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Fine-tuned remote laser welding of aluminum to copper with local beam oscillation

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Abstract

Local beam oscillation in remote laser welding of aluminum to copper was investigated. Sheets of 1 mm thickness were welded in overlap configuration with aluminum as top material. The laser beam was scanned in a sinusoidal mode perpendicular to the direction of feed and the influence of the oscillation parameters frequency and amplitude on the weld geometry was investigated. Scanning frequencies up to 1 kHz and oscillation amplitudes in the range from 0.25 mm to 1 mm were examined. Throughout the experiments the laser power and the feed rate were kept constant. A decrease of welding depth with amplitude and frequency is found. The scanning amplitude had a strong influence and allowed coarse setting of the welding depth into the lower material, while the frequency allowed fine tuning in the order of 10% of the obtained depth. The oscillation parameters were found to act differently on the aluminum sheet compared to copper sheet regarding the amount of fused material. It is possible to influence the geometry of the fused zones separately for both sheets. Therefore the average composition in the weld can be set with high precision via the oscillation parameters. A setting of the generated intermetallics in the weld zone is possible without adjustment of laser power and feed rate.

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Keywords: Remote laser welding; beam oscillation; dissimilar metals; aluminum; copper; scanning

1. Introduction

A growing range of seminal topics, such as e-mobility and lightweight construction, depend on efficient and secure joining technologies applicable for dissimilar metals, as shown by Kirchhoff, M. (2013). In terms of productivity and automatization remote laser welding is the state of the art joining technology. However, laser

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welding of dissimilar metals usually involves the formation of brittle intermetallic phases. A secure joining process must provide a minimum size of these intermetallics, as they strongly degrade the mechanical and electrical quality of the connection compared to the base metals as Braunovic and Alexandrov (1994) and Rabkin and Ryabov (1970) investigated.

High thermal conductivity and low absorptivity at typical laser wavelengths result in delicate welding processes of the pure materials aluminum and copper itself, as Dausinger and Rapp (1996) and Hess and Schuster (2011) have shown. Intentionally oscillating laser power or focal position have been applied in order to stabilize the welding process. Govekar and Otto (1997) showed that by oscillating the laser power penetration depth in CO_2 laser welding could be stabilized. Toenshoff and Overmeyer (1995) implemented a closed loop control system to dynamically adjust the laser power to stabilize the welding process. Additionally, laser power oscillation has been successfully applied by Seto and Katayama (2001) to prevent the formation of process pores in welding of aluminum alloys. Also local beam oscillation of the laser's focal spot position has been applied to enhance laser welding of single metals as Thiel (2013) reported. These results suggest that also for the complex case of joining aluminum to copper a periodic excitation of the process could be used to control both, the geometrical properties of the weld seam and the distribution of the intermetallic phases. For welding aluminum to copper Poprawe and Schmitt (2007) have investigated a spatial and temporal laser spot modulation regarding the melt pool dynamics. In this paper we report on the influence of a sinusoidal beam oscillation on the resulting geometry and composition of the fusion zone in welding aluminium to copper.

Nomenclature

P	laser power
d_f	focal diameter of laser spot
f	scanning frequency of beam oscillation
A	amplitude of beam oscillation
v_{feed}	feed rate
$v(x,y)$	local laser beam velocity
t	process time
d	welding depth

2. Experimental setup

Electronic grade oxygen-free copper (Cu-OF) and high-purity aluminum (Al99.5) sheets with a thickness of 1 mm each were laser welded in overlap configuration. The experiments were performed using a Laserline laser at a wavelength of 1.085 µm and a delivery fiber of 100 µm core diameter. Local beam oscillation was realized using a Scansonic RLW-A remote laser optics with two scanning mirrors, able to perform 2-dimensional beam scanning with frequencies of up to 1 kHz and amplitudes of up to 3 mm in both directions. The beam was focused on the top of the upper sheet to a focal diameter of 280 µm and a Rayleigh length of 5 mm. To avoid detrimental back reflection into the processing optics it was inclined at an angle of 10° in welding direction. The applied hardware and process properties are summarized in Table 1. In order to allow high speed imaging with a statically positioned camera the processing optics were kept fixed while the sample moved relatively to it in x-direction with feed rate v_{feed} as shown in Fig. 1.

A sinusoidal oscillation of the laser beam perpendicular to the direction of feed (in y-direction) was superimposed to the linear movement in x-direction, so that the beam position in dependence of time can be described by

$$\begin{pmatrix} x(t) \\ y(t) \end{pmatrix} = \begin{pmatrix} v_{feed} \cdot t \\ A \cdot \sin(2\pi f \cdot t) \end{pmatrix}. \tag{1}$$

Oscillation frequencies from 200 Hz to 1 kHz and scanning amplitudes in the range of 0.25 mm to 1 mm were investigated. The feed rate of 6 m/min and the laser power of 3.25 kW were kept constant for all experiments and no additional shielding gas was used.

Table 1. Hardware and process parameters.

Hardware	
Beam source	Laserline LDF 4008LV
Fiber core diameter	100 µm
Wavelength	1.085 µm
Processing optics	Scansonic RLW-A
Magnification	1:2.8
Rayleigh length, z_r	5 mm
Focal diameter, d_f	280 µm
Process parameters	
Top material	Al99.5
Bottom material	Cu-OF
Laser power	3.25 kW
Oscillation amplitude, A	0.25 mm – 1 mm
Feed rate, v_{feed}	6 m/min
Oscillation frequency, f	200 Hz – 1 kHz
Inclination angle optics	10° in direction of feed

For every set of parameters welds of 35 mm length were generated. Five samples were produced per parameter set. A schematic view of the setup, the sinusoidal laser beam track and a top view of a generated weld seam are shown in Fig. 1. Cross sections of the welds were made to analyze the obtained welding depth, the area of fused aluminum and the area of fused copper, as denoted in Fig. 2. For each parameter set four cross sections were evaluated. In addition scanning electron microscopy was used to visualize the materials mixing and to estimate the impact of beam oscillation on the formation of intermetallics.

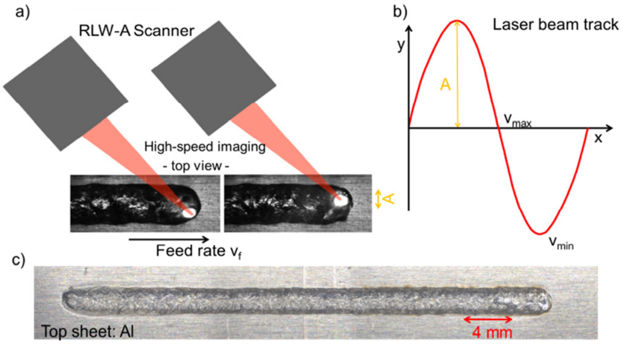

Fig. 1. Experimental setup (a), the sinusoidally scanned laser beam track (b) and the resulting weld seam (c) for A = 0.5 mm and f = 600 Hz.

3. Results

SEM images of typical results when applying local beam oscillation in welding aluminum to copper are pictured in Fig. 2. Since the amount of back scattered electrons increases with atom number, the recorded brightness correlates with the local fraction of copper. This allows a space-resolved, quanlitative estimation of the composition of the welds. Both, the weld geometry and the local distribution of the elements in the fusion zone are influenced by the amplitude and the frequency of the laser beam oscillation. The seam width in aluminum is slightly increased for the larger scanning amplitude of 0.75 mm (Fig. 2 (b)), while the welding depth into the bottom copper sheet is lower. In case of the smaller amplitude of 0.25 mm (a) the mixing of the elements is very inhomogeneous and large cracks are found in the solidified regions of the sheets. For the larger amplitude the relative amount of copper in the weld seam decreases and the fused copper is more homogeneously distributed over the fusion zone. No elongated cracks were found in this case.

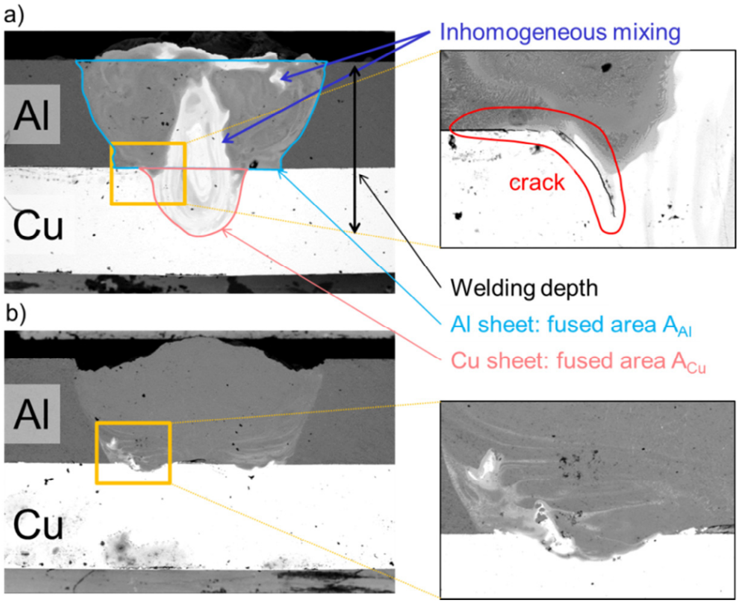

Fig. 2. Scanning electron microscope images of obtained cross sections. Process parameters were (a) A = 0.25 mm, f = 800 Hz and (b) A = 0.75 mm with f = 400 Hz.

For welds with amplitudes larger than 0.25 mm a fusion zone shape as shown in Fig 2 (b) is typical. The welding depth is larger on the sides resulting in a typical tooth-like shape. This results from the locally varying absorbed laser energy per unit length, which is given by $P/v(x,y)$ and reaches its maximum of $P/v_{min} = P/v_{feed}$ at the beam tracks outer turning points (see Fig. 1 (b)). Depending on the oscillation parameters A and f the minimum local laser energy per unit length is given by $P/v_{max} = P/\sqrt{(A2\pi f)^2 + v_{feed}{}^2}$ and reached in the center of the weld. Therefore both, the amplitude and the scanning frequency decrease the locally introduced energy per unit length and in our parameter space this local line energy ranges from about 0.5 kJ/m to about 10 kJ/m for A = 1 mm and f = 1 kHz, and A = 0.25 mm and f = 200 Hz, respectively.

While the local line energy is lowered with both the frequency and the amplitude, the latter also increases the area over which the laser beam is scanned and additionally reduces the disposable energy per scanned area.

The dependence of the maximum welding depth on the oscillation parameters is shown in Fig. 3. The measured depths range from 2 mm, which corresponds to full penetration of both sheets, to less than 1 mm, where no connection of both sheets could be achieved (these measurements are therefore not included in the graphs).

Increasing the frequency as well as increasing the amplitude results in a reduced welding depth, with the amplitude being of stronger influence.

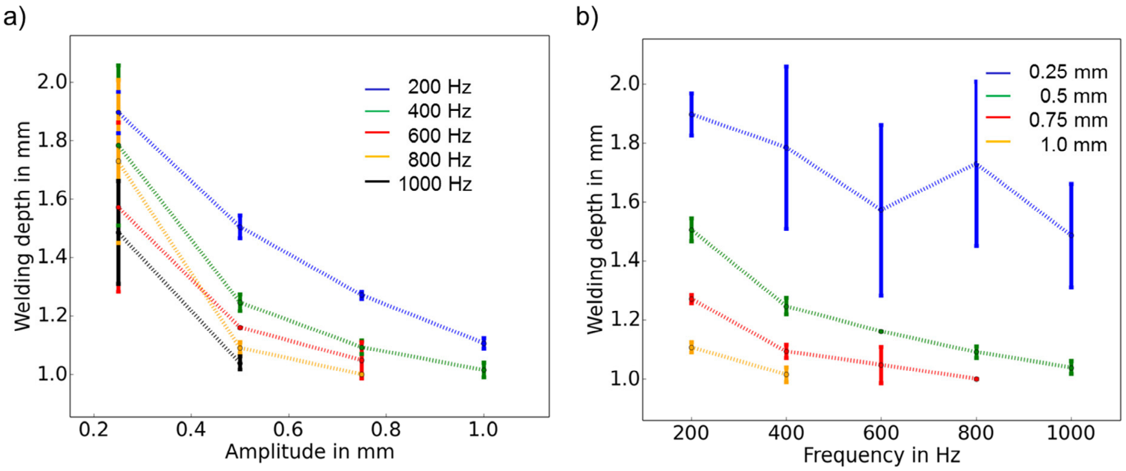

Fig. 3. Average welding depth as a function of scanning amplitude (a) and frequency (b). The vertical error bars denote the standard deviation.

For a scanning amplitude of 0.5 mm (Fig 3 (b), green line), the mean welding depth decreased almost linearly by 215 µm when increasing the frequency from 400 Hz to 1 kHz with very small standard deviations of about less than 10% of the average depth. In contrast, by increasing the amplitude over the interval 0.25 mm – 1 mm (Fig 3 (b)) the process could be set from full penetration to almost no penetration of the lower copper sheet. To quantify the sensitivity of the welding depth d on the two parameters its average derivatives with respect to A and f, $\partial d/\partial A$ and $\partial d/\partial f$, respectively, were determined. These were found to be $\partial d/\partial A = -0.2061$ and $\partial d/\partial f = -0.0516\,\mathrm{mm}/100\,\mathrm{Hz}$, which shows the strong influence of the scanning amplitude compared to the influence of the frequency. Additionally, the smallest scanning amplitude resulted in a more instable welding depth independent of the scanning frequency, which manifested in the large standard deviations of up to 35%.

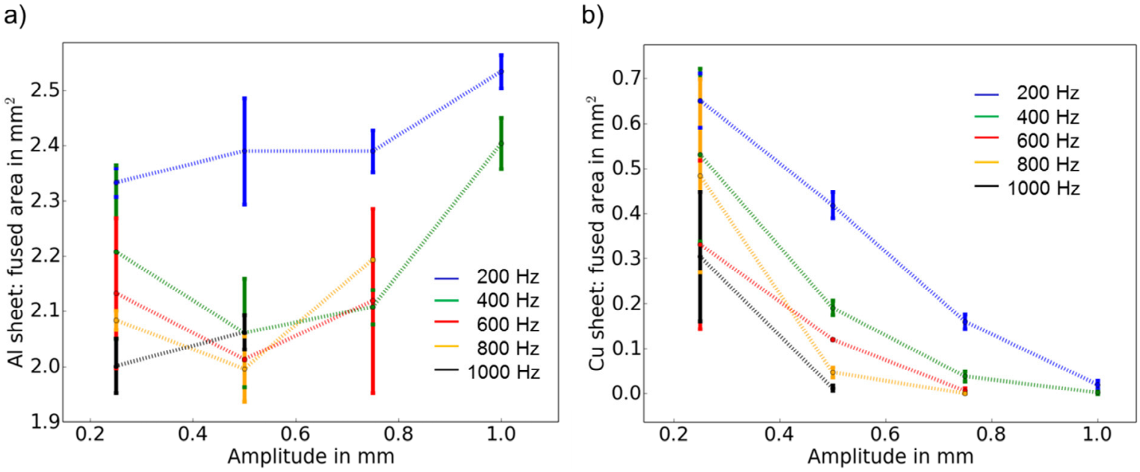

Fig. 4. Area of fused aluminum A_{Al} (a) and copper A_{Cu} (b) in the weld seam as a function of the scanning amplitude.

The areas of fused aluminum and copper determine the average fraction of each element in the fused zone. Their fraction influences the type of the generated intermetallic. Therefore, the fused areas in the aluminum sheet A_{al} and the copper sheet A_{Cu} were both measured from the cross sections of the weld as sketched in Fig. 2. The dependence of the fused areas on the scanning amplitude is shown in Fig. 4. The amount of fused aluminum hardly depends on the scanning amplitude. For lower frequencies it peaked at the 1 mm amplitude. For scanning frequencies higher than 200 Hz and amplitudes lower than 1 mm however, A_{al} was not affected. In this parameter range the effects of lower local energy per unit length and larger scanned area counteract and annihilate. In contrast, the fused area of copper decreased for larger amplitudes. Here the decrease of line energy dominates and A_{Cu} continuously decreases with the scanning amplitude. This effect was found for all scanning frequencies.

Since the geometry of the fused zone is influenced differently for the two sheets by the oscillation parameters, the elements composition in the weld can be set by these. In Fig. 5 the average relative share of copper $S_{Cu} = (A_{Cu} \cdot \rho_{Cu})/(A_{Al} \cdot \rho_{Al})$ in the total fused zone of the cross sections is shown as a function of the oscillation parameters. This is calculated in weight-percentage from the ratio of the area of molten copper and aluminum, each weighted by the density, i.e. $\rho_{Cu} = 8940$kg/m^3 [†] and $\rho_{Al} = 2710$ kg/m^3 [‡]. The obtained values of S_{Cu} ranged from 0 % up to 53 %. For all examined cross sections a value of more than 55 % of copper could not be reached, despite its three times higher density compared to aluminum. Again, a negative correlation of both, f and A to S_{Cu} was found. This manifests in $\partial S_{Cu}/\partial A < 0$ and $\partial S_{Cu}/\partial f < 0$ as shown in Fig. 5. As for the welding depth, the relative share of copper in the weld seam reacts very sensitive to the scanning amplitude, while the scanning frequency has smaller influence.

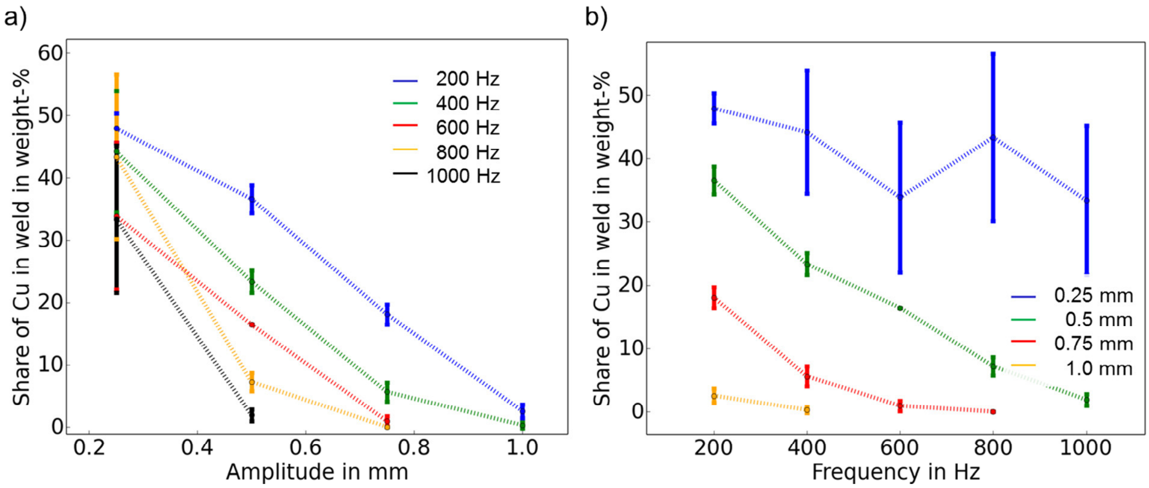

Fig. 5. Relative ratio of copper in the overall fused zone in weight-% as a function of scanning amplitude (a) and frequency (b).

S_{Cu} mainly correlates with the welding depth, as can be seen in Fig. 6. Here the mean values of S_{Cu} and the corresponding welding depth d are plotted for every combination of the oscillation parameters. The data points are fitted for the function $s(d) = a \cdot \ln(d+1)$ with the fit parameter a.

[†] WielandWerke: https://www.wieland.de/mediaPool/content/media/de/datenblaetter/datenblaetter_z/K30.pdf, 04.05.2016, 19.25 CET

[‡] matbase: http://www.matbase.com/material-categories/metals/non-ferrous-metals/wrought-aluminium/material-properties-of-al99-5-din-1712-3-wrought-aluminium-alloy-grade.html#properties, 04.05.2016, 19.25 CET

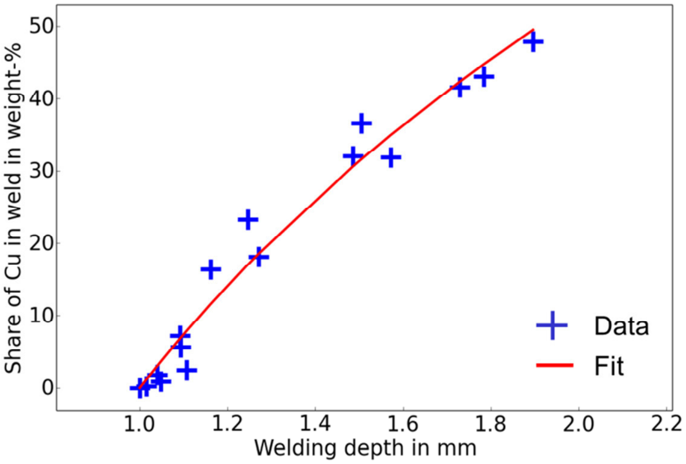

Fig. 6. Dependence of the relative share of copper in the fusion zone on the welding depth. Markers: Mean values for each oscillation parameter. The line is a logarithmic fit to the data.

4. Applacation relevant implications

The formation of intermetallics in the weld seam depends on the chemical composition of the fused zone and the elements mixing. The chemical composition, embodied as the relative share of copper in the weld seam, strongly correlates with the obtained welding depth. As the partial derivatives with respect to the oscillation parameters prove, the adjustment of the scanning amplitude allows a regulation of the welding depth over a wide range, while the frequency enables a very fine tuning with a precision of about 10%. By choosing suitable oscillation parameters it is possible to manage the composition of the welds and therefore influence the creation of intermetallic phases. These, as well as the welds width at the sheets contact area, are critical for the process outcome in terms of electrical resistance or mechanical shear strength. For typical use in electrical applications the actual welding depth is of minor importance, given a steady junction of two sheets is secured and the metallurgical quality is sufficient. However, the the electrical conductivity is proportional to the contact area of the generated joint. With beam oscillation the area over which this joint is established can be adjusted. In contrast to non-scanning laser welding this area can be increased without enlargement of the welding depth. The latter would increase the ratio of copper in the weld and thereby enhance the creation of intermetallics. The amplitude and frequency can easily be changed on the fly depending on seam tracking or in-situ diagnostics.

Furthermore the laser power can be adapted to the oscillation phase. This would allow to prevent the tooth-like shape of the weld seam as pictured in Fig. 2 and to further increase the regularity of the welding depth in the lower copper sheet.

5. Conlcusion

Local laser beam oscillation was applied to tune the welding depth and the geometry of the fused areas in remote laser welding of aluminum to copper. The elements mixing in the fused zone is enhanced and the creation of cracks along the contact area of both sheets is reduced for larger scanning amplitudes. Since the locally introduced laser energy per unit length decreases with both, the oscillations amplitude and the frequency, the obtained welding depths were found to decrease with both parameters. For a constant laser power of 3.25 kW and a feed rate of 6 m/min it was possible to switch from full penetration of both sheets to a lack of bonding by adjustment of these parameters in the investigated frequency range of up to 1 kHz and amplitudes from 0.25 mm to 1 mm. The maximum welding depth could coarsely be set with the oscillation amplitude while the oscillation frequency allowed fine tuning of the obtained depth. The area of molten aluminum can be increased by increasing the oscillation amplitude. However, this effect vanishes for frequencies higher than 400 Hz. In contrast the amount of fused material in the lower copper sheet strongly decreases with scanning amplitude. As a result the average relative share of copper in the weld seam can be influenced in the range from 0 to 53 weight-%.

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References

Kirchhoff, M. (2013). Laser applications in battery production — From cutting foils to welding the case: Proceedings October 29th-30th, 2013, Nuremberg, Germany, 2013.

Braunovic, M. and Alexandrov, N. (1994). Intermetallic compounds at aluminum-to-copper electrical interfaces: effect of temperature and electric current, IEEE Trans. Comp., Packag., Manufact. Technol. A, 17, 78–85, doi:10.1109/95.296372, 1994.

Rabkin, D. M., Ryabov, V. R., Lozovskaya, A. V., and Dovzhenko, V. A. (1970). Preparation and properties of copper-aluminum intermetallic compounds, Powder Metall Met Ceram, 9, 695–700, doi:10.1007/BF00803820, 1970.

Dausinger, F., Rapp, J., Beck, M., Faisst, F., Hack, R., and Hügel, H. (1996). Welding of aluminum: A challenging opportunity for laser technology, J. Laser Appl., 8, 285, doi:10.2351/1.4745434, 1996.

Hess, A., Schuster, R., Heider, A., Weber, R., and Graf, T. (2011). Continuous Wave Laser Welding of Copper with Combined Beams at Wavelengths of 1030nm and of 515nm, Physics Procedia, 12, 88–94, doi:10.1016/j.phpro.2011.03.012, 2011.

E. Govekar, I. G., A. Otto, and M. Geiger (1997). Control of laser beam penetration depth during welding, Control of Oscillations and Chaos, 1997. Proceedings., 1997 1st International Conference, 342 - 344 vol.2, doi:10.1109/COC.1997.631366, 1997.

Toenshoff, H. K., Overmeyer, L., and Alvensleben, F. von (1995). Closed-loop control of material processing with high-power CO2 lasers, Proc. SPIE, 2375, doi:10.1117/12.206976, 1995.

Seto, N., Katayama, S., and Matsunawa, A. (2001). Porosity formation mechanism and suppression procedure in laser welding of aluminium alloys, Welding International, 15, 191–202, 2001.

Thiel, C. (2013). Welding Process Stabilization by Laser Beam Manipulation, Process diagnostic and control in laser beam welding and cutting, 2013.

J. Gedicke , A. Olowski, J. Artal and A. Gillner (2007). Influence of temporal and spatial laser power modulation on melt pool dynamics, Laser Materials Processing (Proc. of the 26th Int. Congress on Applications of Laser and Electro-Optics ICALEO 2007), 816–822, 2007.