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Measurements of weld quality with OCT during laser beam oscillation welding of aluminum alloy for battery production

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Abstract

Successful mass production is closely linked to a quality assurance procedure tailored to the joining process. The oscillating laser beam was used for welding aluminum alloy. Continuous weld depth monitoring was realized with OCT by synchronously controlling the position of the OCT scanner and the processing scanner optics. On the one hand, this ensured the required penetration, which benefits the stabilization of the molten pool and keyhole and thus better weld quality. On the other hand, control of the weld penetration depth is essential to avoid the risk of piercing the battery cell when welding the battery system. The variation of weld depth within the oscillation period was observed and analyzed in conjunction with video recordings. OCT enables highly accurate non-contact process monitoring and quality assurance during remote laser welding and can serve as a corrective and/or preventive measure to achieve zero scrap and optimal battery performance without compromising safety.

Keywords: industrial laser processing; welding, oscillation; optical sensor; optical coherence tomography; process monitoring; quality assessment; weld depth; aluminum alloy; battery; electric vehicle; efficiency

1. Introduction

The development and manufacture of battery systems is an essential part of the production of electric drives. The battery systems must have a high energy and power density to enable a satisfactory range of electric vehicles. To build the battery system, a large number of cells must be electrically connected using cell connectors called busbars [Schmidt et al 2012]. Therefore, the range of an electric vehicle, the performance and the efficiency of a battery system are directly correlated with the electrical conductivity of the

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interconnects. Additionally, higher electrical contact resistance generates more heat at the cell connection. To achieve the best battery performance, the contacts between cell terminals and cell connectors must provide maximum electrical conductivity [Schmidt 2015]. This effect is significant because it adds up over several hundred contacts in a battery system.

To reduce the electrical losses, laser welding is used [Brand et al 2015] because the optimal weld can be realized by laser beam welding. Moreover, joints with low contact resistance and high joint strength can be achieved. Busbars, which are typically made of aluminum with a thickness of several millimeters, can be joined by laser welding. Laser welding offers great advantages in terms of weld shape and depth, as well as limited heat-affected zone. Battery tabs or connecting bars can be welded with remarkable precision and high speed. Laser beam welding does not necessarily involve contact, and a high degree of automation of the cell joining process can be achieved when assembling large batteries.

Aluminum is a material with many potentials. In the field of electromobility, aluminum is one of the most interesting materials because it is a metal with good mechanical strength, corrosion resistance and low weight. The automotive manufacturing industry is particularly interested in aluminum alloys because they can reduce the weight of the battery and the vehicle. The high thermal conductivity and low absorptivity at typical laser wavelengths result in a delicate welding process of aluminum. Laser beam oscillation limits the heat generated and thus allows to restrain the degradation of properties during welding of aluminum [Martukanitz et al 2005, Ji et al 2015, Wang et al 2016, Wang et al 2019]. Beam oscillation is an innovative technique in laser welding that enables controlled heat input, high welding speed, and improved weld quality. When welding electrical contacts of a battery system, the oscillating laser beam is used not only to improve weld quality, but also to increase the weld width while maintaining a small beam diameter, which is required for keyhole welding of highly reflective Al metal. The design of the weld plays an important role in the electrical connections and should preferably have a large joint area without pores to ensure high electrical conductivity [Schmidt et al 2012].

To ensure controlled heat input, improved surface quality, uniform weld depth and high throughput, optical coherence tomography (OCT) monitoring technology is used [Deyneka Dupriez et al 2017] because of its high precision, high temporal resolution and insensitivity to welding conditions. In this work, weld depth control with OCT is proposed to ensure the proper connection of each battery cell, as a deficient weld depth can lead to malfunction due to lack of connection, and a too excessive weld depth can be a reason for the damage of the whole battery. For this purpose, an aluminum alloy was welded with an oscillating laser beam that followed a circular pattern along the circular feed path, while the OCT measurement beam followed the processing beam at each point of the circular pattern with a predefined offset. The novelty of this approach is the weld depth control during welding along the circular feed path in contrast to the previous work by [Galbraith et al 2018]. Using inline coherent imaging, they investigated the effect of the circular wobble (oscillation) pattern on keyhole depth during welding of copper and aluminum alloys with oscillating laser beam along the linear feed path. The present work addresses the above challenge by using a newly developed highly dynamic adaptation of the OCT beam position to the instantaneously changed processing direction [Lessmueller et al 2017], which allows to follow any welding trajectory and any oscillation geometry [Deyneka Dupriez et al 2023].

In this context, the analysis of the weld penetration depth variation with respect to the position on the oscillation circle, and also with respect to the oscillation direction in conjunction with the circle feed direction was a key objective of the present work.

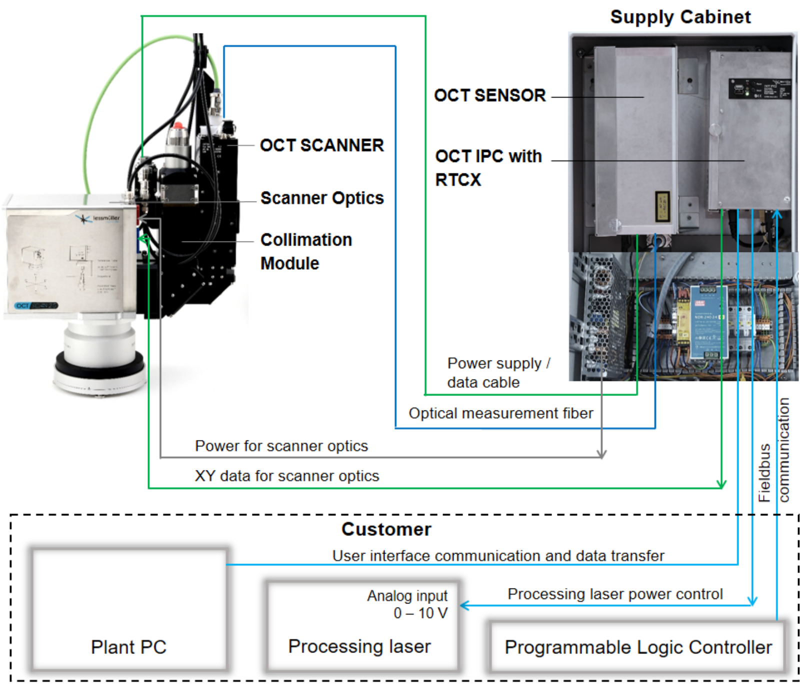


Fig. 1. Schematic welding and measurement setup.

2. Experimental Setup

The laser beam welding experiments were performed on the aluminum alloy EN-AW-1050 (typically used for welding busbars). Welds were created using a Trumpf TruDisk 5000 fiber-coupled multimode IR disk laser with a fiber diameter of 200 µm, a laser wavelength of 1030 nm, and the BrightLine Weld laser beam shaper. With the BrightLine Weld beamformer, the laser beam intensity was distributed 75% to the core (with 50 µm core fiber diameter) and 25% to the ring (with 200 µm ring fiber diameter) to produce a uniform intensity profile and homogeneous weld depth in the aluminum alloy [Kraetzsch et al 2011].

All welds were made under process conditions similar to those of industrial laser welding of aluminum busbars as listed in Table 1. However, in order to achieve a good quality of the weld depth measurements, laser welding was performed with an optimized laser power of 2.5 kW. The laser beam was transmitted to the workpiece by the Lessmüller OCT SCAN 2.5 system (Fig. 1), consisting of the SCANLAB intelliSCAN 30 2D galvanometer scanner with integrated Lessmüller collimation module and the Lessmüller OCT 3D RTCX system. An F-theta lens of the intelliSCAN 30 focusing optics has a focal length of 460 mm, resulting in a processing laser spot diameter of 198 µm on the workpiece surface. The galvanometer scanner was used for high-frequency beam oscillation. The circular feed movement was superimposed with an independent circular oscillation (transverse to the feed direction), as illustrated in Fig. 2(a), (b).

A real follow-up mode with OCT became possible by combining the intelliSCAN 30 scanner optics and the OCT RTCX extension with synchronous interface for the signals transmitted every 20 µs to the OCT SCANNER and to the intelliSCAN 30. A high-speed OCT SCANNER together with the OCT SENSOR and the OCT IPC constitutes the components of the OCT 3D RTCX system. Details of the system setup can be found elsewhere

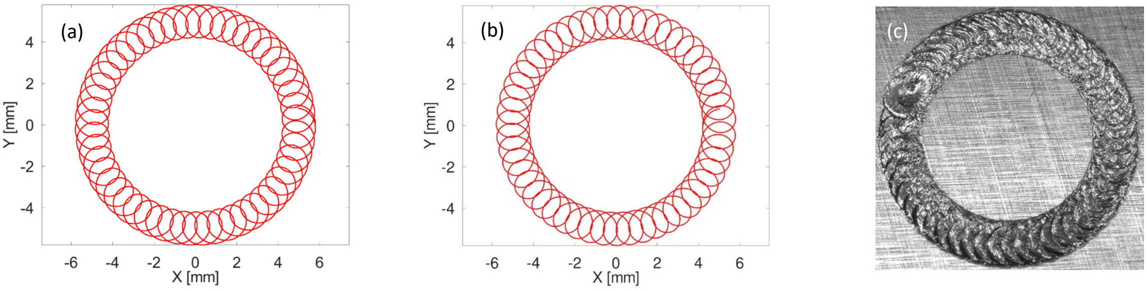


Fig. 2. Schematic representation of the oscillation pattern: (a) clockwise feed movement superimposed on clockwise oscillation or counterclockwise feed movement superimposed on counterclockwise oscillation; (b) counterclockwise feed movement superimposed on clockwise oscillation or clockwise feed movement superimposed on counterclockwise oscillation; (c) photo of a typical weld.

Table 1. Welding process conditions

Laser power	2.5 kW
BrightLine Weld fiber core/ring ratio	75% (50 µm diameter) / 25% (200 µm diameter)
Welding speed	95 mm/s
Oscillation frequency	150 Hz
Oscillation radius	0.8 mm
Feed circle diameter	10 mm

[Deyneka Dupriez et al 2023]. This arrangement allowed synchronous control of both the position of the OCT SCANNER and the focusing scanner optics. OCT weld depth measurements were made at a rate of 250 kHz in real time. The OCT spot was offset in the direction behind the processing beam in order to meet the hottest point, i.e. the bottom of the keyhole [Birnesser 2011]. In order to evaluate the weld depth at every point along the circular oscillation pattern, the OCT beam position had to be adjusted online in a highly dynamic manner using the instantaneous direction vector [Deyneka Dupriez et al 2023, Lessmueller et al 2017]. The absolute value of the weld depth was determined as the difference of two measurements: one inside the keyhole and another on the workpiece surface serving as a reference.

Lessmüller's collimation module features a motorized z-shift for focus control and automatic adjustment to maintain the required weld depth, but this was not in use in the present study.

The welding process was recorded with a CHRONOS 1.4 high-speed camera mounted on the tripod operating at a recording rate of 8816 fps and a resolution of 640 x 200 px.

3. Results and Discussion

The results of all weld depth measurements with OCT over the entire welding time during the welding of each circular weld are presented in Fig. 3. Homogeneous weld contours were observed (see example photo in Fig. 2(c)).

The majority of the measured weld depth values varied in the range of -0.4 to -1 mm. During the first 60-80 ms, the weld depth tended to increase with increasing weld path overlap (Fig. 3), which can be attributed to the heat accumulation.

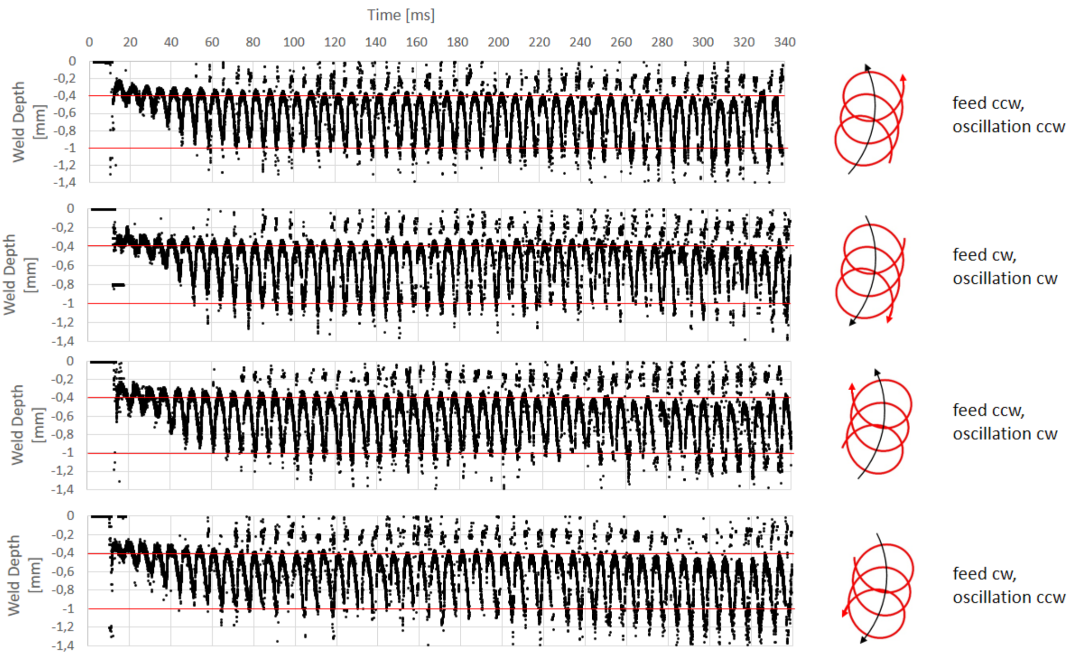


Fig. 3. Weld depth measured with OCT over the entire weld achieved during welding in all possible combinations of oscillation and feed movement directions (see red flash on the red oscillation curve and black flash on the black feed direction curve on the left). The horizontal red lines schematically show the range of the most frequently measured weld depth

Fig. 3 shows that the oscillating movement of the laser beam resulted in an oscillating weld depth. Similar results have already been presented by [Galbraith et al 2018, Deyneka Dupriez et al 2023]. The authors analyzed the weld depth as a function of the radial angle around the oscillation circle and found that the shallowest weld depth was observed at the leading edge of the oscillation pattern relative to the feed direction (so-called leading position), while the weld depth was deepest at the rear end of the feed direction (so-called trailing position). In the present work, the difference in weld depth between these points was determined to be approximately 0.6 - 0.7 mm. Galbraith et al. observed the largest difference between the penetration (weld) depth at the leading and trailing positions of about 0.4 mm when welding Al at a welding speed of 100 mm/s compared to the workpieces welded at lower welding speeds (oscillation frequency of 500 Hz and oscillation radius of 0.25 mm were used).

A closer examination revealed the asymmetry of the weld depth with respect to the cardinal points (Fig. 4). The asymmetry was more pronounced for the oscillations with forward direction inside the feed circle (Fig. 4(c) and (d)) than for the oscillations with forward direction outside the feed circle (Fig. 4(a) and (b)). To explain this behavior, the changes in weld depth during welding of a single oscillation loop were analyzed. The results of this analysis are shown in Fig. 5. Here, the cardinal points, i.e. the leading and trailing positions, as well as the middle (half time) and one quarter (quarter time) of the forward semicircle (Pos. 1 and Pos. 2, respectively) and the backward semicircle (Pos. 3 and Pos. 4, respectively) are marked on both the oscillation pattern and the weld depth curve. The positions of the intersections (Pos. 5 and Pos. 6) were roughly estimated from the oscillation pattern. The slow side in the backward movement is colored grey, the fast side in the forward movement is colored light grey. In addition, the melt regions in Fig. 5 are shown as hatched areas, taking into account the estimated width of the melt pool (approx. 0.8 mm [Deyneka Dupriez et al 2023]) around the

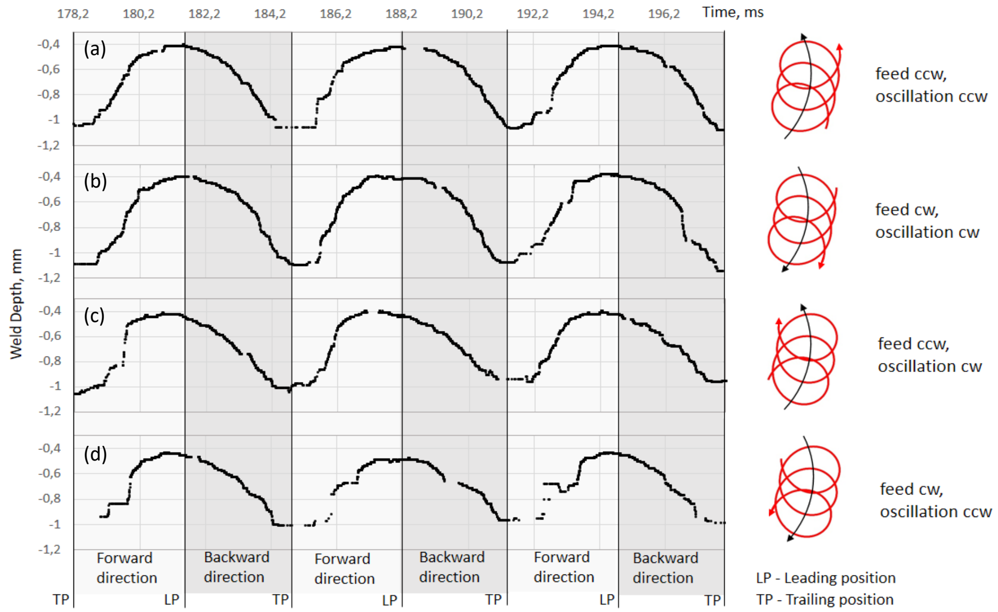


Fig. 4. Extract of the filtered OCT weld depth measurements during three oscillation loops with the marked cardinal points and the corresponding schematic representation of the laser beam movement and the feed direction on the right

intersections and the different welding speeds in the forward and backward directions [Galbraith et al 2018, Deyneka Dupriez et al 2023].

When the laser moved forward inside the feed circle, a faster decrease in weld penetration depth to the boundary of the melt region and thus a steeper weld penetration depth curve was observed (Fig. 5(c) and (d)) compared to the oscillation conditions when the laser beam moved forward outside the feed circle (Fig. 5(a) and (b)). Between the boundaries of the melt regions (hatched areas), the laser beam moved over the non-melted material, whose temperature decreased with distance from the melt region. After passing the leading position, the temperature increased slightly due to the approach to the melt region, thus affecting the increase of the weld depth. However, in the case of backward welding outside the feed circle (Fig. 5(c) and (d)), the heating rate in this phase was probably higher than in the case of backward welding inside the feed circle (Fig. 5(a) and (b)). Therefore, the weld depth in the first case reached lower value near the melt region. Comparing the movements of the laser beam shown in Figs. 5(b) and (d), the time (or distance) from the intersection to the leading position was longer when the laser beam moved forward outside the feed circle than when it moved forward inside the feed circle. This effect is opposite for the backward direction, which obviously affected the heat accumulation and presumably the asymmetry of the weld depth curve.

Furthermore, the long forward path inside the feed circle was shortened by moving the laser beam along the circular trajectory with the smaller radius. The long forward path outside the feed circle became even longer due to the movement along the circular trajectory with the larger radius. The difference in circumferential speeds at the inner and outer edges of the feed circle was estimated to be only 1%. The assumption that the movement speeds on the inner and outer feed circle influence the weld penetration depth [Deyneka Dupriez et al 2023] can therefore be neglected.

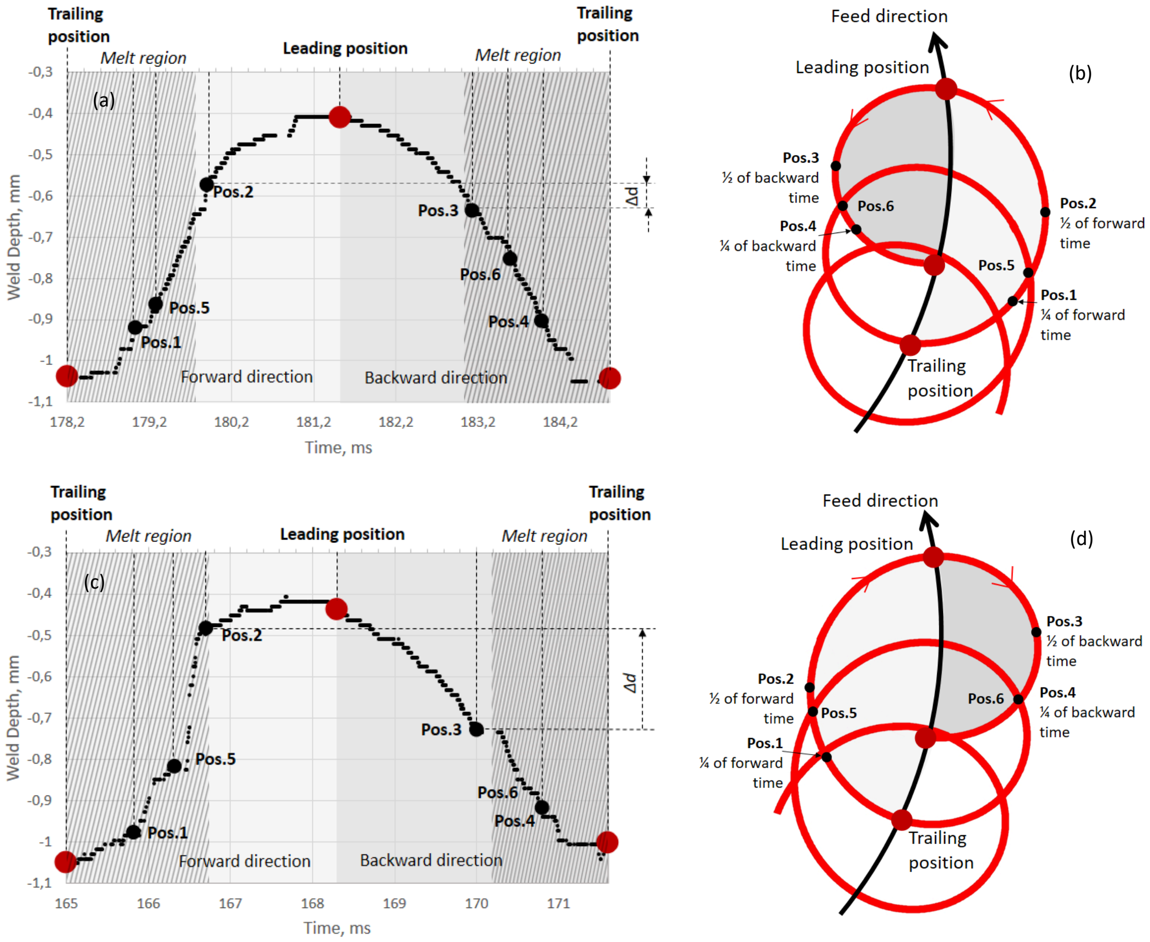


Fig. 5. (a), (c) cut-out from the filtered OCT weld depth measurements during one oscillation loop; (b), (d) corresponding schematic representation of the oscillation pattern

The average difference *Δd* of the weld depth measured in Pos. 2 and Pos. 3 was evaluated and it was found that for the forward direction inside the feed circle *Δd* = 0.2 mm and for the forward direction outside the feed circle *Δd* = 0.1 mm. The weld depth in Pos. 2, which was close to the intersection Pos. 5, was always shallower than in Pos. 3, which was close to the intersection Pos. 6. It is worth noting that in the case of the forward direction inside the feed circle, even if Pos. 2 was closer to the intersection than Pos. 3 was (see Fig. 5(b)), the weld depth in Pos. 2 was still shallower than in Pos. 3. The reason for this is the lower welding speed and hence higher heat accumulation in the backward direction compared to the higher welding speed and hence lower heat accumulation in the forward direction.

On average, a slightly lower amount of material was melted in the forward direction than in the backward direction: a factor of 0.9 regardless of the feed and oscillation direction. This is due to the higher welding speed (a factor of 1.3) in the forward direction [Galbraith et al 2018, Deyneka Dupriez et al 2023].

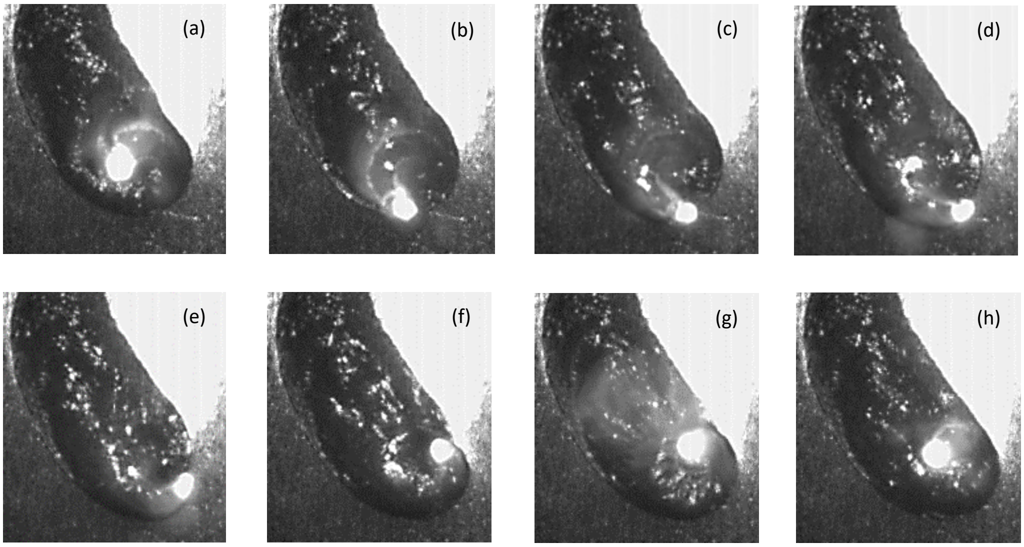


Fig. 6. Sequence of snapshots from the video recording of the oscillating movement of the laser beam, showing the processing laser at different positions within an oscillation loop: (a)-(d) in forward direction; (e)-(h) in backward direction

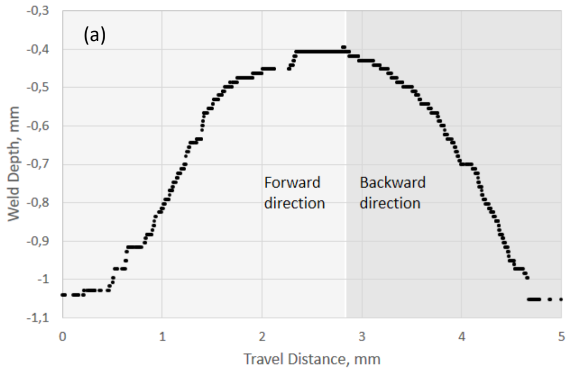
The video recording of oscillation welding (Fig. 6) supports the above analysis of the weld depth variation (Fig. 5). Approximately halfway of the forward movement (Fig. 6(b)) the laser beam leaved the melting region and halfway of the backward movement the laser beam entered the melting region (Fig. 6(f)). The size of the glowing weld spot was larger when the processing beam moved in the melt region where the weld was deeper (Fig. 6(a), (b), (g), (h)) whereas the weld spot size diminished when the processing beam moved on the non-melted material, resulting in a shallower keyhole (Fig. 6(c), (d), (e), (f)).

Based on the different speeds in the forward and backward directions, Chen et al. 2021 simulated and observed the cross-sectional morphology of the weld on an aluminum alloy produced with an oscillating laser beam. The bottom of the weld was tilted, with the deeper part on the backward side of the oscillation loop. A tilted weld bottom made by oscillation welding has already been presented by several authors [Chelladurai Asirvatham et al 2022, Wang et al 2018].

Considering different speeds in forward and backward direction, the weld depth can be shown as a function of the travel distance (Fig. 7) within an oscillation loop. From Fig. 7 it can be seen that the weld depth decreased halfway the travel distance (2.5 mm) and increased halfway the travel distance, while during the first and last 1.5 mm a strong drop and rise of the weld depth, respectively, can be observed. For 2 mm of travel distance in the middle of the oscillation loop, the change in weld depth was less pronounced: up to 0.15 mm.

4. Conclusion

Oscillation laser welding has been used to join battery components for electric vehicles made of aluminum alloys to influence the joining area, which is proportional to the joint conductivity or electrical resistance. The intentionally oscillating laser is recognized also for stabilizing the welding process, being unstable due to the higher reflection and the higher thermal conductivity of Al. A fiber laser was used in combination with a galvanometer scanner and parameters similar to those industrially optimized for laser welding of aluminum busbars were employed.



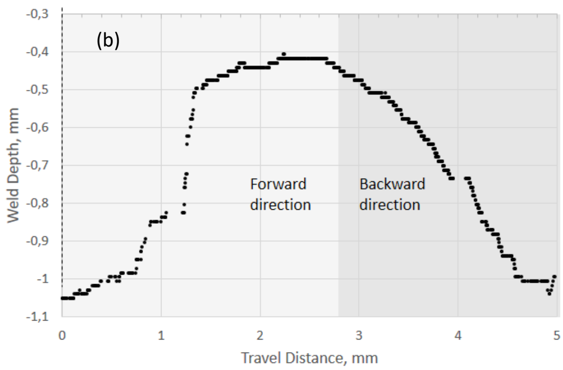


Fig. 7. Cut-out from the filtered OCT weld depth measurements over the travel distance along one oscillation loop in case of: (a) counterclockwise feed movement superimposed on counterclockwise oscillation; (b) counterclockwise feed movement superimposed on clockwise oscillation

Of particular importance is the application of real-time high-speed weld depth measurements with OCT, realized by the OCT RTCX extension for the intelliSCAN 30 scanner optics, to guarantee the high dynamic follow-up mode.

In this work, the circular oscillating laser beam moved along the circular feed trajectory and the position-dependent weld depth was acquired with OCT. The oscillation behavior of the weld depth correlated with the oscillating movement of the laser beam and showed peak values at the time of the leading and trailing points. An asymmetric appearance of the weld depth with respect to the cardinal points was revealed, which is believed to be related to the geometry of the oscillation pattern together with the variation of the local welding speeds and energy distribution proximate to the molten areas. It was found that the asymmetry was more pronounced in the oscillation conditions when the laser beam moved in the forward direction inside the feed circle. According to our interpretation, the laser beam moved slower in the backward direction than in the forward direction due to the different circumferential speeds, causing on average a higher amount of material melted in the backward direction than in the forward direction and thus resulting in the smoother side of the weld depth curve.

The oscillation movement was designed so that the laser beam crossed the welding path (or molten areas) several times. The weld depth increased as the laser beam approached the intersection of the previous circle, as heat accumulated around the intersection. It decreased as the laser beam left the melt region. When the laser beam melted the non-melted area, most of the melt volume in the rear area had lower thermal effect on the weld depth.

This work emphasizes the advantage of OCT process monitoring while welding aluminum busbars. OCT offers a way to automatize the process, increase productivity and reduce overall power losses in the battery of an electric vehicle. The new knowledge gained from this work should provide a basis for achieving the above objectives.

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