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Productivity and Consistency of Remote Seam Tracking with OCT

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Abstract

High speed automated processing, flexibility and reduced flange width (leading to reduced vehicle mass) are the potential advantages for enhanced productivity realized by application of optical coherence tomography (OCT) for seam tracking and quality assurance in remote laser lap welding. The aim of this work is to evaluate the repeatability and reproducibility of the joint profile measurements obtained by OCT at various angles of incidence and high welding velocity. The tests were performed on Al and steel sheets typically used in automotive industry, particularly for car body welding. The orientation of the upper sheet, edge quality as well as the gap size were varied. Optimized joint detection algorithm was used. The OCT tests demonstrated reliable measurements at different angles of incidence with good repeatability and reproducibility. The outliers are discussed. The results show that OCT is a stable and reliable technique for remote seam tracking applications during industrial laser processing.

Keywords: optical coherence tomography; laser welding; automotive industry; remote; gap

1. Introduction

Environmental, governmental, and human demands stimulate the automotive industry to improve fuel economy. Traditional vehicle manufacturers are aiming to decrease the weight of vehicles through the use of new materials, especially lightweight aluminum alloys and thinner flanges. In order to meet these demands, laser welding is widely used for the construction of such advanced automotive body structures and is of particular interest because of its high speed, low heat input, and flexibility. It was reported by Luft et. al. (2015) that reduced process time, high welding velocity and reduced laser power by laser welding save 53% of time and lead to 24% lower CO2 emission.

Vehicle structures are composed of a variety of materials, including mild steel, high strength steel, and aluminum. Currently, the highly formable Aluminum 5000 (Al 5000) alloys are used mostly for inner panel applications, whilst the heat-treatable Aluminum 6000 (Al 6000) alloys are preferred for outer panel applications. Al 5000-series aluminum is alloyed with magnesium whereas Al 6000-series aluminum contains both silicon and magnesium. Galvanized steel, with its protective layer of zinc oxide on the surface, and anodized steel offer high strength, corrosion and wear resistance enhancing vehicle body life. Anodizing provides also better adhesion for paint primers and glues.

In order to get better throughput and improve cost per part or hour, the automotive industry demands cost reduction in different areas of production, including laser processing. Accelerating manufacturing requires new tracking capability to support high volume production. Therefore, the effort is put onto upgrading of the laser processing components by applying innovative laser scanning and monitoring technology. Among them is the OCT system. Coaxial measurement configuration and high processing rate of OCT considerably enhance the laser welding productivity and decrease defect rates.

2. **Experimental**

The tests were performed using remote and non-remote laser welding optics mounted on an ABB IRB 4600-60/2.05 robot. The robot end-effector had the capability of moving in 3D workspace.

The PFO 3D 450 mm scanner optics of Trumpf GmbH & Co. KG (Fig. 1(a)) with aspect ratio 1:3.26 was applied for angle variation tests at travel speed of 9 m/min. The materials used for this study were galvanized and anodized steel sheets (0.73 mm thick) as well as Al 5000 (2 mm thick) and Al 6000 (1.3 mm thick) sheets for automotive applications.

Seam tracking tests on automotive aluminum door panel and on zinc-coated automotive steel door panel were performed with remote welding optics at travel speed of 3 m/min. Aspect ratio 1:6 of the remote optics resulted in a 600 µm laser spot size on the workpiece. Steel door panel was also lap welded using 2 kW solid state laser and 100 µm optical fiber at welding speed of 3 m/min.

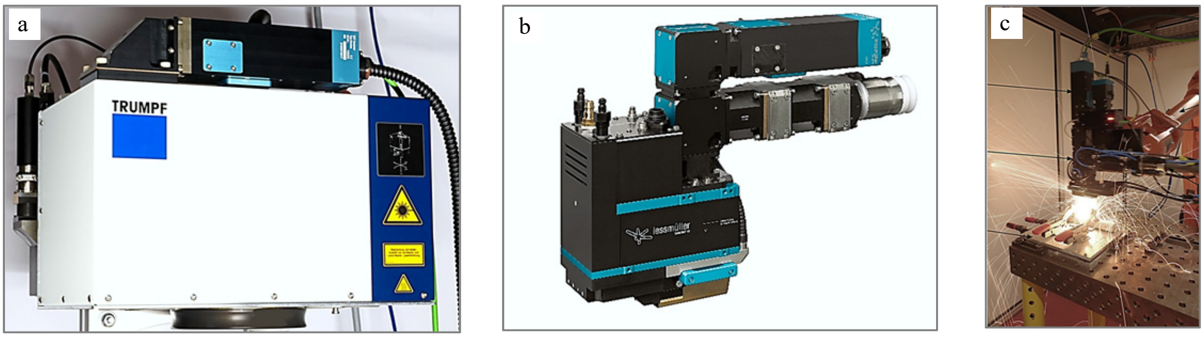

Fig. 1. (a) PFO 3D 450 mm scanner optics and (b) LSO welding optics equipped with OCT; (c) mounted on the robot end-effector LSO optics during active welding.

LSO welding optics of Lessmüller Lasertechnik GmbH (Fig. 1(b)) was applied for gap bridging tests with 3 m/min welding speed, 1.6 kW TRUMP TruDisk 4002 laser (λ = 1030 nm) of Trumpf GmbH & Co. KG, and 200 µm optical fiber. Aspect ratio 1:1 of the LSO optics was and laser beam was defocused to obtain 600 µm laser spot on the workpiece. DX56 steel sheets having lap joint gaps between 0.1 and 0.7 mm were welded. After welding, specimens with bridged gaps were cut from transverse sections of the welds and the cut surfaces were prepared for light microscopy inspection by polishing and etching to display bead shape and microstructure. The bead images were made using a Leica DM 2700M optical microscope.

All above-mentioned welding optics were equipped with OCT (Lessmüller Lasertechnik GmbH) for real-time seam tracking. The OCT system has an axial measurement range of 12 mm and an axial resolution of 12 µm. All OCT images represent the scans realized perpendicular to the welding direction, 1.5 mm in front of the welding point. The measurements were performed with acquisition rate of 70 kHz. The OCT sensor was equipped with SLED producing radiation with a wavelength of 840 nm. The angle of incidence, gap size between upper and bottom sheet as well as the distance to the clamping tools was varied. The developed and optimized by Lessmüller Lasertechnik speckle reduction algorithm and joint detection algorithm were used for remote edge detection at various conditions. This algorithm can also be used to determine the gap size (when the upper sheet thickness is known) and the angle of incidence.

3. Repeatability and reproducibility tests

Lap joints of galvanized and anodized steel, Al 5000 and Al 6000 were used for seam tracking tests with OCT at different angles of incidence varied between 0° and 50° and gaps varied between 0 mm and 0.5 mm. Figures 2, 3 show the joint profiles obtained by OCT at minimal and maximal angle of incidence and with minimal and maximal gap. Vertical cyan lines represent automatically detected joint position. The tracking results are not affected by the burr orientation, inside or outside the weld.

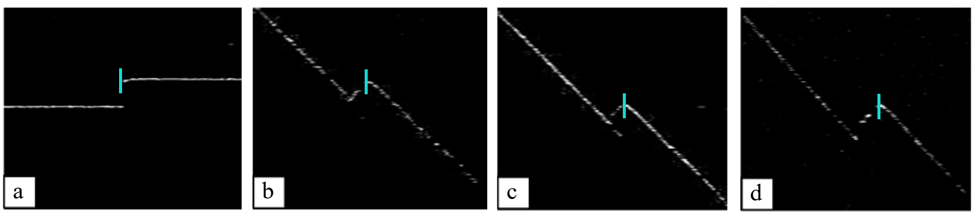

Fig. 2. OCT image of the fillet joint of steel sheets: (a) galvanized steel under 0° angle of incidence; (b) galvanized steel under 50° angle of incidence; (c) anodized steel under 50° angle of incidence; (d) galvanized steel with 0.5 mm gap under 50° angle of incidence. Automatically detected joint position is marked with a vertical cyan line.

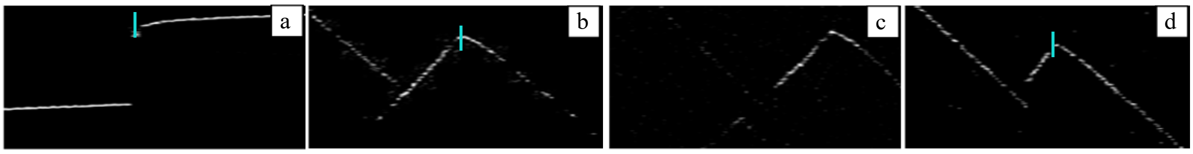

Fig. 3. OCT image of the fillet joint of aluminum sheets: (a) Al 5000 under 0° angle of incidence; (b) Al 5000 under 50° angle of incidence; (c) Al 5000 under 50° angle of incidence (failed joint recognition due to high surface reflectivity); (d) Al 6000 with 0.5 mm gap under 50° angle of incidence. Automatically detected joint position is marked with a vertical cyan line.

In Table 1, the test results are summarized. Testing of anodized and galvanized steel delivered satisfactory results at any angle of accidence.

Table 1. Seam tracking results on various workpieces.

Workpiece	Upper sheet thickness	Angle of incidence	Faults	Cause of the faults
Galvanized steel sheets	0.73 mm	0° – 50°	0%	
Anodized steel sheets	0.73 mm	0° – 50°	0%	
Al 5000 sheets	2 mm	0° – 35°	0%	
Al 5000 sheets	2 mm	35° - 50°	1,7%	High surface reflectivity
Al 6000 sheets	2 mm	0° – 50°	0%	
Aluminum automotive door panel	0.8 mm	15%	0%	
Steel automotive door panel, welding tests	0.8 mm	15%	0.6%	Weld smoke

It appeared that due to the high reflectivity of the smooth Al 5000 surface automated joint detection may become difficult at angles of incidence higher that 35°. The poor coupling of the light energy, due in part to the high density of free electrons in the solid, makes aluminum one of the best reflectors of light. Week diffuse reflection of the OCT measured light cause low intensity OCT signals resulting in degraded quality of the OCT images (Fig. 3(c)) that disables automated joint recognition. However, several other factors such as the surface roughness and the alloying elements in the metal also affect the reflection. Therefore, as shown in Fig. 3 and in Table 1, the OCT images obtained from the magnesium-silicon alloyed Al 6000 sheets are superior to those from magnesium alloyed Al 5000 sheets due to the lower reflectivity of Al 6000 alloy.

In order to test the OCT tracking ability on the non-linear seam, the notch was mechanically produced on the upper Al 5000 and galvanized steel sheets (Fig. 4 (a), (c)). Fig. 4 (b), (d) represent the tracking paths detected by OCT. The divergence from the predetermined linear path is perfectly reconstructed by OCT.

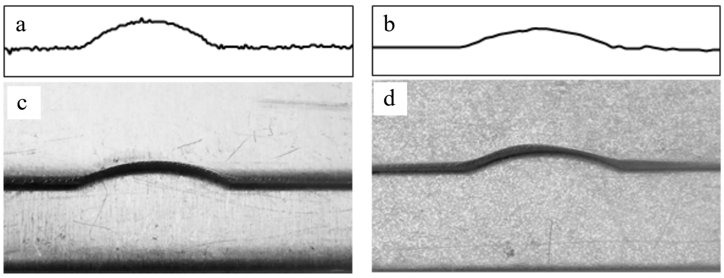

Fig 4. Tracking paths obtained from the OCT scans combined along the seam with the 10 mm wide and mm deep notch with corresponding joint photographs: (a), (c) on Al 5000; (b), (d) on galvanized steel.

It was also found that stable and reliable joint position detection of the fillet joint at 0° angle of incidence is possible when upper or bottom sheet flanges (or distance to clams or fastening elements) are not smaller than 0.3 mm. This limit slightly increases at higher angles of incidence to 0.4-0.5 mm at 50°.

4. Welding tests

4.1. Welding of automotive door panel

The consistency of the Lesmüller Lasertechnik real-time seam tracking OCT system was furthermore confirmed by welding tests on a steel automotive door panel. Fig. 6a shows a set of 32 fillet welds performed under 15° angle of incidence under remote configuration using the OCT seam tracking facility. Detailed description of the test results can be found elsewhere (Deyneka Dupriez (2018)).

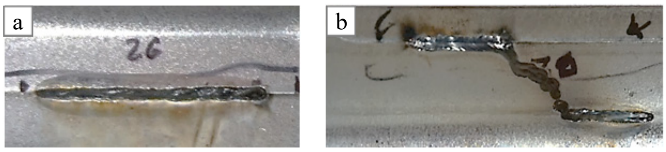

Fig 5. Fillet welds on steel car door: (a) Good quality weld; (b) failed weld due to the weld smoke accumulated at the middle of the welding process.

Most of the welds were of a good quality (see Fig. 5(a)). Only two welds failed (see Fig. 5(b)), most likely because of weld smoke containing metal fume. Molten metal particles disturb the OCT measurement and consequently welding process. This can be improved by increasing the distance between the OCT pre-process scan (Deyneka Dupriez et. al. (2016)) and welding point. Here that distance was kept 1.5 mm, the upper sheet thickness was 0.8 mm, gap varied between 0 mm and 0.3 mm. Processing laser beam hit the workpiece directly at the detected joint position without a lateral offset.

4.2. Bridging of joint gaps

Lens Shifting Optics (LSO) of Lessmüller Lasertechnik ensured precise laser welding by adjusting automatically welding position (lateral and axial) in combination with the smart tracking and monitoring system like OCT. LSO with OCT was successfully applied for automated gap bridging using the defined combination of laser power, focus position as well as lateral laser position. A LSO unit welded of 0.65 mm thick zinc-coated automotive steel under 20° angle of incidence with various gap sizes up to 0.8 mm.

Zander (2016) has proven the Albert's et. al. (2013) statement that any lateral offset is necessary by welding the steel sheets with the gaps of 0.1 – 0.2 mm. The gap bridging can be realized by accurate real-time automated control of lateral and vertical laser beam position directly at the detected joint. Zander (2016) also showed that in case of the gaps larger than 0.2 mm up to 0.8 mm the processing laser has to be shifted (offset) from the joint to the upper sheet to ensure joining as more material is required to fill the larger gaps. For the 0.3-0.6 mm large gaps the offsets of 0.5-0.7 x gap size provided satisfactory results (see Fig. 6). However, the offset limit of ca. 0.5 mm should not be exceeded.

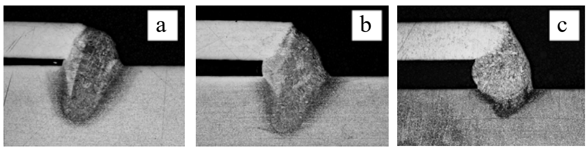

Fig 6. Cross sectional images of bridged gaps on DX56 steel: (a) 0.1 mm gap, 0 mm welding offset; (b) 0.3 mm gap, welding offset 0.5 x gap size; (c) 0.5 mm gap, welding offset 0.7 x gap size.

Therefore, LSO-OCT system enables gap bridging without additional material or time- and cost-unfavorable laser beam oscillation (Fixemer (2015)) that permits welding under remote condition with enhanced welding speed, without use of the complicated oscillating optics.

5. Conclusion

Fast and accurate seam tracking with OCT ensures premium quality welds regardless of the joint orientation and the gap size, measured by OCT in real-time. Being seamless adapted to any welding optics (remote or non-remote) OCT offers consistent automated welding of fillet welds complying with industrial quality requirements. The obvious benefit for the automobile industry is enhanced component reproducibility in a mass production that drives costs down and increases the throughput.

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