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Assessment of laser weld bead quality via acoustic emission and optical coherence tomography

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Abstract. Laser welding processes are inherently dynamic, and precise monitoring can validate process stability and product quality especially when laser parameters are not optimized, potentially resulting in quality variations within a single pass. In this study, an optical microphone is employed to monitor airborne acoustic emissions (AE) generated during a bead-on-plate laser welding process on E36 grade structural steels, while optical coherence tomography (OCT) is used to measure the keyhole depth. The optical microphone measures broadband and airborne acoustic data, recording transient events within the process, such as keyhole dynamics and metal vaporisation from the melt pool. With this multi-sensor monitoring approach, the correlation between process parameters, keyhole depth and weld profile is investigated. The results have shown a positive relationship between laser power changes in both acoustic emission characteristics and keyhole depth. By comparing these datasets, we identify distinct acoustic signatures corresponding to welding modes and penetration completeness. These findings demonstrate the methodology for integration of airborne acoustic emission signature with OCT for real-time diagnostics of laser welding processes. This multi-sensor approach, when integrated into a control loop, has the potential to enhance quality assurance for various manufacturing applications.

1. Introduction

The pursuit of enhanced in-process monitoring has become a key topic in laser welding for high-strength steels [1]. Comprehensive measurement and evaluation of diverse signals are essential for understanding welding process dynamics and identifying potential defects [2]. Employing multiple sensors enables real-time monitoring and control [3], and the main sensors employed for these purposes have been acoustic emission (AE) [4], optical coherence tomography (OCT) [5] and weld images [6].

To accurately capture airborne AE, the sensor employs an optical cavity formed by two miniaturized mirrors through which light is transmitted [7]. Changes in air pressure alter the cavity's refractive index, modulating the transmitted light's wavelength. These optical variations are subsequently converted into a digital signal with a high acquisition rate, providing detailed information about the airborne AE. The acquired airborne AE signal is initially represented in the time domain, describing the temporal variations [8]. To analyse the frequency components, Short-



time Fourier transform (STFT) is used [9], and numerical techniques like moving average are used to indicate the trend of acoustic emission at a certain frequency range within the process.

Complementary, OCT is an interferometric technique that measures optical path length differences based on interference fringe patterns [5]. A key advantage of OCT is its high acquisition rate, enabling rapid subsurface imaging. However, the accuracy of OCT measurements can be compromised by process emissions such as fumes, spatter, and dust, which can interfere with the reflected light [10]. Overestimation of depth can also occur when multiple reflection takes place at the bottom of the capillary [7]. Other possible drawbacks can be the incorrect lagging distance that does not encompass the keyhole area at different laser powers, and the low signal-to-noise ratio can lead to reduced measurement density of the keyhole depth.

The primary objective of this study is to develop and validate an in-process multi-sensor monitoring methodology that can establish correlations between process parameters and weld quality with airborne AE signals and keyhole depth measurements and to identify the acoustic signature of penetration completeness. Its high acquisition rate and sensitivity makes it possible to draw a detailed assessment of the acoustic signatures generated during laser welding [11].

2. Experimental setup

Laser welding experiments were performed on bead-on-plate configurations using NV E36 structural steel from SSAB, which were cut with fibre laser into workpieces with dimensions of 400 x 50 x 4 mm. It consisted of 0.055% C, 0.20% Si, 1.35% Mn, 0.009% P, 0.002% S, 0.030% Al, 0.025% Nb, 0.008% V, 0.016% Ti, 0.012% Cu, 0.05% Cr, 0.04% Ni, 0.005% Mo, with Fe as the balance. The laser source was an IPG YLS-10000 operating at a wavelength of 1070 nm, with a beam radius of 0.396 mm at the focal plane. A constant welding speed of 3 m/min was maintained, while the laser power was systematically varied from 1.0 kW to 6.0 kW in 500 W increments with steady shielding gas, argon, shown in figure 1(a). An ABB 6-axis articulated general purpose Robot IRB 4600 was used to handle the movement of the laser and sensors. Acoustic emission signals were acquired with Xarion Eta250 Ultra optical microphone positioned 140 mm from the process zone, operating at a 2 MHz sampling rate. Data acquisition and processing were performed via a QASS Optimizer4D industrial computer equipped with a preamplifier. Monitoring of keyhole depth was achieved using IPG LDD-700 with a tracking algorithm above the signal intensity threshold 18 dB. Both sensors were activated 200 milliseconds prior to laser initiation and deactivated 300 milliseconds afterwards to establish a temporal buffer for noise mitigation. To evaluate the AE signature of the process, frequency-domain analysis was conducted using fast Fourier transform (FFT) with a 2048-sample window, yielding a frequency resolution of 0.98 kHz.

Post-process inspection was measured using a focus variation microscopy (FVM) system, Bruker Alicona InfiniteFocus, equipped with a 1900 WD30 objective [12]. The vertical scanning

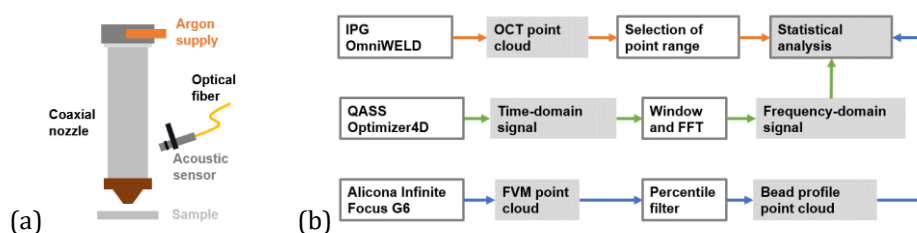


Figure 1. Schematic of acoustic sensor installation (a). The data processing workflow of two in-process monitoring sensors and one post-process inspection (b).

microscope stitched the point cloud to generate a composite image of 200 mm × 38 mm [13]. All the data were processed with an in-house developed MATLAB algorithm [10] to analyse the acoustic signal and the keyhole data, and the steps are outlined in figure 1(b).

FVM enables quantitative characterization of surface topography, facilitating assessment of weld bead quality and determination of penetration completeness when both sides are examined. To conclude the study, the cross section of the bead is ground, polished and etched to disclose the geometry of the fusion zone and heat-affected zone (HAZ) as a validation of the analysis. Statistical analysis techniques are employed to interpret these signals, aiming to provide quantitative insights into the stability and consistency of the laser welding process [14].

3. Results and discussion

Using the proposed method, the acoustic emission data in the frequency domain can be plotted in figure 2(a) to exhibit the signature across the acoustic frequency 1 to 100 kHz. To distinguish the laser power level based on the signature, two acoustic frequencies were selected, 9.77 kHz, and 42.97 kHz, marked by two dashed boxes. Other candidates of the frequency range are 2.93, 19.53 and 26.36 kHz, and the figures are plotted in the supplementary materials.

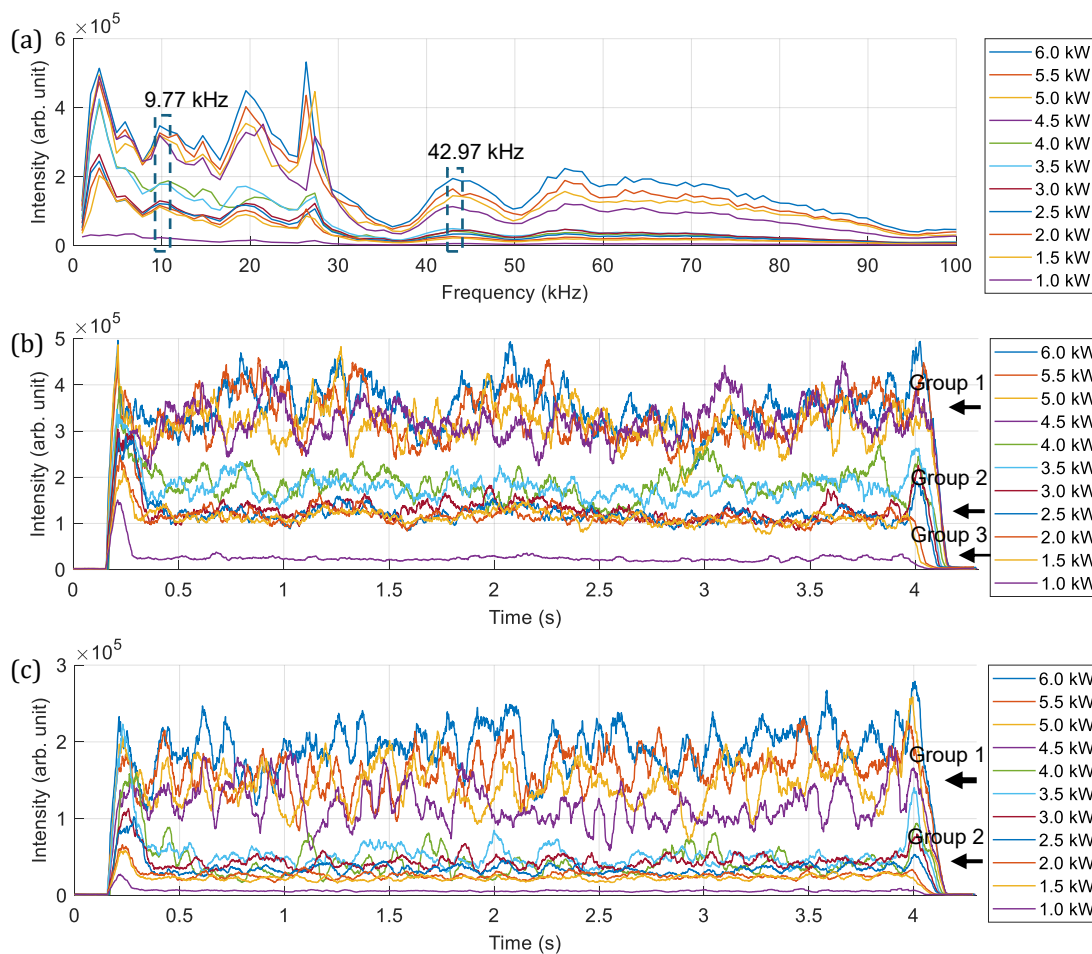


Figure 2. Acoustic emission of the laser welding process, the average intensity in the frequency range 1 kHz to 100 kHz (a). The selected frequency within the process of (b) 9.77 kHz, and (c) 42.97 kHz to reveal the tendency between laser powers from 1.0 kW to 6.0 kW.

In the first selected frequency of 9.77 kHz, shown in figure 2(b), there are three groups of the intensity: from 6.0 to 4.5 kW, 4.0 to 1.5 kW and 1 kW. The leading group is above the threshold of the complete penetration on 4 mm E36 steels, and it can be considered an indicator for assessing the penetration level, which is crucial for evaluating weld quality. The lowest intensity of acoustic emission corresponds to the lowest laser power, which only causes the conduction mode, while the middle group can achieve keyhole welding [15], but it cannot reach the complete penetration. For the second selected frequency of 42.97 kHz in figure 2(c), only two groups are qualitatively identified with the boundary between 4.0 and 4.5 kW, which are beneficial to use as a threshold to distinguish the complete penetration. Concurrently, the acoustic emission variations appear to follow a regular pattern, which could be further investigated with a larger dataset.

For keyhole monitoring with OCT, it is found that there is a 0.4 mm horizontal offset of the keyhole centre trailing behind the laser spot centre during welding at 4.0 kW. This value is set as a constant for keyhole depth measurement with different laser powers. In figure 3, the keyhole depth from various laser power is evident that laser power 1.0 kW only enters the conduction mode, while 1.5 kW to 4.0 kW achieves keyhole welding but the penetration is incomplete. Over 4.5 kW, complete penetration on 4 mm thick steel plates is made, but the point cloud density is significantly reduced compared to lower laser power conditions.

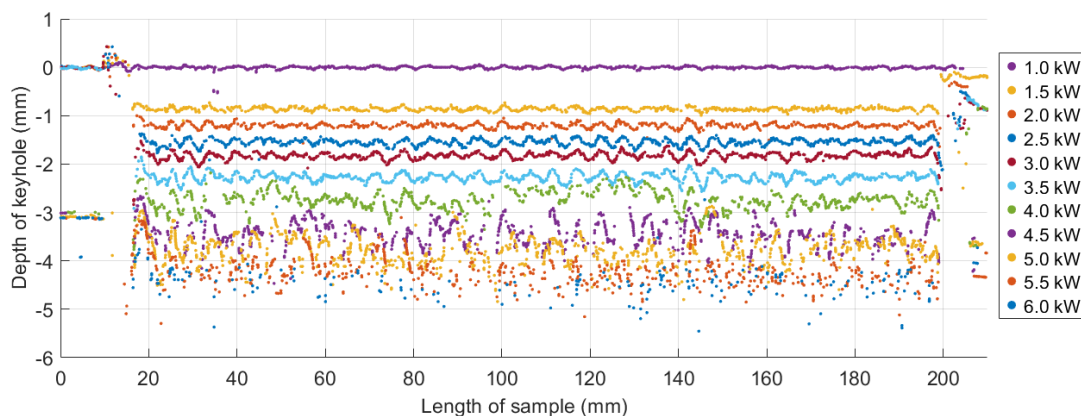


Figure 3. Keyhole depth and its fluctuation throughout the bead-on-plate welding process.

Two possible hypotheses could be formulated: 1) the opening of the keyhole bottom causes the passing through of the probe beam, and 2) the centre of keyhole changes from different laser power but the monitoring parameters are not adjusted correspondingly. Another observation of the keyhole depth regards the fluctuation cycle, which is the same throughout the process regardless of the power, and can be further investigated to understand the keyhole dynamics. Although the relative distance between the laser head and the workpiece could be considered a potential source of fluctuation, it was ruled out because keyhole depth measurement accounted for the workpiece height, monitored in the vicinity of the process zone during the entire pass.

FVM surface inspection is conducted to validate the quality of the weld bead, presented in figure 4. Incomplete penetration is observed stochastically, but the phenomenon is typically accompanied by excess weld metal formation on the front surface. Therefore, the inverse correlation between excessive penetration and excess weld metal is demonstrated, and it can serve as an indicator for penetration completeness within the laser power range. When the power is higher than 5.5 kW, the inverse correlation is not applied as complete penetration of the 4 mm

steels is fulfilled, shown in the supplementary materials. Based on the colour scale, it can be confirmed that both incomplete penetration and excessive penetration happen within a single pass of the laser welding process. These two sites are cut for metallurgical analysis. In figure 5 (a),

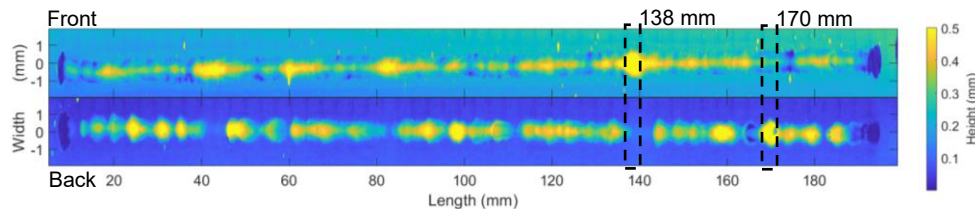


Figure 4. Surface geometry in the scale of micrometre of 5.0 kW laser power measured with focus variation microscopy on both sides of the bead.

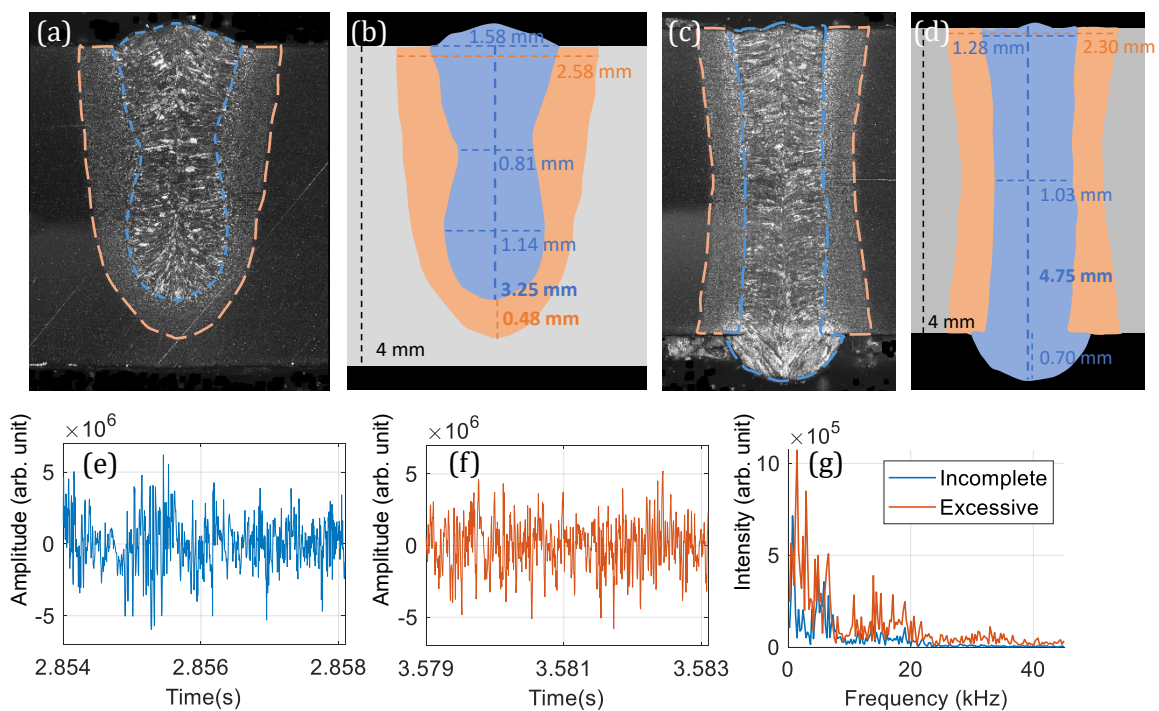


Figure 5. Cross section of (a) incomplete (c) excessive penetration weld bead from an optical microscope, and the measurement (b) (d) of fusion zone and heat-affected zone. Acoustic signal of incomplete (e) and excessive (f) penetration from two sites, and their frequency comparison (g).

the fusion zone is indicated by a blue dashed line, while the heat-affected zone is marked with an orange dashed line, and the penetration depth is merely 3.25 mm. Figure 5 (c) depicts the narrow fusion zone alongside penetration that extends to the depth of 4.75 mm, indicating excessive penetration. The timestamps from the two sites are obtained, in figure 5 (e) and (f), but the time-domain analysis yields minimal information. Consequently, FFT analysis is performed to examine the frequency components in figure 5(g), revealing a clear distinction: the acoustic signature associated with excessive penetration is more prominent.

4. Conclusion

This study demonstrates that the optical microphone is a viable alternative to optical coherence tomography for distinguishing laser welding modes and detecting penetration completeness

during laser welding of NV E36 steels, as the variations in keyhole dynamics and metal vaporisation cause acoustic emission signatures at specific frequencies. The validity of these findings is confirmed through focus variation microscopy inspection of both the weld surfaces and cross sections, which reveals microstructural changes in the fusion zone and heat-affected zone when the laser power condition is not optimized. Acoustic signatures of incomplete and excessive penetrations are presented, and the generic acoustic emission across laser powers are displayed. Future work will focus on synchronising multiple data modalities to enable a more comprehensive analysis of acoustic emission features, further enhancing the understanding and monitoring of weld quality.

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