejections, additional high-speed images were taken transverse to the welding direction. The schematic setup is shown in Fig. 2 (a).



(a) (b)

Fig. 2. (a) Schematic experimental setup for welding trials with dynamic beam oscillation welding of copper at the X-ray laboratory of IFSW in Stuttgart, Germany; (b) Cumulated X-ray images from two different positions during an oscillation period T.

Due to the use of a small beam diameter (~ 37 µm) and the partly high relative velocities of the beam during oscillation, very narrow capillaries result. Additionally the contrast between the object/capillary and the full material for copper samples is reduced, which makes it difficult to observe a fluctuating capillary. Therefore the thickness is limited to small thicknesses (under 2 mm). Due to that the risk of a heat accumulation during the process is rising. To reduce the heat accumulation the copper sample was positioned between two graphite plates to increase the heat dissipation.

In the X-ray image, the capillary is visible only sporadically in individual images, which strongly limits the analysis of dynamic effects with respect to pore, melt ejection and spatter formation. However, by calculating cumulated images for different time segments of a period, the capillary was made visible for the corresponding time segment. For two time segments of a period T, the cumulated images are shown at maximum deflection in and against the feed direction. Despite the formation of cumulated images, the capillary appears visible only partially from the background. The position, depth and width can be determined. The cumulated images allow the capillary dynamics to be analyzed over an averaged period. For this purpose, the maximum capillary depth was determined, which occurs at the reversal point against the feed rate/global welding speed, T = 0/20 as well as at capillary depth at the half of the period, see Fig. 2 (b).

For post process evaluation, metallographic analysis and microscopy recordings were used. To evaluate the outer seam quality different quality categories were defined. Fig. 3. (a) shows a five star assessment scale with typical seam appearance. For high quality (five and four stars) the appearance of the weld seam is homogeneous with a very low amount of spatters and blow outs. The seam with a three star rating has irregularities which are still acceptable like overflow of molten material and some spatters. A two star evaluation means low quality with a high amount of blow outs/craters but positive sections in the weld seam, too. Furthermore, the picture on the bottom shows a kind of cutting regime with mainly melt ejections, which can also be considered as scrap.

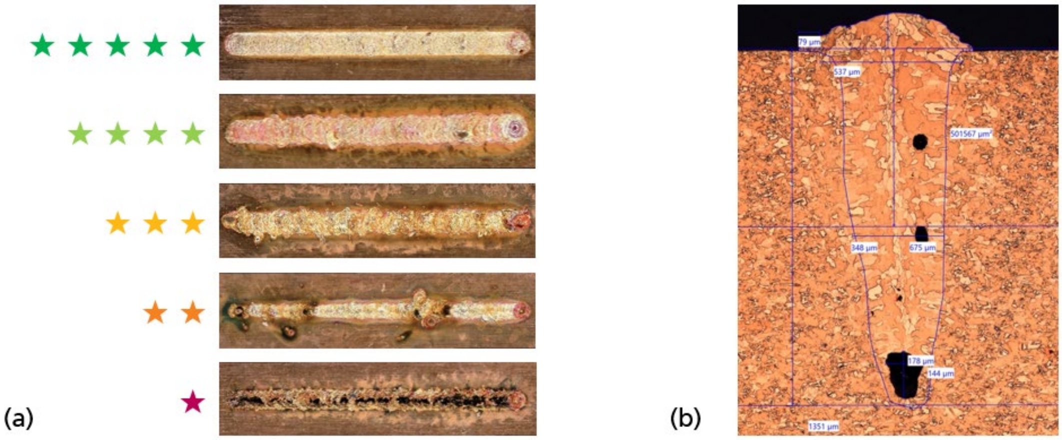


Fig. 3. (a) Characteristic seam appearance for five star quality assessment; (b) cross section of a bead on plate welding with measurements of weld seam geometry and welding defects like pores

The determination of the inner weld seam quality is done by metallographic analysis in combination with standards like DIN EN ISO 13919-2 and DIN EN ISO 5817. Typical parameter like penetration depth, seam width and weld seam area were measured (Fig. 3. (b)) as well as welding defects like pores, clusters of pores or weld concavity included into the quality assessment.

3. Results and discussion

3.1. Process windows

The diagram in Fig. 4. shows a comprehensive parameter variation (see Table 1) with corresponding quality evaluation according to the defined classifications and standards. The influence of the beam path speed for oscillation welding on the resulting weld seam quality is evident. It should be noted that all trials without oscillation in the investigated range of the welding speed and laser power result in a bad quality (one or two stars).

At beam path speeds below 30 m/min, the proportion of trials with low rating (one or two stars) is significantly increased. For high energy per unit length and low beam path speeds the quality is worse, too. Mainly instable processes with melt ejections as well as low overlap of the beam path occur.

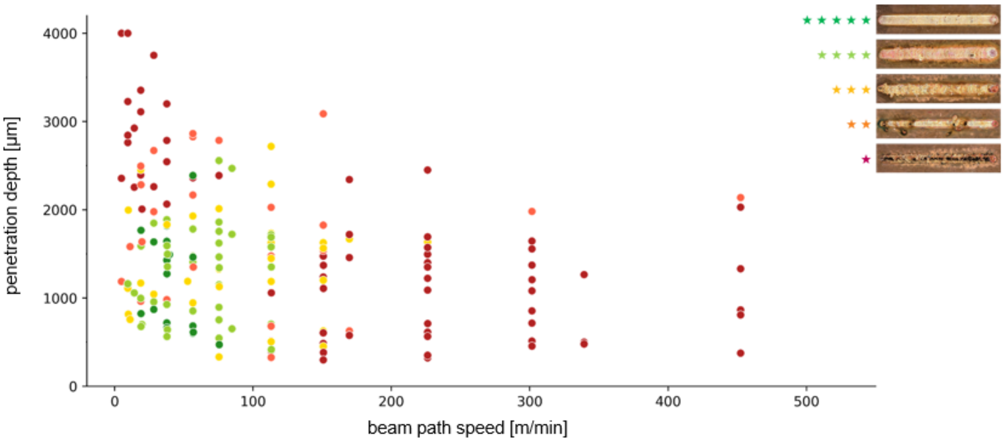


Fig. 4. Influence of the beam path speed on the resulting weld seam quality for different energy per unit length for dynamic beam oscillation welding of copper

In the range between 30 and 100 m/min are those welds with acceptable (three stars) to very high seam quality (five stars). The process stability in this area is increased and spatter as well pore formation decreases. A cause of the higher quality could be, that the capillary is stabilized at higher beam path speed. That outcome is also known from static beam guidance (Heider, 2018). With 0.4 mm to 2.5 mm a wide range of welding depths is possible with only one optical setup. If the beam path speed exceeds 200 m/min, the selected parameters result in only low quality ratings due to increased melt ejections. As a consequence of the high intensity with regard to the single mode beam and the high relative movement of the beam, which leads to low interaction time, a kind of remote laser cutting process occur (Musiol, 2015).

3.2. X-ray analysis

During the circular movement of the laser in the welding direction, it is assumed that the capillary encounters more material with lower temperature on the front reversal point, which in some cases drastically reduces the capillary depth. Furthermore there is a change of the local beam path speed as well as the local energy input during one oscillation period, which results in differences of the capillary depth. The relationship between capillary depth and its maximum difference is shown in Fig. 5. for different amplitudes at 500 Hz and a variation of the frequency at an amplitude of 0.2 mm. The welding speed was set to 5 m/min at a laser power of 2000 W.

Fig. 5. (a) shows that for a frequency of 500 Hz, the maximum capillary depth decreases with increasing amplitude and levels off at a certain value. The maximum difference (Δ) of the capillary depth increases with increasing amplitude, whereby a jump of approx. 0.5 mm in the maximum difference of the capillary depth is visible between the amplitudes of 0.1 mm and 0.2 mm. The course of the curves can be based on the increasing speed but the low thickness of the samples and the special heat dissipation has to be taken into consideration as well.

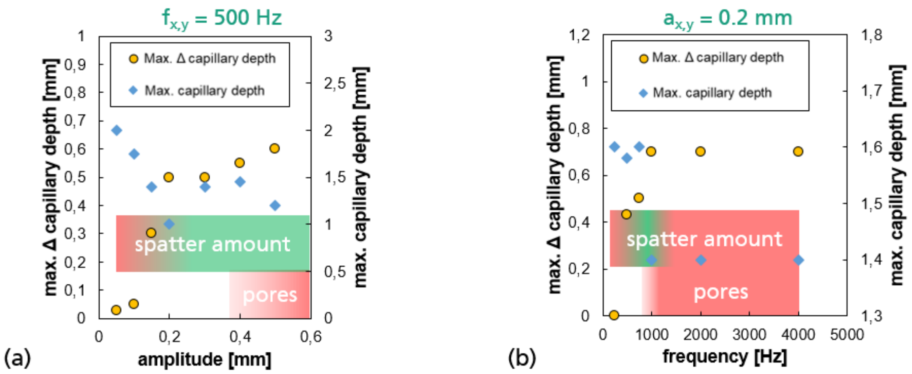


Fig. 5. (a) Maximum capillary depth and its maximum capillary depth difference during one period with circular beam oscillation as a function of amplitude and; (b) frequency. Determined from X-ray images. Qualitatively, the number of spatters and pores is also plotted. Green = less spatters and red = many spatters and pores. For Cu-OF at a welding speed of 5 m/min and a laser power of 2000W.

A similar behavior can be seen with the frequency variation in Fig. 5. (b). From 750 Hz to 1000 Hz, the capillary depth drops abruptly by 0.2 mm, whereas the maximum difference in capillary depth jumps to a value of approx. 0.7 mm and also does not change for higher frequencies. The maximum capillary depth also remains constant. However, with frequencies above 1000 Hz, the number of pores increases rapidly, as does the number of spatters. The optimum for a reduction of spatter is between 750 - 1000 Hz due to the stabilizing effect of the capillary for higher beam path speeds. For the amplitude variation, the optimum for the amplitude is 0.3 mm, since pores are created from 0.4 mm. It is assumed that for the high beam path speed and thus high flow rates, a pinching off of the capillary occurs. Another cause could be, that the overlap rate of the beam path is too low for the chosen welding speed (Mahrle et al., 2007) and for high amplitudes the oscillating narrow capillary cannot degas generated bubbles in the melt pool which results in pore formation.

3.3. Exemplary process limitation – humping phenomena during dynamic beam oscillation welding

The phenomena, which is illustrated in Fig. 6. shows one process limitation at low weld seam depths in the range of 0.5 to 0.8 mm. The parameter from Table 2 lead to a large process interaction in comparison to the beam diameter and a beam path speed of approx. 75 m/min. In this area normally good seam qualities can be expected. But the quality of the weld was rated as bad. In the following the cause of that low quality will be explained. Additionally, it should be noted that the laser power is quite low.

Table 2. Parameter for humping phenomena during dynamic beam oscillation welding

Parameter	Laser power	Welding speed	Amplitude x,y	Frequency x,y
Value	1000W	1,5 m/min	0.4 mm	500 Hz

In Fig. 6. (a) a long melt pool with a narrow width behind the keyhole is visible. The melt pool is formed on the track of the beam on the oscillation pattern. Due to the high speed of the beam and the narrow shape of the melt pool high melt flow leads to building of a hump at the end of the molten area Fig. 6. (b). In Fig 6. (c) the beam interacts with the generated melt hump and a melt ejection occur. This process is repeated in the progress of the weld seam (Fig. 6. (d)) and finally results in bad quality, which is shown in the cross section in Fig. 6. (e) as a crater and solidified hump as well as in the surface of the seam in Fig. 6. (f).

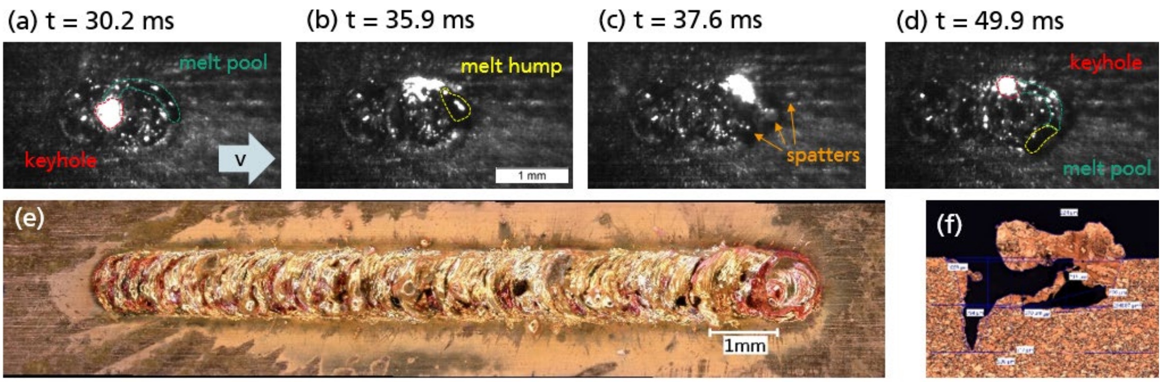


Fig. 6. (a-d) Sequence of humping phenomena during beam oscillation welding of copper; (e) surface of weld seam; (f) cross section

It is crucial to understand the causes of these or similar weld defects. One solution to solve the humping issue is to reduce the process interaction zone and concentrate the energy distribution to a smaller field. An adaption of the amplitude of the scan circle is possible and leads to high quality of the weld seam (Fig. 7. (a)). Another cause of humping are high flow rates of the melt due to a small melt film besides the keyhole (Reinheimer et al., 2022). Therefore, a further solution is to reduce the frequency or rather the beam path speed to avoid humping and reduce the length of the melt pool behind the keyhole, see Fig. 7. (b).

Fig. 7. Possible solutions to avoid humping phenomena during dynamic beam oscillation welding of copper – high speed recording of melt pool, picture of seam surface and cross section for (a) reduction of process interaction zone/amplitude and (b) reduction of beam path speed/frequency

4. Transfer of findings

Another difficult to weld material is aluminum die cast. Because of entrapped gases there is a high defect rate regarding pore formation and blow outs. During laser beam welding with static beam guidance (see Fig. 8. (a)) big bubbles in the melt pool occur, which have a long lifetime and results in pores. Dynamic beam oscillation enables the reduction of porosity (Fig. 8. (b)) by gradual degassing of cavies and the resulting bubbles in the melt pool (Dittrich et al., 2017 and Börner et al., 2021). X-ray recordings during the process were made at the TOMCAT beamline of Swiss Light Source (SLS) in Villigen (CH). The material as well as the setup for the trials at the SLS is described in Börner et al., 2021.

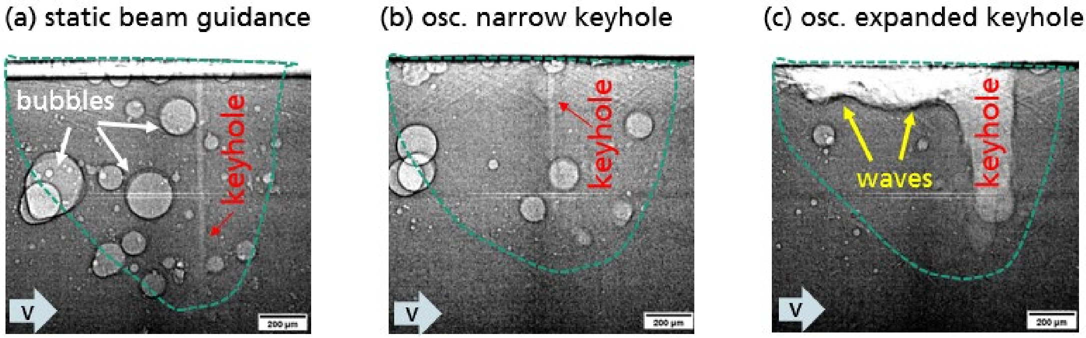


Fig. 8. Synchrotron X-ray recordings for different beam bath speeds and keyhole shapes during aluminum die cast welding (a) static beam guidance; (b) oscillated narrow keyhole with low beam path speed; (c) oscillated expanded keyhole due to high beam path speed

The synchrotron X-ray recordings in Fig. 8. schematically shows that the beam path speed is an important influencing factor for aluminum die cast welding, too. At high beam path speed an expansion of the keyhole is obvious during oscillation ((see Fig. 8. (c)). Thereby the melt pool behavior is influenced, waves are build up and the bubbles are pushed close to the keyhole where they easily can degas. This shows that dynamic beam oscillation is a potential solution for high quality welds also for other difficult to weld materials.

5. Conclusion

The processing and especially the joining of copper components in high quality is a key for increasing the efficiency of e-mobility applications. Laser beam welding has excellent potential to increase the productivity due to the high flexibility and high process automation. During laser beam welding with static beam guidance process stability is not given with regard to formation of spatters and blow outs. Dynamic beam oscillation can improve the quality by adaption of the energy distribution to the work piece. With one laser and one optical setup various welding depths can be achieved, which can be used for a wide range of applications. Deep process know-how, which is enabled by the process analysis using different diagnostic tools, is crucial for target-oriented optimization of the process. In this paper the focus of the investigations was on the influence of the oscillation parameters on the weld seam quality. It was established that the beam path speed is a major factor in this context. Due to the analysis of process limitations it is possible to counteract the causes and increase the process window. In addition to the transfer to other materials like aluminum alloys, the transfer to 3D beam oscillation and other beam shaping technologies like coherent beam combining are exciting topics in the near future.

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