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OCT for Controlled and Precise Robotic Arc Welding and Tactile Laser Welding and Brazing

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Abstract

The capability of OCT technology for real-time seam tracking and weld bead quality evaluation was examined in robot-guided automated GMAW and tactile laser welding and brazing of automotive parts made of bare steel, coated steel and aluminum with different joint types at different welding speeds. The permissible gap size and gap compensation were investigated for both automated conventional and tactile laser welding. During tactile laser welding and brazing, the filler wire speed and laser power were varied. Satisfactory results were achieved: The industry-proven, standardized OCT functions and fieldbus communication enabled accurate and consistent seam tracking, gap bridging and online quality monitoring of the seam topography of the tested materials during processing with variable welding or brazing parameters. Thanks to the flexibility, insensitivity to environmental conditions and very high accuracy of the OCT system, the joining processes could be precisely controlled.

Keywords: Optical coherence tomography; tactile laser welding; laser brazing; arc welding; seam tracking; seam quality monitoring; high accuracy; consistency

1. Introduction

Optical coherence tomography (OCT) is a technique originally developed for noninvasive cross-sectional imaging in biological tissues. The core of the OCT system is a fiber-optic Michelson interferometer that typically utilizes low-coherence light with wavelength of typically 830 nm from a super luminescent diode which is divided into the sample and reference arm. The sample is positioned in the sample arm of the interferometer. Light reflections from the sample are combined with those from the reference mirror of the reference arm. The photodetector captures interferometric modulation of the output intensity when the optical path lengths of the reference and sample arms are closely matched and hence axial location of the sample can be determined with high accuracy. Lateral scanning mechanism of the OCT scanner makes possible three-dimensional imaging. Low-coherence imaging is used for contactless in vivo measurement of deep tissues, for example measurements in various eye structures [Fercher et al, 1988 and Huang et al, 1991]. OCT is widely employed as a high-resolution imaging modality to provide real-time cross-sectional views of the surgical field, enabling dynamic visualization of the surgical procedure, including laser surgery [Boppart et al, 1998], and the interactions between instruments and tissue.

Beyond its well-established role in biomedical use, OCT has gained attention in industrial applications due to its high spatial resolution and acquisition rate. It has emerged as a powerful tool for in situ characterization of material structures and nondestructive quality inspection and analysis of industrial products like polymers, printed electronic components, optical devices, and industrial fluids [Fu et al, 2024]. The advantages of OCT are also implemented for laser welding to monitor and control the quality of laser processing online.

Initially, similar to laser surgery, inline coherent imaging was utilized to examine the laser penetration depth in metallic workpieces by guiding the measuring beam coaxially to the processing laser beam [Ji et al, 2025]. Further developed OCT

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scanners made it possible to scan the pre- and post-processing area to acquire the surface topography in order to reliably control the welding location and provide real-time alerts for welding defects [Deyneka Dupriez and Truckenbrodt, 2016].

Nowadays, OCT is integrated into a large number of welding heads, both fixed and scanning optics. Thanks to real-time high-speed communication between the robot or scanning optics and the OCT scanner, the OCT measurement beam follows the processing beam, even with sharp change in the welding trajectory, and the orientation of the OCT scan figure changes accordingly [Deyneka Dupriez, 2021]. This became advantageous for laser beam oscillation welding which favorable for wide shallow seam, hot cracking reduction and prevention of the formation of process pores and molten pool ejections in the weld [Mann et al, 2017]. Owing the benefit of the highly dynamical displacement of the OCT beam according to the current processing direction, it was found that the penetration depth of the processing laser was influenced by the heat accumulation due to the overlapping motion [Deyneka Dupriez et al, 2023]. It was shown that the keyhole in the front part of the processing trajectory was shorter than in the rear part of the circular path. In order to realize the circular oscillations superimposed on the linear or circular feed direction, the laser beam had to pass through the molten areas that caused the greatest weld depth at the back of the oscillation circle [Deyneka Dupriez, 2023]. At the very front, the laser beam melted a large amount of solid material in order to move forward along the feed direction.

Recently, transparent Plexiglas was welded for online side observation of the laser beam penetration and melt propagation [Deyneka Dupriez and Nöbauer, 2025]. The video recording of the Plexiglas from the side made it possible to follow the development of the cross-section weld profile at each individual point of the oscillation pattern. Using OCT, the topography of the weld crater was video recorded and analyzed in the post-process and it was found to be deepest at the positions of the overlapping oscillation circles. This result confirms previous OCT weld depth measurements during oscillation welding of aluminum alloys. Similar results were recently obtained by computer simulation of the welding process with a clockwise oscillating laser beam: the periodic expansion and contraction of the keyhole was observed in the rear parts and in front of the weld pool, respectively [Ai et al, 2023].

Inline OCT was also coaxially integrated into the 3D laser printing process to detect the characteristic topography deviations that enables closed-loop process control and hence enhances the reproducibility and precision of automated additive laser manufacturing [Stehmar et al 2022 and Bernauer et al 2024]. OCT was likewise successfully applied for real time morphology monitoring during laser drilling into metallic samples [Webster et al 2010].

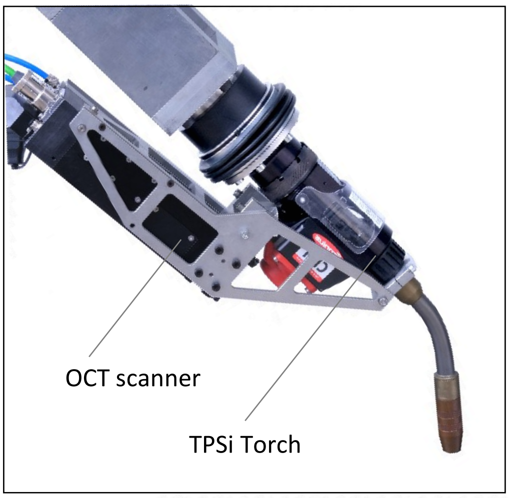
In this work the traditional welding techniques were modernized with modern sensors enabling a further increase in productivity in automated gas metal arc welding (GMAW) and tactile laser welding and brazing. OCT system was integrated into tactile processing head and robot-guided automated conventional welder for the initial joint detection and inspection of the processed area instead or additionally to the commonly used camera systems. It is demonstrated that this combination enables fast and efficient laser welding and brazing.

2. Experimental setup

The OCT system comprises an OCT sensor, an OCT scanner for 3D imaging and an OCT IPC. Only the OCT scanner is usually mounted on the welding torch or laser welding head (Fig. 1). The OCT sensor and IPC OCT are installed in the control cabinet. During operation, OCT continuously records each weld seam, capturing both video and complete measurement datasets. These OCT height measurements are directly correlated with process data, allowing early detection of deviations and prevention of costly rejects. Via the user interface, operators can monitor the live position of the joint in the workspace and view the joining process in real time—even outside the welding area or laser safety cell.

2.1. Robotic arc welding

In contrast to the standard OCT system, the OCT can measure the surface topography in front of and behind the arc as an independent system when the OCT scanner is mounted onto the welding torch (see Fig. 1(a)). A detailed description of the standalone Lessmüller OCT system can be found elsewhere [Deyneka Dupriez and Adolph, 2024]. Some system features are listed here: The typical resolution of the detected position is 5 µm, with the OCT system offering a maximum axial measurement range of 12 mm in all configurations. Depending on the focusing module of the standalone OCT scanner, nominal working distances of 300 mm, 400 mm or 600 mm are available (see Table 1).



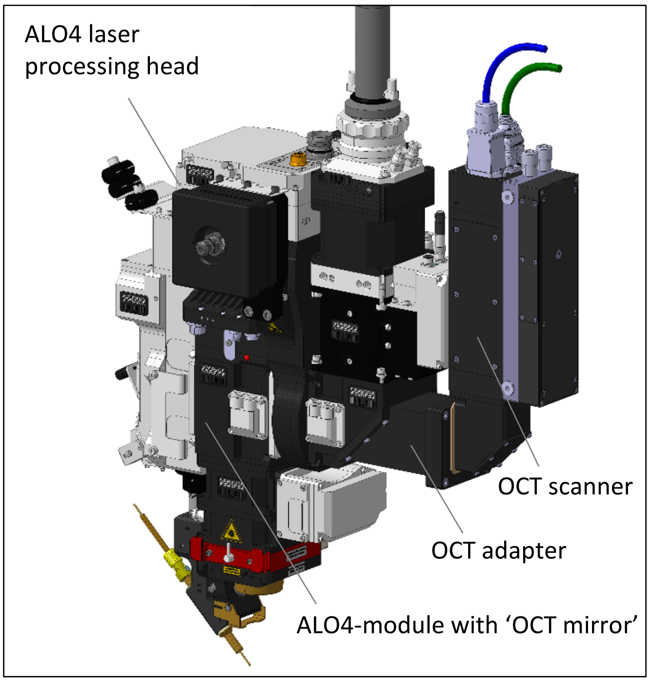


Fig. 1. Traditional welding technique modernized with OCT: (a) TPSi torch for arc welding; (b) ALO4 laser processing head for tactile laser welding.

Table 1. Working distance and lateral scan radius of the standalone OCT

Focus length of the OCT focusing lens	300 mm	400 mm	600 mm
Working distance	300 +/- 50 mm	400 +/- 50 mm	600 + 50/- 150 mm
Lateral scan radius	25 mm	35 mm	55 mm

Automotive parts made of bare steel, coated steel and aluminum with three joint types - lap joint, T-joint and butt joint - were arc welded at a robot speed of 0.5 - 2 mm/s. OCT was used for real-time seam tracking and quality inspection. The OCT IPC contains a PCI card for fieldbus communication with the robot. The system identifies the joint, compares the actual edge position with the programmed robot path and adjusts the robot movement via an interface with a PLC and the robot. If the measured seam topography or fault deviates from the specifications, the OCT immediately sends a signal to the PLC.

To ensure reliable seam tracking and evaluation of the weld quality, the optimum length of the OCT scan line across the seam in front of the arc was set at 10 - 15 mm, and the distance to the process from the seam tracking line was 7 - 10 mm. The line length behind the arc across the weld bead was 15 - 20 mm and the distance to the post-processing line was 15 mm. The tests were carried out with Fanuc or KUKA robots holding the arc torch. The standalone OCT system can also be used for offline detection of weld defects.

2.2. Tactile laser welding

During laser welding with an infrared laser, the OCT measuring beam is directed coaxially to the processing laser to assess the target area [Deyneka Dupriez and Truckenbrodt, 2016]. OCT scanner can be seamlessly integrated into the tactile laser processing head, enabling precise real-time post-process control [Deyneka Dupriez and Marben, 2025] and automatic adjustment of the filler wire position. OCT functionality has been successfully tested with the ALO4, ALO4basic, and ALO-L optics. The OCT scanner was mounted on the ALO4 head using a specially designed adapter (see Fig. 1(b)).

The ALO4 laser beam path includes two deflection mirrors. To ensure optimal OCT signal quality, the system uses a specially developed OCT mirror (IQFO mirror: Infrared laser / QA system / Front OCT) within the ALO4's deflection module. This OCT-specific mirror allows the OCT beam to transmit efficiently while maintaining signal quality regardless of the swiveling axis position. To maximize reflectivity of the OCT beam in the coupling mirror, a DFS mirror was used in conjunction with the OCT mirror in the non-swiveling deflection path. A DFS mirror exhibits very good p-polarization. As a result, constant values of around 70% in the wavelength range 810 nm to 880 nm are achieved for p- and s-polarization when reflecting the IQFO mirror at an angle of 45°.

OCT measurements are also compatible with double-focus modules. For precise orientation of the OCT scan line, the system receives the current rotation angle from the ALO4 via fieldbus communication. The OCT and ALO4 are operated through separate control units. This configuration enables both automatic wire misalignment compensation and the recording and analysis of seam topography during processing. The OCT scanner performs two sequential scans across the joint, deflecting the measurement beam 2 mm before and 10 mm after the Tool Center Point (TCP).

The application areas include laser welding and laser brazing of both steel and aluminum alloys for welding Y-seams at flanged joints, which are common in structural and automotive components. Fillet welds on lap joints and T-joints can also be joined efficiently and with high quality.

In this laser welding setup, the material used was AW6082 aluminum alloy with a sheet thickness of 3 mm. The overlap joints were welded using a laser power of 5 kW at a welding speed of 3 m/min. The beam was applied with a trailing angle of 5° and a scanning angle (SA) of 30°, with a focus offset of –6 mm. To ensure proper shielding, argon was supplied at a direct flow rate of 10 l/min. A filler wire made of AlSi12 (ER 4047) with a diameter of 1.6 mm was used, fed at a rate of 3.5 m/min.

For laser brazing, sheets of DC04 steel with a thickness of 0.8 mm were used. The brazing was performed on a flanging joint configured in a roof geometry. The laser beam was applied with a trailing angle of 5°, while the scanning angle (SA) was set to 0°. Laser power ranged from 2.3 to 3 kW, a variable focus offset was used, and the brazing speed was maintained at 3 m/min. The filler wire, made of CuSi3 with a diameter of 1.6 mm, was fed at a rate between 2.8 and 3.4 m/min, depending on the process requirements.

Beyond just tracking, OCT feeds live data back to the robot and laser system, enabling adaptive control of parameters like laser power, wire feed speed, and travel speed. If the gap changes, for example, the system can automatically adjust parameters to maintain consistent weld or braze quality.

3. Test results

3.1. Real-time quantitative joint evaluation and weld quality assessment using OCT during GMAW

OCT demonstrated its effectiveness in real-time seam tracking and quality assessment during robotic GMAW. Under the measurement conditions employed, a consistently high-quality OCT signal is achieved (Fig. 2).

The OCT system enables the measurement of the joint gap. For T-joints exhibiting a rollover (see Fig. 2(a)), the precision of gap measurement is influenced by both the gap dimension and the extent of the rollover, primarily because the entire rollover isn't fully accessible to the OCT system. The rollover limits the minimum detectable gap in T-joints to 0.6 mm; smaller gaps cause reflection-induced measurement inaccuracies. Measured gap accuracy for T-joints, including rollover, is better than 0.2 mm, with repeatability under 0.05 mm [Deyneka Dupriez and Adolph, 2024].

For lap joints (see Fig. 2(b)), the observable gap size is constrained by the OCT system's focus range of ±6 mm, meaning the combined thickness of the top sheet and the gap size must not exceed 6 mm. Notably, the OCT system precisely measures gaps up to 2.5 mm in lap joints with an accuracy of better than 0.1 mm, ensuring excellent repeatability in gap detection, quantified at less than 0.005 mm [Deyneka Dupriez and Adolph, 2024].

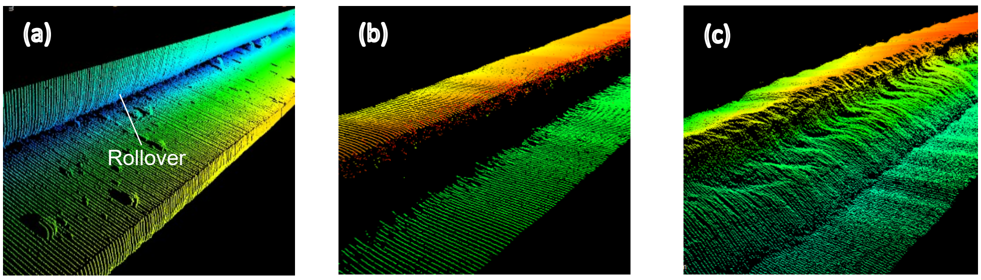


Fig. 2. Typical 3D OCT images taken during arc welding depict real-time seam tracking in pre-process of (a) the T-joint and (b) the lap joint; (c) shows online quality inspection in post-process over the lap joint.

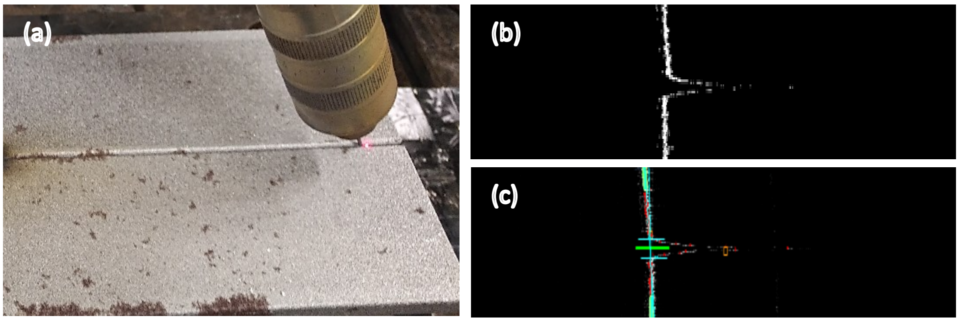


Fig. 3. (a) Photograph of the torch tip positioned at the butt joint; (b) typical OCT images of real-time seam tracking in pre-process during arc welding and (c) real-time evaluation of the OCT image: vertical green line represents the TCP.

The Fig. 3 illustrates seam tracking in the context of arc welding of the butt joint, using optical coherence tomography (OCT). Fig. 3(a) provides a photographic view of the setup, showing a torch tip precisely positioned over a butt joint. A small pink line, visible at the point of contact between the torch and the joint, is indicating the OCT beam trajectory across the joint. Fig. 3(b) presents a characteristic OCT image of the real-time seam tracking and features a prominent, horizontally stretched lines in its center, which represent the cross-section of the butt joint being visualized. Fig. 3(c) provides a real-time evaluation of an OCT image and contains analytical overlays: among others, a vertical green line denoting the Tool Center Point (TCP).

Integrated to robotic GMAW, OCT offers real-time weld seam verification, capable of identifying various visual weld defects. Should the analyzed seam characteristics fall outside the tolerance limits, the OCT system signals a defective weld or, if configured per customer specifications, triggers a process halt.

The OCT system automatically verifies weld length by detecting the seam's start and end points. This data, combined with robot-generated coordinates, allows for the precise calculation of the actual weld seam length. For circular welds, this

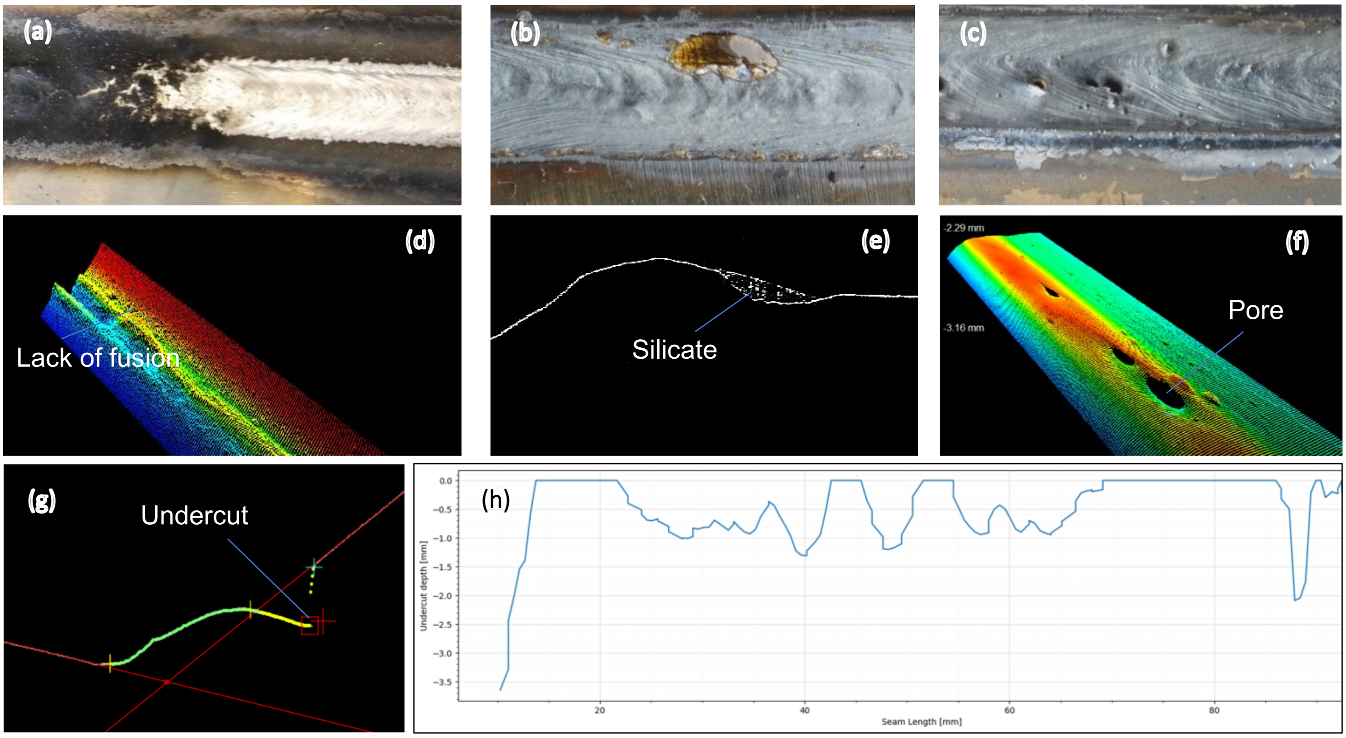


Fig. 4. (a-c) Photographs and (d-f) corresponding OCT images of the faults occurred during arc welding; (g) OCT image of undercut and (h) evaluated undercut depth along the entire seam.

process involves a series of short steps to sum the individual seam lengths. Furthermore, OCT measures critical weld seam geometries, including seam width, seam area, leg length, and throat [Deyneka Dupriez and Adolph, 2024], providing customers with precise numerical data. The system also analyzes the weld bead's profile, assessing convexity or concavity to ensure adherence to specified tolerances.

Silicates are a consequence of the deoxidation process during arc welding, where silicon (from the wire or base metal) reacts with oxygen and floats to the surface of the solidifying weld pool. Silicate can sometimes be recognized by a characteristic double line in the OCT results (see Fig. 6(e)), its reliable identification is dependent on factors like scan quality and silicate transparency. While surface cracks, porosity, and craters, indicating lack of fusion, are discernible and evaluable on the OCT image of the seam surface (Fig. 6).

Undercuts are identifiable as distinct notches on the sides of the weld bead in the OCT images (Fig. 6(g)). Fig. 6(g) displays a cross-sectional view of a weld topography, where a green line represents the weld bead and a yellow section signifies an undercut defect in the weld. Fig. 6(h) offers a quantitative analysis of undercut depth, measured with OCT, along the entire 90 mm weld seam. This graph clearly shows varying undercut severities through distinct dips, with a particularly sharp, deep undercut (approximately -2.0 mm) appearing near the seam's end.

Experimental evidence confirms that welding smoke does not diminish the quality of the OCT signal. While flying spatter is occasionally detected by OCT and appears in the resulting images, its presence has minimal impact on the accuracy of automated seam tracking and overall weld inspection.

3.2. Application of OCT for filler wire positioning and real-time weld inspection during tactile laser welding

OCT was used to precisely evaluate the filler wire position, thereby locating it within the TCP [Deyneka Dupriez and Marben, 2025] (see Fig. 5). A photograph in Fig. 5(a) shows a filler wire positioned at a lap joint. A schematically drawn cyan line indicates the trajectory of the OCT scan, showing precisely where the optical measurement is being taken relative to the welding components. Fig. 5(b) is the resulting unprocessed OCT image showing the shape of the wire and the lap joint. Fig. 5(c) depicts the OCT image with automatic evaluation: a yellow line fits the cross-section of the wire tip with the red crosshairs indicating its position; other red crosshairs show the TCP and the bright-blue crosshairs - the wire edges. Finally, Fig. 5(d) demonstrates the corrected wire position in the TCP, indicating a refined positioning step in the automated welding process.

OCT imaging is commonly used for the precise localization of weld joints. In tactile laser welding, OCT is essential for both real-time assessment of the filler wire position relative to the joint, ensuring accurate placement and for conducting online weld bead quality inspection.

Fig. 6 and 7 illustrate various weld characteristics and the capabilities of OCT imaging for their analysis [Deyneka Dupriez and Marben, 2025]. On the left side of the Fig. 6, a photograph of a lap joint is presented alongside its corresponding 3D OCT image. This OCT scan provides detailed topographical information, clearly depicting the joint and its internal gap. On the right side, Fig. 6(c) and (d) specifically highlight pores within a weld bead produced by tactile laser welding, showing how these defects appear in both photographic and OCT data. This underscores robust capability of OCT not only to visualize surface geometry but also to detect, display and evaluate internal features like pores and joint gaps, thereby providing valuable qualitative and quantitative information.

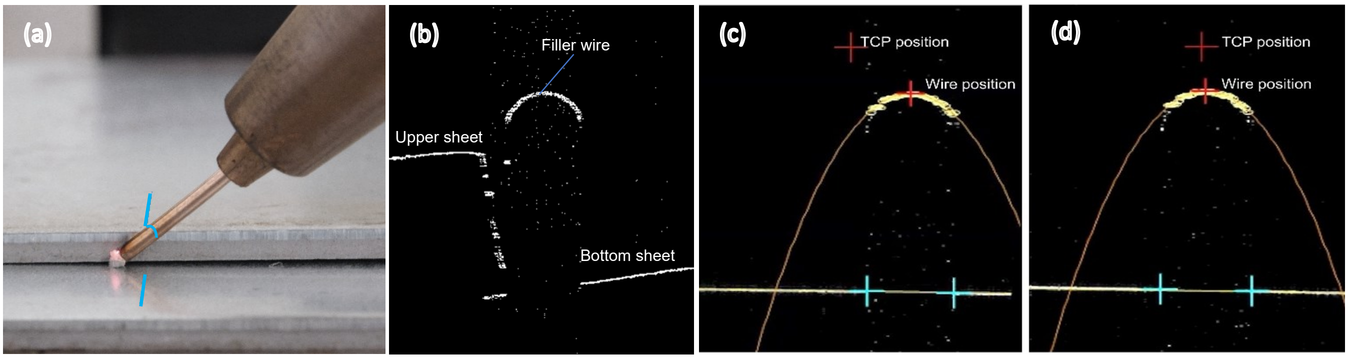


Fig. 5. (a) Photograph of the filler wire at the lap joint with the schematically drawn trajectory of the OCT line (cyan line); (b) corresponding OCT image; (c) OCT image with automated evaluation of the wire position; (d) corrected wire position relatively to the TCP.

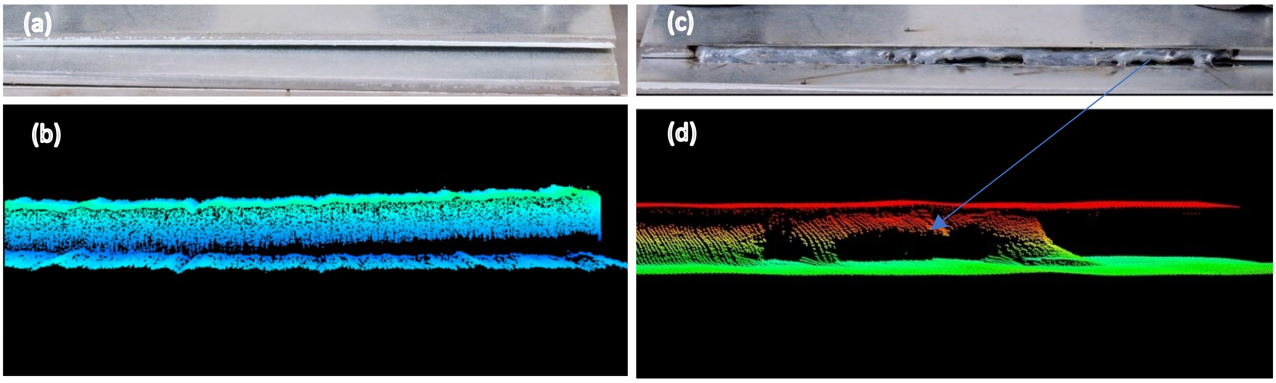


Fig. 6. (a), (c) Photographs and (b), (d) corresponding 3D OCT images of the (b) lap joint with the gap and (d) weld bead with the pores created via tactile laser welding.

Fig. 7 effectively demonstrates the power of OCT in visualizing of welds produced under various processing conditions during tactile laser welding, illustrating both good quality weld, and common welding faults. Qualitatively good weld is characterized by a smooth, well-formed bead (Fig. 7(a)). Fig. 7(b) and (c) depict issues related to bonding: (b) shows a lack of bonding to the bottom sheet, often resulting from the processing laser spot shifting towards the upper sheet or reduced laser power (down to 4 kW); while (c) reveals no bonding to the top sheet, typically due to the processing laser spot shifting towards the bottom sheet. Fig. 7(d) reveals an ununiformed weld bead, a consequence of increased welding wire speed (up to 6 m/min) or the absence of shielding gas, leading to inconsistent weld shape and height along its length. Fig. 7(e) highlights a wide weld bead, attributed to increased laser power (up to 7 kW). Finally, Fig. 7(f) demonstrates under-cambering, which can result from decreased welding wire speed (to 1.5 m/min) or even the complete absence of wire, where the weld bead

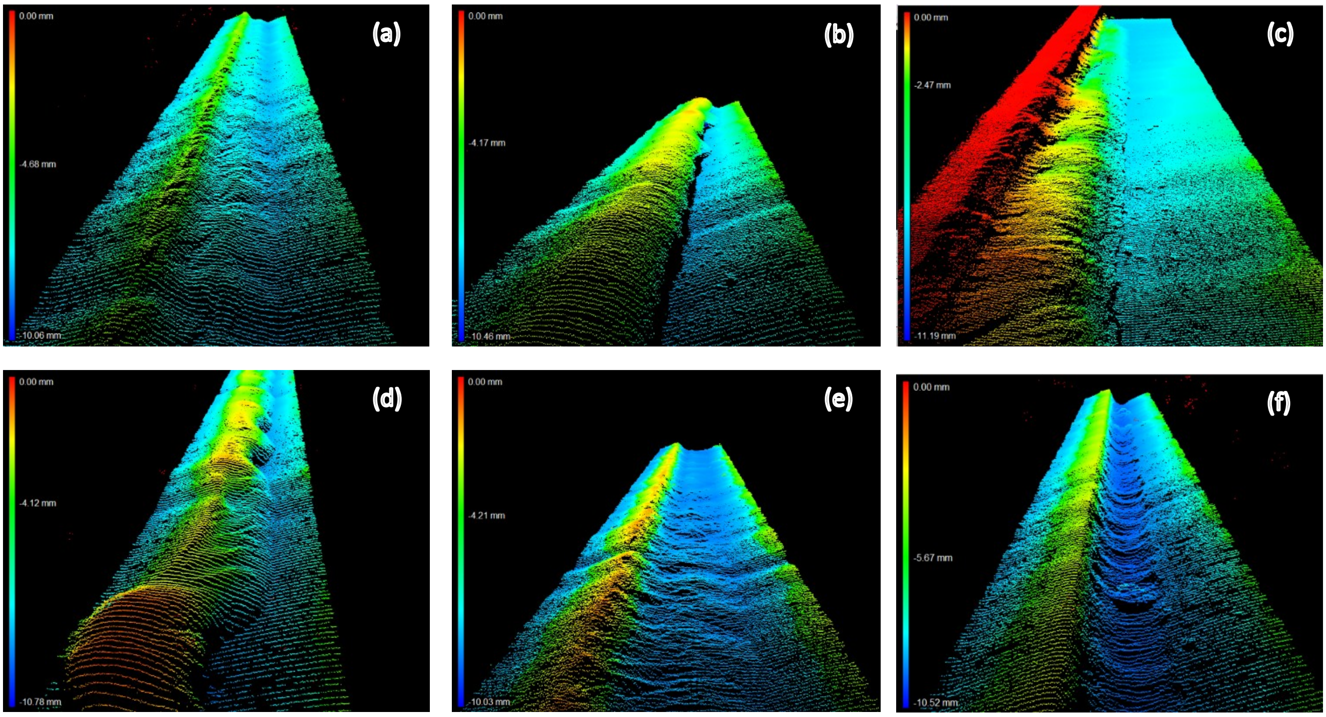


Fig. 7. 3D OCT images of the welds produced by tactile laser welding under different processing conditions, featuring (a) a good quality weld and common faults: (b) no bonding to the bottom sheet; (c) no bonding to the top sheet; (d) an ununiformed weld bead; (e) a wide weld bead; and (f) under-cambering.

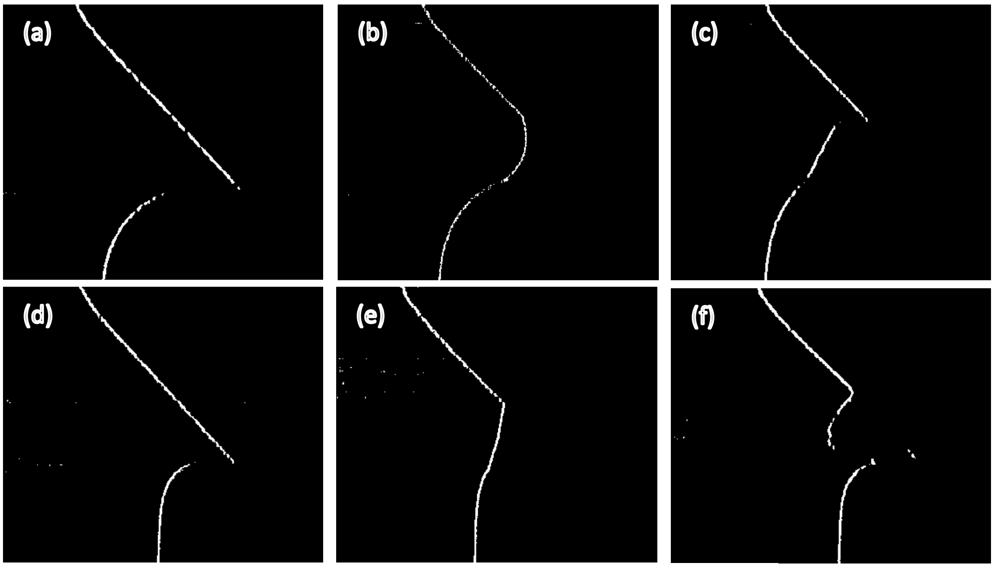


Fig. 8. 2D OCT images of (a), (d): the flanged joints (roof geometry), (b), (e): produced during laser brazing seams and (c), (f): faulty brazed seams showing no bonding to one of the sheet.

exhibits a concave or sunken profile. These images underscore the effectiveness of 3D OCT in visualizing subtle weld geometry details and identifying various defects, thus providing critical information for quality control in laser welding.

3.3. OCT for laser brazing

Laser-brazed seams are now a well-established standard in the automotive industry for joints requiring stringent quality, particularly in highly visible areas such as roof-to-side-panel connections or trunk lids [Grimm and Schmidt, 2009]. Laser brazing consistently produces optically flawless and robust seams, minimizing component distortion while maximizing efficiency. The success of this process hinges critically on precise laser beam focusing, as even minor deviations can cause brazing defects. To meet the requirements for flawless manufacturing, both high-accuracy system technology and subsequent seam control are essential. Current camera-based online monitoring systems permit real-time defect detection but often provide only qualitative information. OCT, however, enables an online quality control system that eliminates the need for expensive offline quality checks. Drawing conclusions regarding brazing quality additionally necessitates synchronous monitoring of crucial process parameters, including robot track speed, wire feeding rate, and laser power.

Scansonic's laser optics, particularly their ALO4, have a proven track record, notably in car body manufacturing. The ALO4 enables precise control over all process-relevant parameters for seam tracking, thereby ensuring an optimal brazing outcome. OCT, integrated into Scansonic's ALO4, can accurately detect the joint geometry in real-time during brazing, even for complex geometries or variations in the component. This enables the laser optics (e.g., Scansonic's ALO4) to continuously adjust laser beam position and focus, ensuring optimal joint alignment. OCT performs precise measurement of critical dimensions like gap width, overlap, etc. before brazing begins, allowing for correction or rejection of faulty parts before material is wasted. OCT can also evaluate various seam imperfections during the brazing process, such as lack of fill/underfill, excessive braze material/overfill, porosity, lack of bonding and surface irregularities like bumps, ripples, or other imperfections on the braze surface.

Fig. 8 illustrates application of OCT in visualizing various conditions of flanged joints (specifically, a 'roof geometry'), showcasing both successfully brazed seams and common faults produced during laser brazing. Fig. 8 (a) and (d) depict the initial flanged joint geometry. Fig. 8(b) shows an example of a successfully brazed seam with uniform filling, while Fig. 8(e) illustrates an underfilled braze. Fig. 8 (c) and (f) represent faulty brazed seams characterized by a lack of bonding to one of the sheets. In Fig. 8(c), the braze material connects to one sheet but fails to fully bond to the other, leaving a distinct gap. Similarly, Fig. 8(f) shows an irregular braze material profile disconnected from one of the sheet surfaces, confirming a lack of proper bonding. This effectively capability demonstrates of OCT to visualize critical details of joint and brazing quality, particularly the presence or absence of complete bonding and other brazing defects.

4. Conclusion

Optical Coherence Tomography (OCT) significantly streamlines semi- or fully automated laser welding, enabling efficient high-volume and high-speed production by eliminating the need for costly, time-consuming offline seam inspection. Integrated into robotic arc welders or tactile laser welding heads, the OCT system actively prevents weld defects and incomplete welds, thus reducing production stops and downtime. Advantages of tactile welding optics equipped with OCT include precise control of the filler wire position and optimal quality assurance. Furthermore, OCT supports laser wire brazing, offering a low-heat solution ideal for joining sensitive materials. The practical application of OCT for real-time seam tracking and weld or braze inspection is demonstrated.

Capability of OCT to provide high-resolution, real-time 3D data of both the joint and weld or braze, combined with its non-contact nature and inherent robustness, positions it as an exceptionally valuable tool for optimizing arc welding and tactile laser welding and brazing processes, ensuring consistent high quality, minimizing defects, and facilitating automated control.

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