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A Study on Defect Monitoring in Stainless Steel Laser Welding Processes Using a Multi-Sensor System

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Abstract

Laser welding has been widely used in various manufacturing industries due to its high energy density, low heat input, and excellent productivity. In battery systems for electric vehicles (EVs), cooling panels require reliable joining processes to ensure structural integrity and effective thermal management. Although aluminum alloys are commonly used for weight reduction, their relatively low melting temperature can compromise structural integrity under severe thermal conditions such as thermal runaway. Therefore, SUS304L are being considered as alternative materials to enhance safety and structural integrity.

In this study, a multi-sensor-based monitoring approach is proposed for defect detection during laser welding of SUS304L using an Adjustable Ring Mode (ARM) laser. A photodiode was used to detect infrared (IR) and ultraviolet (UV) optical signals during welding to analyze variations in plasma and melt pool behavior, while an infrared thermal camera was employed

to measure the temperature distribution in the weld zone. Various defect scenarios were introduced to investigate signal characteristics under different welding conditions. In addition, two thermal imaging approaches were compared: total area analysis for observing the overall thermal distribution along the weld bead and local area analysis for tracking the laser heat source and molten pool. The results showed that porosity was mainly associated with abnormal UV signal fluctuations, whereas undercut was more clearly reflected by irregular IR peaks. Non-penetration was characterized by increased IR signal variation together with changes in the local thermal response. Local area analysis provided a more stable thermal response around the laser interaction zone than total area analysis. Combining the IR, UV, and local thermal responses enabled the defect-related signal characteristics to be compared within a single monitoring framework.

Keywords: Laser welding, Adjustable Ring Mode (ARM) laser, Process monitoring, Multi-sensor, Thermal imaging

1. Introduction

With the increasing adoption of electric and hybrid vehicles, ensuring the safety, reliability, and thermal management performance of battery systems is recognized as a key technological challenge [1, 2]. The battery case and cooling panel are structural components that protect the battery cells from external impacts and effectively dissipate heat generated during the charging and discharging process. Therefore, the part requires sufficient mechanical strength, stable bonding quality, and high airtightness to prevent leakage. Aluminum alloys have been widely used in conventional battery cooling components for the purpose of weight reduction, but due to their relatively low melting point and thermal stability limitations, there is a possibility that their structural integrity may deteriorate under extreme conditions such as thermal runaway [2].

Accordingly, the applicability of austenitic stainless steel, particularly SUS304L, which has excellent heat resistance and mechanical properties, is being examined [3].

Laser welding is evaluated as an effective process for the precision joining of thin-wall structures, such as battery cooling panels, due to its low heat input, small thermal deformation, high productivity, and ease of automation [3, 4]. In addition, with the application of Adjustable Ring Mode (ARM) lasers capable of controlling the output distribution between the center and the ring, it has been reported that there is potential for improved molten pool stability, reduced spatter, and improved welding quality compared to conventional single-mode lasers [4]. However, due to high energy density and rapid thermal cycling, laser welding can result in defects such as keyhole instability, porosity, undercut, insufficient penetration, and over-penetration. Since these defects directly affect not only the mechanical reliability of the battery cooling panel but also its airtightness and leakage stability, monitoring technology capable of detecting defects in real time during the process and determining the quality status is required.

Laser welding process monitoring technology has evolved to evaluate welding conditions by utilizing optical, acoustic, thermal, and video signals generated during the process. You et al. summarized sensor-based monitoring technologies applicable to laser welding processes and reported that process condition analysis using optical and video signals is effective for real-time quality control [5]. Purtonen et al. systematically examined laser process monitoring and adaptive control technologies, emphasizing that sensor-based real-time monitoring will play a crucial role in the future development of smart manufacturing and closed-loop control systems [6]. Ancona et al. suggested the possibility of real-time process monitoring using plasma light emission signals in CO₂ laser welding [7], and Sibillano et al. reported that welding quality can be evaluated through plasma emission spectrum analysis [8]. Eriksson et al. analyzed the optical signals generated during laser welding using photodiodes and suggested that the signals have a close correlation with keyhole and molten pool behavior [9]. In addition, Park performed

welding quality monitoring in the aluminum alloy laser welding process through time and frequency domain analysis of photodiode-based plasma signals [10], and Lee et al. reported that the laser welding process status can be evaluated in real time using plasma plume signals [11]. These studies demonstrate that optical signal measurement using photodiodes is an effective method for detecting abnormal conditions and defects in the laser welding process.

Meanwhile, thermal imaging cameras can measure the temperature distribution and heat transfer behavior of the weld zone in a non-contact manner, making them effective for monitoring laser welding quality. Sreedhar et al. reported that it is possible to evaluate welding quality by measuring the temperature distribution generated during the welding process using an infrared thermal imaging camera [12]. Buongiorno et al. proposed a method for identifying laser welding defects based on infrared thermal imaging data [13]. In particular, since thermal imaging information can provide spatial heat distribution in the molten pool and heat-affected zone, unlike the temporal signal changes provided by photodiode signals, it is useful for complementing optical signal-based monitoring results.

Recently, research on multi-sensor-based monitoring that combines sensors providing different physical information has been conducted to overcome the limitations of single-sensor-based monitoring. Kong et al. emphasized the importance of sensor fusion technology in welding quality monitoring [14], and Wang et al. proposed a method to classify laser welding defects by combining optical and image signals [15]. Klaiber et al. proposed a laser welding quality evaluation method using multi-sensor data [16]. These prior studies suggest that utilizing optical, thermal, and image information simultaneously can improve the reliability of defect detection compared to single-sensor-based judgment.

Previous studies have mainly focused on single-sensor monitoring or the detection of individual defect types. Direct comparison of IR, UV, and thermal responses for different defects under the same ARM laser welding condition remains limited. In particular, the signal

responses associated with porosity, undercut, and insufficient penetration in SUS304L lap welding have not been systematically compared.

In this study, IR/UV photodiodes and an infrared thermal camera were applied to ARM laser welding of SUS304L. The measured signals were compared with X-ray images, surface bead appearance, and cross-sectional observations under normal, porosity, undercut, and insufficient-penetration conditions.

2. Experimental condition

The material used in this study is SUS304L, and its chemical composition is summarized in Table 1. For the fabrication of the battery pack case, the thickness of the SUS304L was selected to be 1.2 mm, and the penetration depth according to the laser welding parameters was verified through overlap welding.

Table 1. Chemical composition of SUS304L

	C	Si	Mn	Ni	Cr	N	S	P	Fe
SUS304L	0.03	0.75	2.00	8.00- 10.50	18.00- 19.50	0.10	0.015	0.045	Bal.

The laser head and welding equipment configuration used for laser welding is as shown in Figure 1, and the specifications of each piece of equipment are summarized in Table 2.

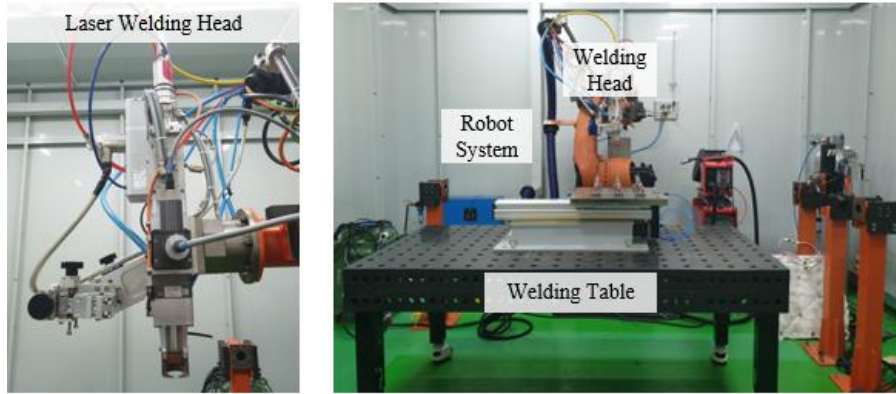


Figure 1. Laser welding system

Table 2. Specification of welding machine

No.	Item		Specification	Note
1	Laser generator	Optical cable LLK-D	Center : Max 2,000 W Ring : Max 4,000 W	COHERENT
2	Laser head	Laser welding head	BIMO (6 kW)	HIGHYAG
3	Robot	Robot system	KR60HA(60kg)	KUKA

In this study, an ARM laser was used as the laser heat source. As shown in Figure 2, the ARM laser is characterized by different outputs in the Center and Ring sections to produce a pre-heating effect, which can remove foreign substances from the surface, stabilize the temperature gradient to reduce surface spatter, and improve mechanical properties [17]. Furthermore, Table 3 summarizes the laser welding conditions using an ARM laser heat source. Each experiment of laser welding was repeated three times under the same conditions to check reproducibility.

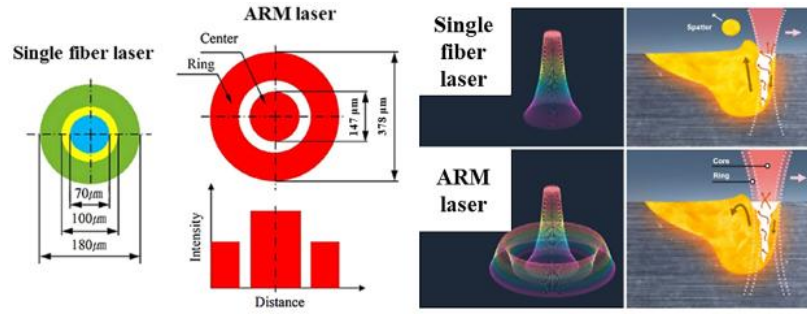


Figure 2. ARM laser welding properties [17]

Table 3. Test condition of laser welding (Repeating 3 times)

Laser Power (kW)		Travel speed (m/min)	Laser beam diameter (μm)	Focal length (mm)	Defocusing (mm)
Center	Ring				
1.5	1.5	8	378	250	0
2.0	2.0				

3. Multi-sensor system

The multi-sensor used in this study utilized a photodiode to measure IR and UV signals and a thermal imaging camera to measure the thermal intensity of the weld. IR and UV signal measuring photodiodes were installed next to the laser oscillator to detect light reflections generated during welding, and the system was configured with a thermal imaging camera installed at two locations—the total area position and the local area position—to compare measurement patterns according to location. In the total-area position, the thermal camera was set to capture the entire weld area. For the local-area position, the thermal camera was positioned to follow the welding heat source more closely. By comparing these two positions, we observed both the overall thermal behavior and the local thermal behavior around the laser heat source. Figure 3 roughly shows the configuration diagram of the multi-sensor monitoring system. In addition, Table 4 summarize the specification of sensors and infrared thermal

camera. In particular, the UV-sensitive photodiode signal was obtained using a band-pass filter in the 350–400 nm wavelength range, while the near-infrared signal was measured in the 800–1700 nm range.

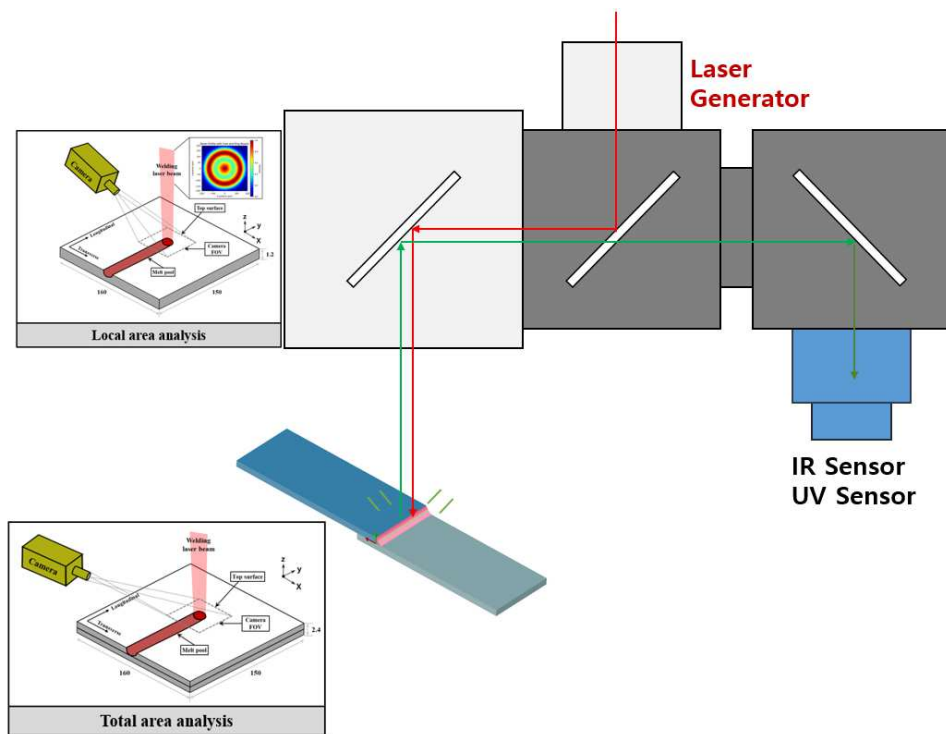


Figure 3. Schematic diagram of multi-sensor monitoring system

Table 4. Specification of sensors and infrared thermal camera

Photodiode Sensor		
Type	Visible Ray	Near Infrared Ray
Wavelength Range	350 – 400 nm (using UV band-pass filter)	800 – 1700 nm
Active Area	13 mm ²	3.1 mm ²
Sampling Frequency	Normal : 10kHz / Max : 100kHz	Normal : 10kHz / Max : 100kHz

Operating Temperature	-20 to 60 °C	-20 to 60 °C
Storage Temperature	-55 to 125 °C	-55 to 125 °C
Infrared Thermal Camera		
Resolution	320 x 256 pixels	
Frame rate	1k Hz	
Dimensions	46 * 46 * 53 mm	
Modes	IWR/ITR, CDS, ROI	

4. Results and Discussion

4.1 IR/UV Signal Characteristics and Weld Quality under Normal Welding Condition

Prior to analyzing defect-related sensor responses, the signal characteristics under the normal welding condition were examined to establish a reference for comparison. The 4 kW condition, which produced stable partial penetration into the lower sheet, was selected as the normal welding condition. Three repeated welding tests were performed under the same conditions to evaluate the reproducibility of the IR/UV signal response.

As shown in Figure 4, under normal welding conditions, the IR signal generally fell within the 2–3 V range, while the UV signal remained stable at around 1 V. In particular, no sharp peaks or abnormal signal drops associated with defect formation were observed in the intermediate sections of the weld. This indicates that the behavior of the molten pool and keyhole remained relatively stable under normal conditions.

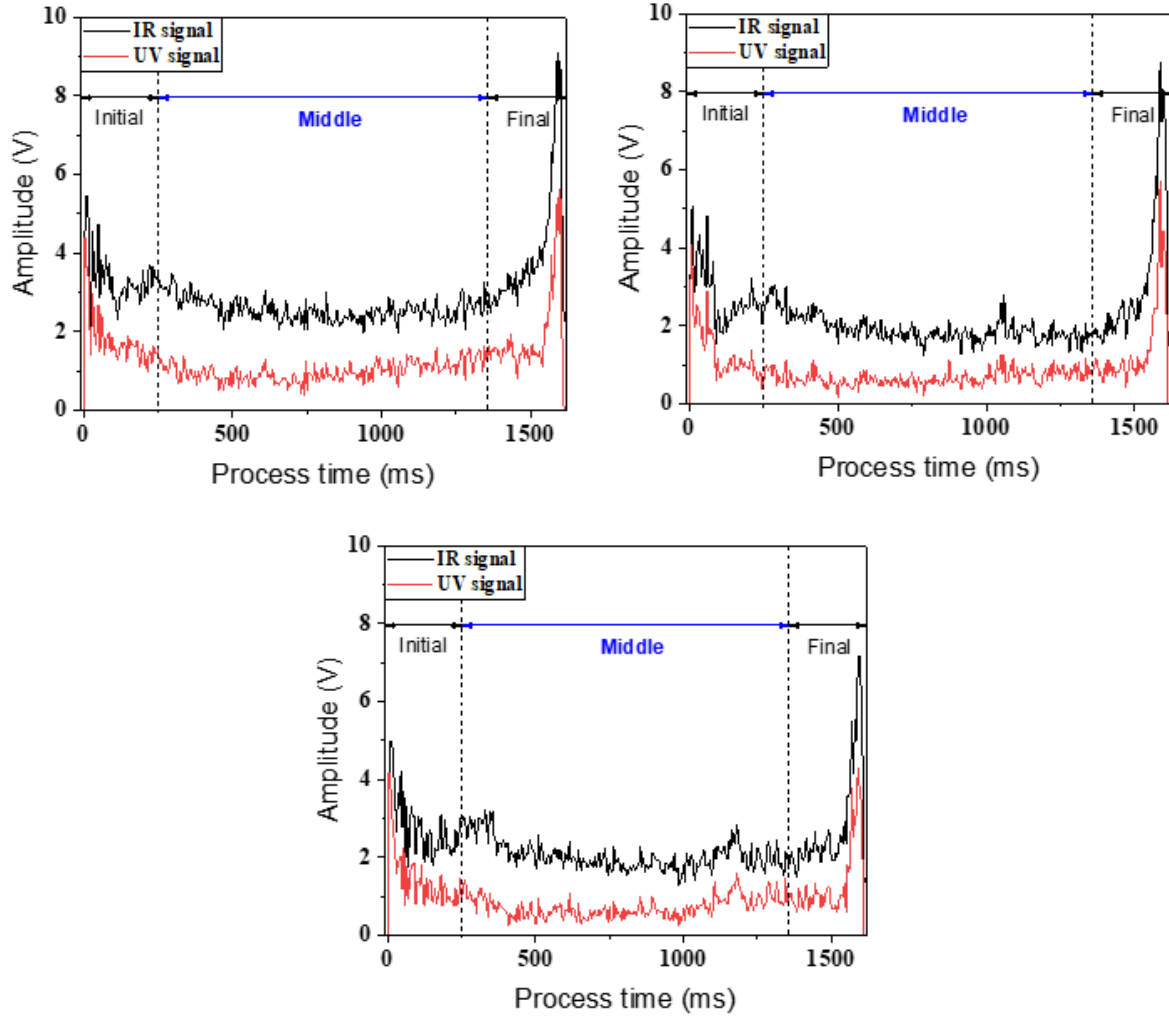


Figure 4. IR/UV signal characteristics under normal welding conditions

As shown in Figure 5 (a), no distinct porosity or internal defects were observed in the weld zone under normal conditions, and the surface bead exhibited a continuous profile without excessive penetration into the lower sheet. These results are consistent with the absence of abnormal peaks or rapid signal fluctuations in the IR/UV signals.

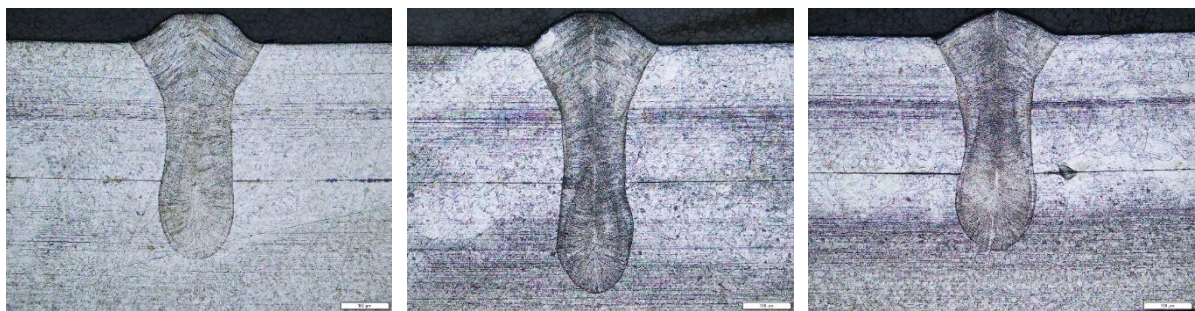
As shown in Figure 5 (b) and (c), cross-sectional analysis revealed that stable partial penetration toward the lower sheet was achieved under normal conditions, with no abrupt discontinuities or defect-like features observed in the penetration profile. This corresponds to the stable maintenance of IR/UV signals during the intermediate stage of the welding process.



(a) X-ray image



(b) Surface bead



(c) Cross-section

Figure 5. Weld quality under normal welding conditions: (a) X-ray image, (b) Surface bead, (c) Cross-section.

Therefore, as summarized in Table 5, the stable IR/UV signals, defect-free X-ray results, continuous surface beads, and stable partial-penetration cross-sections observed under normal welding conditions can serve as a baseline for identifying the abnormal signal variations that occur under conditions involving porosity and undercut.

Table 5. Detecting results of sensors by normal welding

Condition	IR signal	UV signal	X-ray image	Surface bead	Cross-section
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Normal welding	Stable (2-3 V)	Stable (1 V)	No noticeable internal defect	Continuous bead	Stable partial penetration
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4.2 IR/UV Signal Characteristics and Weld Quality under Abnormal Welding Condition

Based on the IR/UV signal characteristics observed under normal welding conditions, this section analyzes how photodiode signals change when porosity and undercut defects occur. Porosity and undercut are typical localized defects encountered during laser welding, closely associated with keyhole instability and weld pool shape instability, respectively. In this study, X-ray images and cross-sectional observations served as reference data to identify the presence and location of defects, which were then compared with the variations in IR/UV signals.

As indicated by the red arrows in Figure 6, conditions involving porosity defects resulted in UV signal patterns—specifically abnormal signal drops and irregular peaks—that differed from those observed under normal conditions. Notably, increased UV signal volatility was observed in regions where porosity was concentrated; this is attributed to instabilities in keyhole behavior and plasma emission during laser welding. Since UV signals are generally sensitive to changes in plasma and keyhole dynamics, these fluctuations may reflect transient keyhole instability or vapor-plume variation associated with porosity formation. Additionally, localized porosity was observed near the weld line in X-ray images as shown in Figure 7 (a).

In contrast, under undercut defect conditions, irregular peaks were observed in the IR signal—indicated by the blue arrows in Figure 6—distinguishing them from the stable IR signal patterns seen under normal conditions. Given the close relationship between the IR signal and the thermal behavior of the melt pool, these irregular fluctuations are attributed to phenomena such as unstable molten metal flow at the bead edges, localized heat concentration, or changes in the melt pool boundary geometry during undercut formation. Furthermore, cross-sectional analysis (Figure 7(b)) confirmed the presence of localized undercut features at the bead edges.

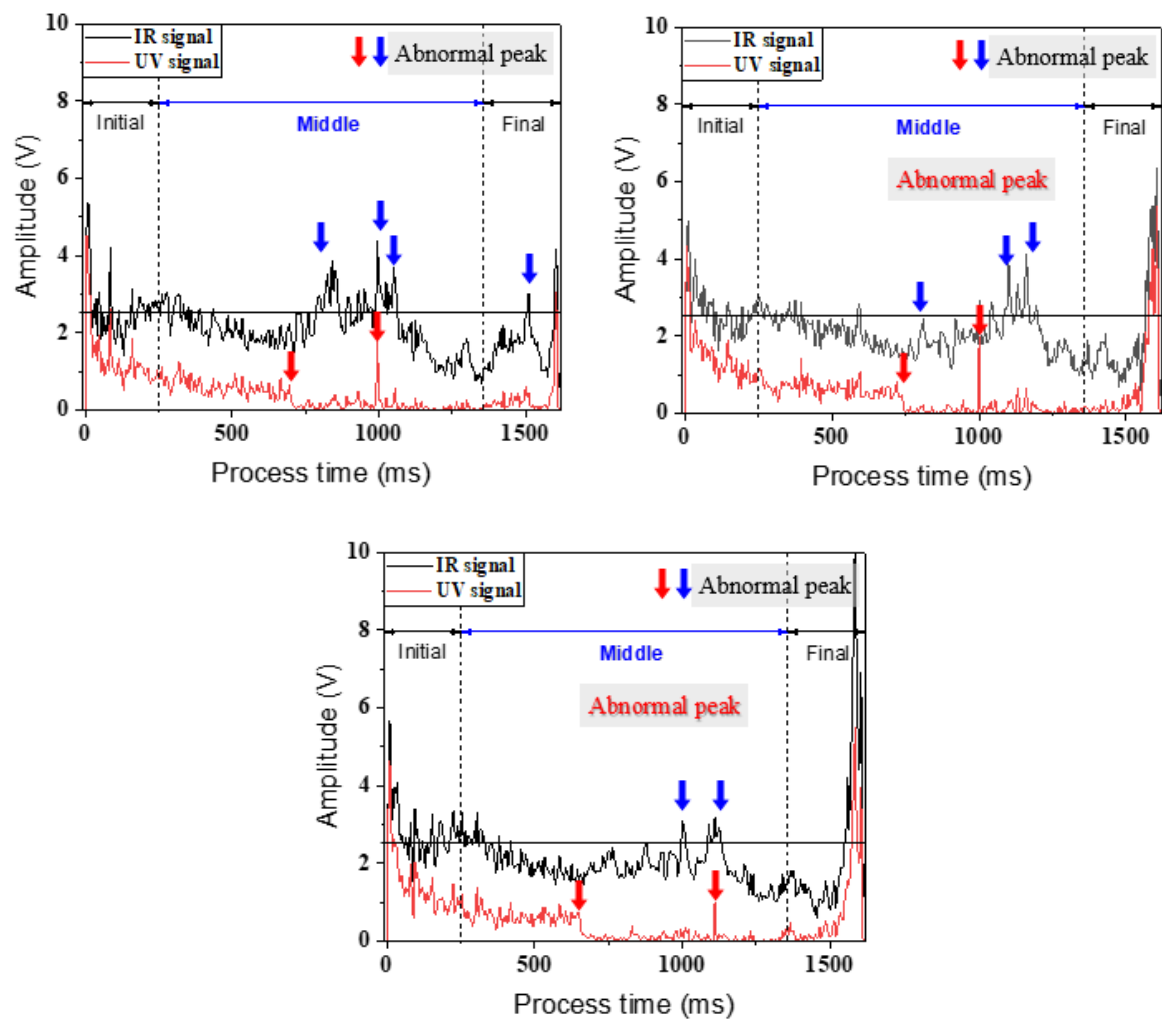
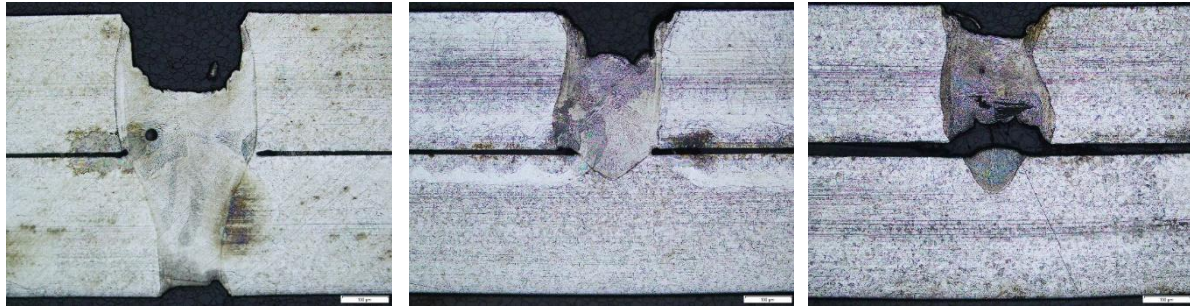


Figure 6. IR/UV signal characteristics under abnormal welding conditions.



(a) X-ray image



(b) Cross-section

Figure 7. Weld quality under abnormal welding conditions: (a) X-ray image, (b) Cross-section.

Porosity was mainly associated with abnormal decreases and irregular peaks in the UV signal, whereas undercut showed a clearer relationship with irregular IR peaks. The two signals therefore provided different information depending on the defect type. Table 6 summarizes the corresponding signal characteristics and weld observations.

Table 6. Detecting results of sensors by abnormal welding

Condition	IR signal	UV signal	X-ray image	Surface bead	Cross-section
Abnormal welding	Abnormal Peak	Abnormal Peak	Porosity	Non-continuous bead	Undercut

4.3 Thermal Imaging-Based Monitoring: Total Area Analysis and Local Area Seam Tracking

Photodiode signals provide time-dependent information during welding, whereas infrared thermal imaging shows the spatial distribution of the heat source and molten pool. In this study, two thermal imaging methods were used: total area analysis and local area analysis.

In total area analysis, the thermal camera observed a wide region including the entire weld bead. This method was useful for examining the thermal history along the welding direction and for comparing thermal changes with the surface bead and X-ray results.

In local area analysis, the camera followed the laser heat source and molten pool during welding. Because the measurement area remained close to the interaction zone, this method was more sensitive to local changes in heat-source behavior. It was therefore used to compare the thermal response between the non-penetration and stable partial-penetration conditions.

The two methods served different purposes. Total area analysis provided information on the overall thermal distribution, while local area analysis focused on the thermal response around the laser interaction zone. Their roles in defect monitoring are summarized in Table 7.

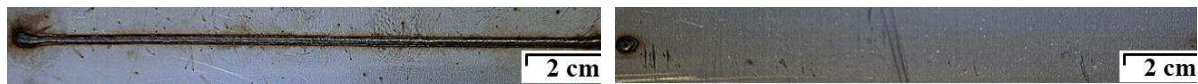
Table 7. Advantages and roles based on thermal camera analysis

Analysis method	Monitoring target	Main information	Advantage	Role in defect monitoring
Total area analysis	Entire weld bead/ Wide region	Spatial thermal distribution along the weld bead	Effective for observing overall bead thermal history	Comparison with X-ray image, surface bead, and defect location
Local area analysis	Laser heat source/ Molten pool region	Maximum thermal intensity and local heat source stability	Effective for tracking heat source behavior during welding	Identification of insufficient penetration and thermal instability

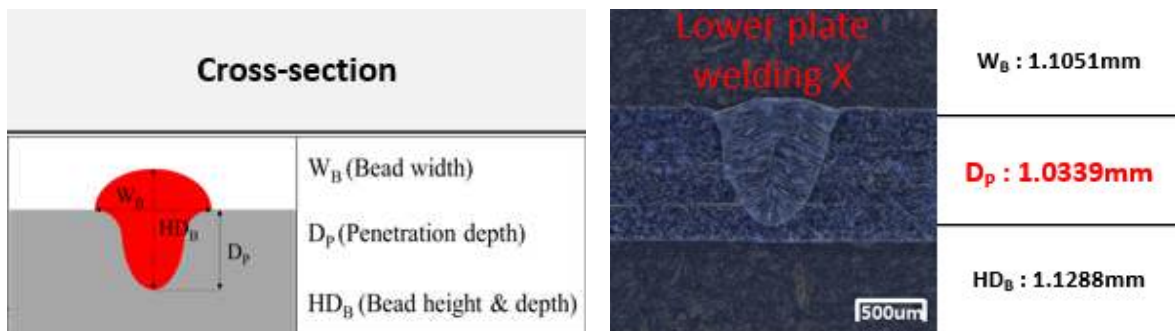
4.4 Multi-Sensor-Based Detection of Non-Penetration Defects

In this section, we analyzed the results of thermal imaging—based on total area analysis and local area analysis using IR/UV photodiode signals and an infrared thermal imaging camera—

regarding the non-penetration defect that occurred under the 3 kW condition. As previously mentioned, while the 4 kW condition resulted in normal welding or stable partial penetration, the 3 kW condition led to a non-penetration defect where the weld failed to sufficiently penetrate the lower sheet, as shown in Figure 8. This phenomenon is attributed to the fact that the keyhole and melt pool failed to grow stably down to the lower sheet due to the low laser power. Therefore, comparing the 3 kW and 4 kW conditions is effective for establishing a reference signal to identify lack-of-penetration defects.



(a) Surface bead

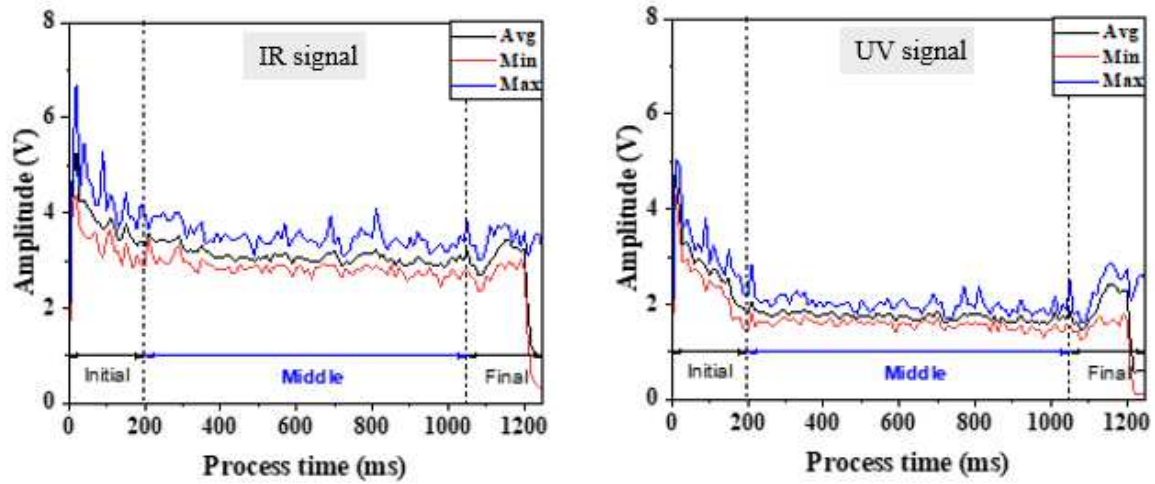


(b) Cross-section

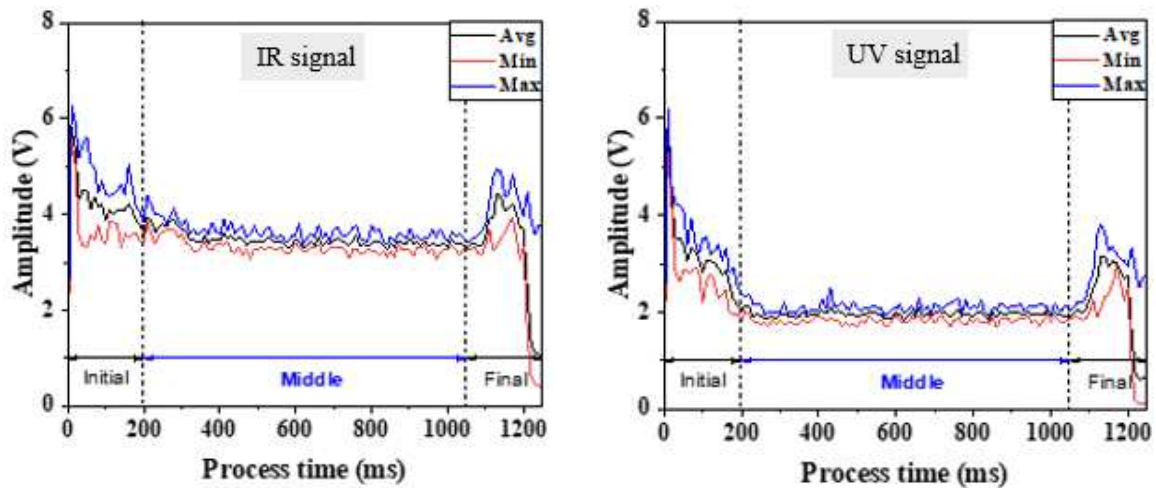
Figure 8. Weld bead morphology under the 3 kW non-penetration condition: (a) surface bead and (b) cross-section

Figure 9 presents the IR and UV signals in terms of their three-run average, maximum, and minimum values. The results revealed IR signal variations under the non-penetration condition that differed from those observed under normal conditions. Notably, at the 3 kW power level, the difference between the maximum and minimum IR signal values tended to increase, indicating that the thermal behavior of the molten pool differed from that of a stable penetration

state. Unlike the abrupt drops or irregular peaks associated with porosity defects, the UV signal provided relatively supplementary information for identifying non-penetration. Therefore, the fluctuation characteristics of the IR signal serve as a more critical indicator than the UV signal for detecting non-penetration conditions.



(a) Laser power: 3 kW



(b) Laser power: 4 kW

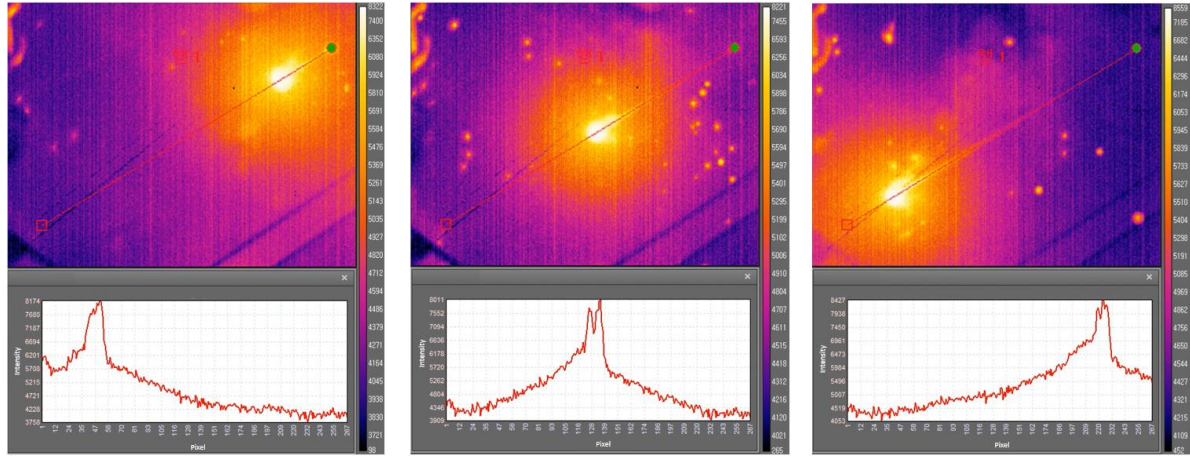
Figure 9. IR and UV signal responses under 3 kW and 4 kW welding conditions

As shown in Figure 10, total area analysis was used to examine the thermal distribution over a wide region including the entire weld bead. This approach is advantageous for examining the spatial and temporal thermal behavior along the welding direction, as thermal distributions around the weld pool have been reported to provide useful information for online weld quality monitoring [12]. Under the 3 kW condition, a clear thermal response was observed along the welding direction, although the cross-sectional result showed insufficient penetration into the lower sheet. The 4 kW condition produced a more concentrated thermal distribution around the welding zone and resulted in stable partial penetration.

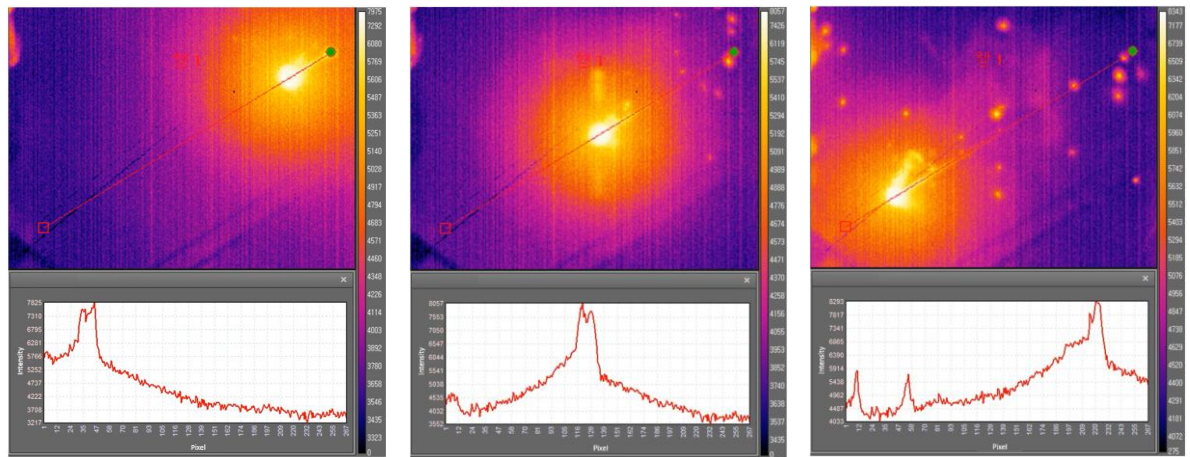
The apparent thermal intensity measured at 4 kW was not always higher than that measured at 3 kW. This difference can be explained by the heat-transfer behavior during welding. In laser welding, insufficient keyhole formation tends to promote heat transfer predominantly near the workpiece surface, whereas the formation of a stable keyhole enables laser energy to be transferred more effectively in the depth direction [3-4,18-19]. At 3 kW, insufficient penetration can increase the contribution of surface heat diffusion, whereas at 4 kW, a larger portion of the supplied energy is transferred toward the depth direction as penetration develops. Therefore, the thermal intensity obtained from total area analysis should not be interpreted directly as a measure of penetration depth.

In addition, several localized high-intensity spots were observed around the heat source, particularly during the progression of welding. These spots were associated with spatter and produced short-term peaks in the thermal signal. Previous studies have demonstrated that spatter formation during laser welding is closely related to dynamic molten-pool behavior and metal-vapor-induced melt ejection [21-22]. Spatter can also be detected through optical and near-infrared imaging because the ejected molten droplets produce distinct high-intensity features relative to the surrounding process zone [21]. For this reason, the maximum intensity measured in total area analysis can be affected by spatter as well as by the thermal state of the

molten pool. The spatial distribution of the thermal response should therefore be considered together with the intensity profile when evaluating weld behavior.



(a) Laser power: 3 kW



(b) Laser power: 4 kW

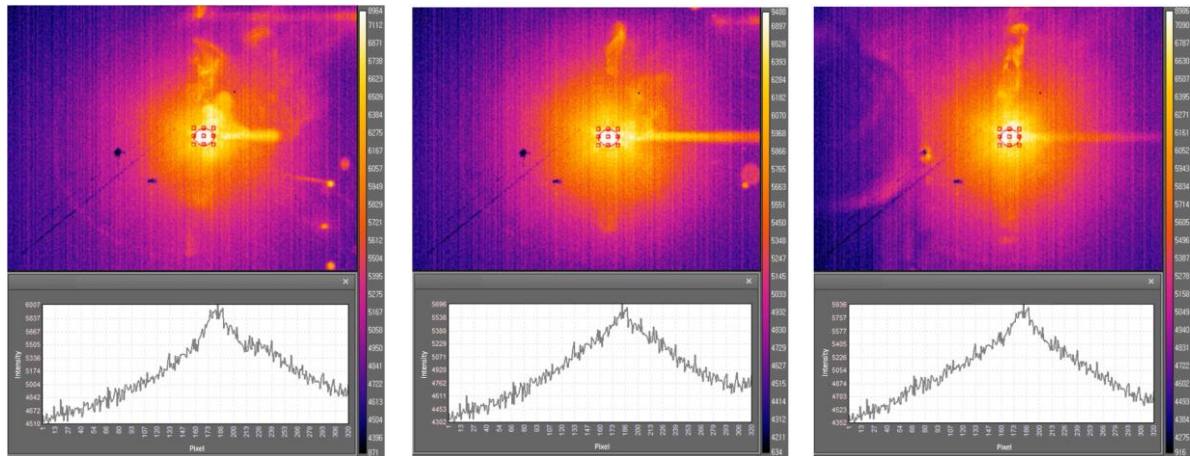
Figure 10. Total area thermal imaging results under 3 kW and 4 kW conditions

Figure 11 shows the local area thermal response around the laser heat source and molten pool. In this analysis, the representative thermal intensity was calculated from the average of nine measurement points around the heat source. The 4 kW condition showed a more consistent

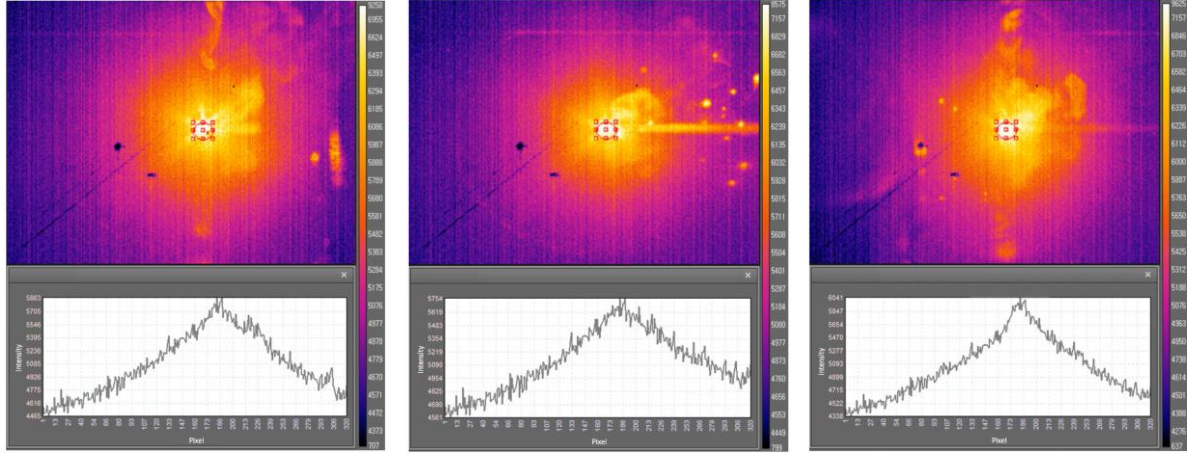
local thermal response than the 3 kW condition, which agreed with the difference in penetration observed in the cross-sections.

The thermal intensity obtained from local area analysis was lower than that from total area analysis because the two methods used different signal-processing procedures. In local area analysis, the values from nine points were averaged, which reduced the effect of isolated high-intensity regions. This averaging also suppressed short-term fluctuations caused by spatter or other local thermal events.

The absolute intensity values from total and local area analyses should therefore not be compared directly. Total area analysis is more appropriate for examining the overall thermal distribution, whereas local area analysis is better suited to tracking the thermal behavior around the laser interaction zone. For real-time monitoring, the local area method provides a more stable signal for evaluating penetration behavior.



(a) Laser power: 3 kW



(b) Laser power: 4 kW

Figure 11. Local area thermal imaging results under 3 kW and 4 kW conditions

4.5 Proposed Criteria for Multi-Sensor-Based Defect Monitoring

Based on the results described in the previous sections, the IR/UV photodiode signals and thermal imaging data were combined to establish defect-monitoring criteria. The sensor responses differed depending on the type of defect, and no single signal was sufficient to describe all welding conditions. Therefore, the monitoring criteria were defined using the signal characteristics that showed the clearest response for each defect type.

For thermal imaging, local area analysis was more suitable for real-time monitoring than total area analysis. Total area analysis was useful for observing the thermal history over the entire weld bead, but the measured intensity was affected by surface heat diffusion and local high-intensity events such as spatter. Local area analysis continuously followed the laser heat source and molten pool and provided a more stable representation of the thermal response near the welding zone. For this reason, local area analysis was selected as the primary thermal monitoring method, while total area analysis was used as a supplementary tool for evaluating the overall thermal distribution.

The monitoring criteria derived from the experiments are summarized in Table 8. Stable IR/UV signals were used as the reference for normal welding. Porosity was mainly associated with abnormal UV fluctuations, whereas undercut showed local irregular peaks in the IR signal. Non-penetration was identified from the variation in the IR signal together with the local thermal response. These criteria are specific to the present SUS304L material, ARM laser conditions, and sensor arrangement, and further tests are required before applying them to a wider range of welding conditions.

Table 8. Proposed multi-sensor-based monitoring criteria

Welding condition		Main Monitoring Signal	Characteristic response	Thermal camera role	Proposed monitoring criterion
Normal		IR+UV	Stable signals without abnormal peaks	Stable local thermal response	Reference condition
Abnormal	Porosity	UV	Abnormal drop and irregular peaks	Supplementary	UV fluctuation
	Undercut	IR	Local irregular peaks	Supplementary	IR peak variation
	Non-penetration	IR + Thermal imaging	Increased IR max-min variation	Local thermal response	IR variation + Local thermal response

5. Summary and conclusion

This study investigated defect monitoring during ARM laser welding of SUS304L using

IR/UV photodiode signals and infrared thermal imaging. The sensor signals were compared with X-ray images, surface bead appearance, and cross-sectional observations under normal, porosity, undercut, and non-penetration conditions. The main findings are summarized as follows.

- Under normal welding conditions, the IR signal remained mainly within 2–3 V and the UV signal around 1 V, with no noticeable abnormal peaks in the middle section of the weld. Porosity showed abnormal drops and irregular peaks in the UV signal, while undercut was more clearly associated with local irregular peaks in the IR signal.
- The 3 kW non-penetration condition showed a larger difference between the maximum and minimum IR signal values than the 4 kW stable partial-penetration condition. The UV signal showed a weaker response to non-penetration, indicating that IR signal variation is a more useful indicator for this defect.
- Total area thermal imaging was useful for observing the overall thermal distribution along the weld bead, but the measured intensity was influenced by surface heat diffusion and transient high-intensity events. Local area analysis provided a more stable thermal response near the laser heat source and molten pool. Therefore, local area analysis is more suitable for real-time monitoring, while total area analysis is better used as a supplementary method.
- The combined use of IR, UV, and local thermal signals revealed distinct response patterns for each defect type. These response patterns were used to establish the proposed monitoring criteria under the present experimental conditions. Additional validation under different laser powers, welding speeds, material thicknesses, and joint conditions is required before the criteria can be generalized.

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Employment

The authors declare that they have no relevant employment interests related to this work.

Financial interests

The authors declare that they have no financial interests related to this work.

Author contributions

Conceptualization: Jeong Yeol Park, Changwook Ji; Methodology: Jeong Yeol Park, Changwook Ji, Sang Hyun Park; Formal analysis and investigation: Jeong Yeol Park, Seonghyun Kim, Hyun Uk Jun; Writing – original draft preparation: Jeong Yeol Park; Writing – review and editing: Jeong Yeol Park, Changwook Ji; Funding acquisition: Jeong Yeol Park, Changwook Ji, Sang Hyun Park; Resources: Jeong Yeol Park, Changwook Ji; Supervision: Jeong Yeol Park, Changwook Ji.

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