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# Laser deep penetration weld seams with high surface quality

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**Abstract**

In former publications, the authors showed that laser deep penetration welding with transversely beam oscillation and wire feeding increases the gap bridging ability for butt-joint configurations. Within these experiments the following phenomena was found. A circular cavity, the so-called buttonhole, was formed directly behind the laser spot at certain oscillation frequencies. Its diameter corresponds nearly to the melt pool width. The existence of the buttonhole seemed to correlate with high surface quality of the seam. In this study, welding experiments with 1.5 mm thick aluminum sheets (EN AW-6082) in butt-joint configuration with filler wire delivery have been carried out. The results show that a process window with a stable buttonhole exists. It is proven that buttonhole welding allows reliable welding processes with very smooth almost ripple-free seam surface.

Keywords: laser beam welding; beam oscillation; visible seam quality; aluminium

## 1. Introduction

It is well known that a positive optical perception of an object stands for high product quality and highly affects the purchasing decision of the customer, see e. g. Haenraets et al., 2012. According to Beaess and Seiffert, 2013, this means for welding that visible seams have to be very precisely produced to fulfill the increasing optical requirements of high-quality products. In serial car production laser beam brazing is used to produce such visible seams with highest optical requirements. Examples are visible seams on the rear lid, see e. g. the work of Tang et al., 2013, or visible seams on the car roof, e. g. Engelbrecht, 2009. The investigations of Heitmanek et al., 2014, have shown the possibility to increase the seam appearance by using beam oscillation in brazing direction to pre-heat the work peace and improve the wettability of molten

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filler wire. A successively applied two beam method for laser beam brazing with pre-heating was presented by Mittelstädt et al., 2014. Sander and Reimann, 2015, published a description of relevant optical criteria for visible seams. According to them, spatters, pores, notches and seam holes lead to the exclusion of a seam, whereas the roughness, the pronunciation of ripples, the homogeneity of the seam course and the bead rounding belong to the parameters with thresholds.

When changing the process mode from laser brazing to laser heat conduction welding, higher joint strengths are possible, see e. g. Schwartz, 2003. In both process modes the amount of absorbed laser energy is nearly one-times the Fresnel-absorption. Inside the keyhole at deep penetration welding the laser beam interacts several times with the keyhole wall until it escapes though its opening. This leads to a distinctive increase of energy coupling into the material. According to the results of Kawahito et al., 2011, the amount of absorbed energy increases to about 90 % during keyhole welding of aluminum or steel materials with solid state laser beams. Accompanied by deep penetration welding are high melt pool dynamics which lead to several unwanted visual appearances such as spatters, pores or notches and cause post processing, see e. g. Volpp, 2017.

According to the investigations of Farrel and Ferrario, 1987, beam oscillation significantly reduces seam defects such as spatters, notches or pores in electron beam welding with keyhole formation. Investigations with one-dimensional laser beam oscillation confirmed the positive influence on reducing seam defects in deep penetration welding, see e. g. Albert and Starcevic, 2016. Dittrich et al., 2013, investigated the influence of the frequency of a circular beam scan motion on the formation of the upper bead on aluminum parts. They found that high scanning frequencies (>400 Hz) lead to turbulences in the melt pool and to a wavy solidification pattern of the upper bead. Mahrle and Beyer, 2007, investigated the influence of the energy distribution varied by one- and two-dimensional beam deflection on the seam quality of laser beam welded zinc coated steel sheets. They found that especially a longitudinal beam oscillation in feed direction lead to a smoother and more uniform seam surface. According to Seefeld and Schultz, 2013, one of the essential advantages of beam oscillation is the wide energy distribution due to the oscillation width and welding with a high intensity at the same time.

Former studies of the authors, Schultz et al., 2014, showed that one-dimensional beam oscillation transversely to the welding direction enables a significant increase of the gap bridging ability (>300 % of the sheet thickness). In high speed videos of the welding process the following phenomena was observed. Behind the oscillating laser a circular cavity was formed in the melt pool. The diameter was nearly the melt pool width. The emergence and collapse of this cavity correlated with the process stability and the pronunciation of seam ripples. A very smooth seam surface and a straight seam course resulted when the cavity was stable during welding. Laser welding with such a cavity has been called "buttonhole welding" in Vollertsen, 2016. Aalderink et al., 2007, also observed such a cavity during bead on plate welding of 1.1 mm thick aluminum sheets. The stability of this catenoidal shaped cavity was strongly related to the sheet thickness and the laser spot diameter. Haglund et al., 2013, confirmed the existence of such a cavity in pulsed laser welding of thin sheets. They observed the reduction of spatters and pores as well as symmetric cross-sections. Disadvantages are the reduction of welding speed as well as the need for ‘run-on’ and ‘run-off’ plates. The formation of the cavity took several millimeters and a hole remained at the end of the seam. Ingmar et al., 2014, continued the investigations and found that the cavity was not formed for ratios of the melt pool width and the sheet thickness of less than 1.5.

In this study, wire melting experiments as well as bead on plate and butt-joint welding experiments were carried out to determine the process window of buttonhole welding with filler wire delivery for 1.5 mm thick aluminum sheets.

## 2. Experimental

A Trumpf TruDisk12002 multi-mode disc laser was used in cw-mode. The beam was delivered through a fiber with a core diameter of 200 µm and collimated by a collimator lens with 200 mm length. The laser processing head was of the type BEO D70 from Trumpf and modified by an ILV DC-Scanner, see Fig. 1. The beam was one-dimensionally oscillated transversely to the welding direction. The focal length of the focusing lens was 200 mm. The nominal focus spot diameter was 200 µm. On the workpiece, a sinusoidal shaped beam path results when combining the beam oscillation with process feed, see Fig. 2a. The energy distribution perpendicular to the welding direction is given in Fig. 2b. The illustrations show the relation between the oscillation parameters, the welding speed and the energy distribution as well as the laser path on the workpiece schematically. The laser welding head was completed by leading filler wire delivery and lagging shielding gas nozzles. Argon flow was 15 l/m. In addition, a helium flow of 10 l/min was applicated into a root chamber. The wire feed system was a Dinse DIX WD300 and WDE300 push-push combination with maximum wire feed speed of 10 m/min. A Vision Research Phantom VEO 410 high speed camera was utilized with 5000 fps in order to observe the welding process.

Laser processing experiments contained wire melting, bead on plate welding and welding in a zero-gap butt-joint configuration. The wire melting experiments and bead on plate welds were carried out to learn about the creation and existence of a buttonhole and delimit the region in which a stable buttonhole welding in a butt-joint configuration with filler wire delivery is possible. For wire melting by laser beam the classification according to Binroth, 1995, was carried out. These are a ‘droplet formation’ which result from a too high energy input, an ‘incomplete melting’ by a too low energy input and a ‘continuous flow’ which result from good energy input.

The used material was 1.5 mm thick EN AW-6082 aluminum sheets and filler wire of type ML 4043 in 1.2 mm diameter. Cross-sections and upper bead seam surfaces were evaluated regarding a seam quality required for visible seams. For this purpose, a buttonhole weld seam was compared to a conventional laser beam weld seam without beam oscillation. The parameter ranges are given with Table 1.

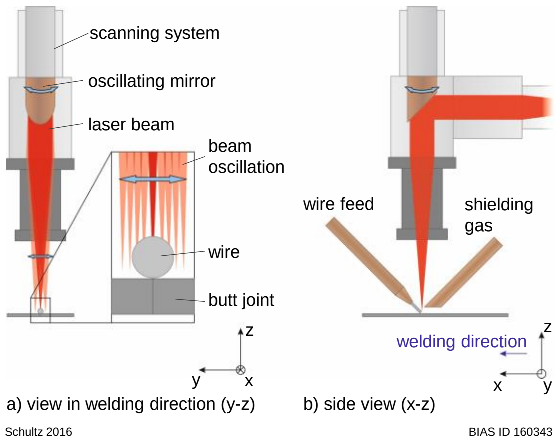


Fig. 1. Schematic illustration of the beam path through the welding head and oscillation transverse to the welding direction

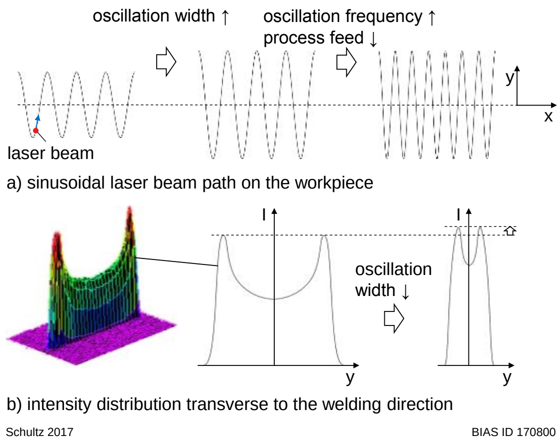


Fig. 2. Influence of a transverse laser beam oscillation during laser beam welding

Table 1. Parameters used in experimental investigations

| Parameter | Unit | Value / range |
|---|---|---|
| Laser power | kW | 0.5 to 8 |
| Focal position to sheet surface | mm | -0.5 |
| Welding speed | m/min | 6 |
| Wire feed speed | m/min | 0 to 9 |
| Oscillation width | mm | 0 to 2.4 |
| Oscillation frequency | Hz | 200 |

## 3. Results

Fig. 3 exemplarily shows the three wire melting conditions from current experiments. Here the droplet formation is presented with Fig. 3a. In this case, the wire melt forms a droplet on its tip which grows against the feed direction during process. The droplet falls off after reaching a certain size. The wire melting condition can be changed to a continuous flow by decreasing the energy input, see Fig 3b. The molten wire flows down vertically on the underlay and forms a nest. Within the nest the original wire form can still be identified. The nest itself is stable and cannot be unwrapped due to merging of the interaction points of molten wire material. The third classification is given by an incompletely molten wire as shown exemplarily in Fig. 3c. This results from a too low laser power or too high wire feed speed. Nevertheless, the energy input is not high enough to melt the wire over its whole cross-section. The wire only bended slightly with the gravitational force behind the laser irradiation position. When it reached the underlay it additionally bended due to the feeding forces. In comparison to a continuous melting the incompletely molten wire forms larger nests and the interaction points within the nest are not merged.

Fig. 4 shows experimental results from wire melting. A linear relation between laser power and wire feed speed can be determined. The melting classifications change in dependence to the feed speed from droplet formation (triangles) to continuous flow (squares) and finally to incomplete melting (circles) with almost every investigated laser power except of 0.5 kW.

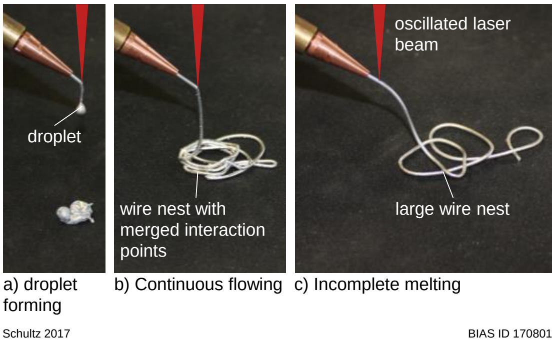


Fig. 3. 8 Wire melting classifications after Binroth, 1995

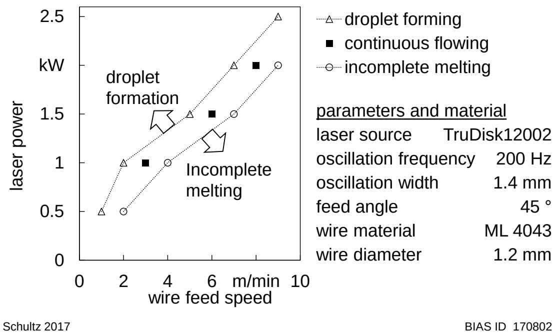


Fig. 4. Influence of the laser power and wire feed speed on the melding condition of filer wire according to the classification of Binroth, 1995

Fig. 5 shows pictures from high speed video recordings from bead on plate welding without filler wire. It can be seen that the existence of a buttonhole relates to the laser power. The melt pool is widened to a width of about 1.8 mm. This results in a square shaped melt pool front, which grows zigzag like in welding direction. Accordingly, 4 kW laser power was not high enough to create a buttonhole. With 5 kW, the threshold was exceeded and a stable buttonhole was formed. It moved at the melt pool front from the weld beginning to the end. The buttonhole had a catenoidal shape and was as wide (dimension transversely to the welding direction) as the melt pool width. It had a slightly elongated length compared to its width. The buttonhole itself oscillated dynamically. Behind the buttonhole the melt pool was calmed down.

Fig. 6 shows the process window for the existence of a buttonhole as function of the laser power and oscillation width. The diagram shows two general situations. Either a self-creation of a buttonhole was possible (circles), or not (squares). The creation of a buttonhole does not mean that it is stable. In its unstable form the created buttonhole ‘detaches’ from the melt pool front and usually remains as a pinhole in the seam. This phenomenon was observed at oscillation widths of 1.9 mm or higher. A requirement was that the sheet has been completely welded through. Generally, no buttonhole was found below the sheet weld through threshold. The stable form of a buttonhole was found within the green region (green circles). It was classified as stable when its creation and existence remained along the whole welding process. The stable form required an oscillation width of at least 1.1 mm.

The findings from previous results were transferred to laser beam buttonhole welding with filler wire delivery in a zero-gap butt-joint configuration. This included the set of a beam oscillation width of 1.6 mm, since it turned out to have the largest laser power range for a stable buttonhole, compare with Fig. 6. In Fig. 7a a picture taken from high speed video recording of the butt-joint process with a zero-gap configuration and filler wire delivery is shown. Within the video recording a stable buttonhole with uniform material transfer from wire to the melt pool front was observed.

Fig. 8 shows the influence of the laser power on the wire feed speed at otherwise constant parameters for buttonhole welding in a butt-joint configuration. It shows that a stable buttonhole exists with decreasing wire feed speed and increasing laser power.

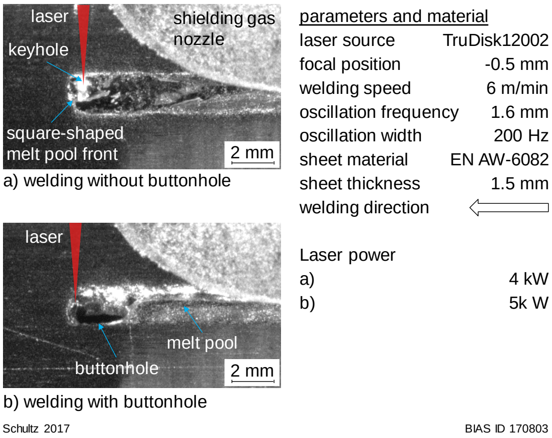


Fig. 5. Bead on plate welding without and with buttonhole

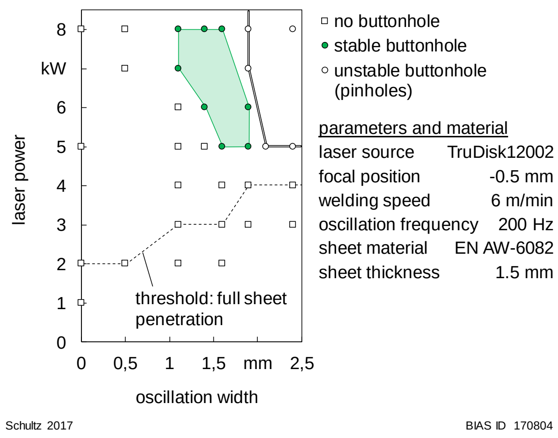


Fig. 6. Influence of the laser power and oscillation width on the existence of a buttonhole at bead on plate welding

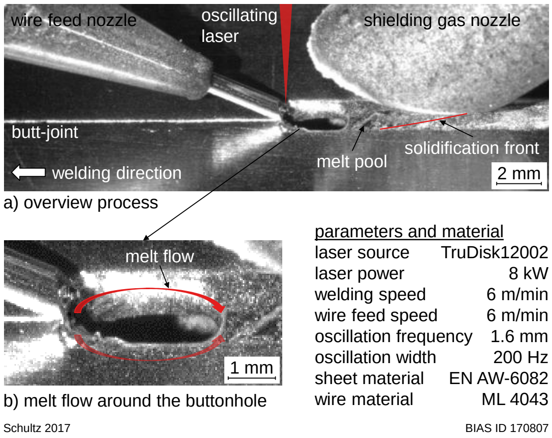


Fig. 7. Laser beam buttonhole welding of a zero-gap butt-joint configuration

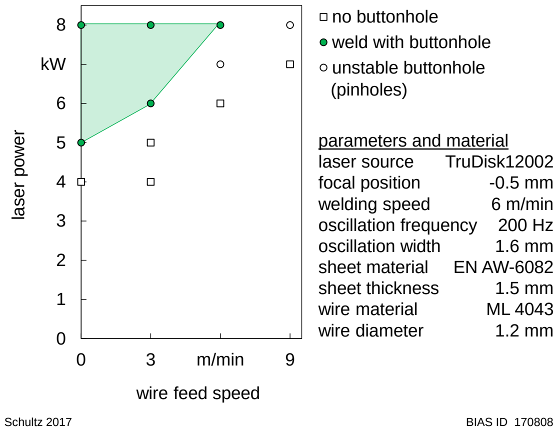


Fig. 8. Influence of the laser power and wire feed speed on the process window of welding with buttonhole

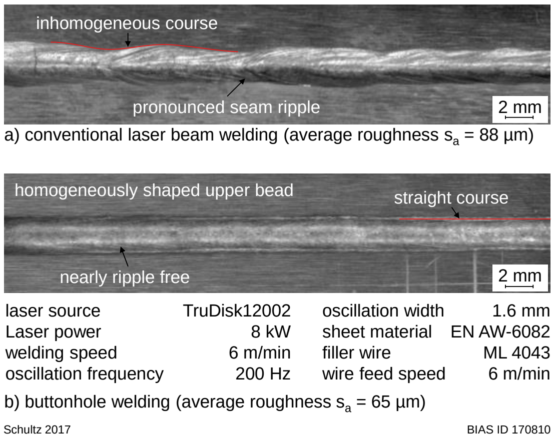


Fig. 9. Comparison between a conventional laser beam welded seam and a seam welded by buttonhole welding

Fig. 9 shows the upper beads of two seams. One is made without laser beam oscillation (Fig. 9a) and the other one by buttonhole welding (Fig. 9b). The welded seam without beam oscillation remained with an inhomogeneous seam course and pronouncing seam ripples. With buttonhole, the seam course remained homogeneously straight and the upper bead solidified nearly without any ripples and reduced surface roughness.

## 4. Discussion

Buttonhole welding is a new laser welding method. It allows deep penetration welding of seams with high surface quality as required for visible seams. The difference of buttonhole welding to previous welding methods with catenoidal cavities, e. g. in Aalderink et al., 2007, is the use of beam oscillation transversely to the welding direction and adding of filler wire to the melt pool. This allows the combination of high welding speeds, high energy absorption and smooth seam surfaces.

It was found that a process window for stable buttonhole welding exists. It requires an energy input that leads to a complete penetration through the sheet material. Fig. 5 shows this case from high speed video recordings for bead on plate welding without filler wire. In Fig. 6 the threshold for full sheet penetration is marked with a dash line.

According to Ericsson et al., 2014, a catedoinal shaped cavity in a melt pool requires a melt pool width that is at least 1.5-times wider than the sheet thickness. For the process presented here the melt pool width can be influenced by the oscillation width and the laser power. If considering this, the threshold to the left side of the stable-buttonhole-area (green area) in Fig. 6 can be understood. With increasing laser power a decreasing oscillation width is necessary to result in a melt pool width that is wide enough to enable a buttonhole to emerge.

To the right side of the stable-buttonhole-area in Fig. 6 the buttonhole is unstable. One possible explanation may be a too wide melt pool width what leads to a process destabilization. As a result, the buttonhole ‘detaches’ from the melt pool front and remains as a pinhole in the seam.

Higher laser powers than 8 kW were not investigated. Nevertheless, it is assumable that the stable-buttonhole-area is valid even for higher laser powers.

It follows that the addition of filler wire to the process increases the need of energy to fulfill the described thresholds. In a simplified contemplation, the necessary laser power for buttonhole welding with filler wire (Fig. 8) can be estimated by adding the laser powers from Fig. 4 (melting condition: continuous flow or early range of droplet formation) and Fig. 6 (area: stable buttonhole).

## 5. Conclusion

- The following requirements must be met to enable a stable buttonhole
    - full penetration through the sheet material
    - the melt pool must be wider than the sheet thickness
    - oversized melt pool widths lead to a buttonhole destabilization and the risk of remaining pinholes

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