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Monitoring laser weld penetration status from the optical signal

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Monitoring laser weld penetration status from the optical signal

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Abstract. Spectrometers have demonstrated their value in laser welding by facilitating the comprehension of welding dynamics and the identification of defects. However, the complex interaction between the laser beam and the material being welded makes it difficult for spectrometers to accurately capture the depth and extent of weld penetration, predominantly because plasma formation during welding interferes. This study presents an innovative approach that integrates laser technology, spectrometers, and advanced data analysis methods to classify and characterize various penetration types in pulse laser welding procedures, with notable computational efficiency. The research entailed the execution of an experiment on a boron steel plate, wherein peak power (1000-1200 kW), pulse duration (2-4 ms), and pulse repetition rate (25-50 Hz) were systematically varied to achieve diverse penetration conditions. Two categories of joints were identified based on their depth of penetration through careful analysis of the collected data. The investigation demonstrated a positive correlation between the depth of weld penetration and the increment of laser energy, with peak power ranging from 1000 kW to 1200 kW. Consequently, an elevation in light intensity was observed related to deeper weld penetration. The information is essential for understanding the relationship between laser energy and weld penetration, highlighting the importance of controlling laser parameters to achieve desired welding results. The spectrums were analyzed using Principal Component Analysis (PCA) to distinguish between different welding conditions. Overlap was observed between data from different weld conditions due to limitations imposed by the restricted dataset. Expanding the sample size can rectify this limitation and improve the accuracy and dependability of analytical outcomes. This study's results provide valuable insights into optimizing welding parameters and improving understanding of the welding process, specifically in Tailor Weld Blanks. The findings offer potential for improving welding quality and strengthening lightweight components in high-performance industries like aerospace and automotive engineering.

1. Introduction

The utilization of spectrometers in laser welding processes has emerged as an invaluable tool for investigating welding dynamics and facilitating the identification of defects. Scholars have leveraged the capabilities of spectrometers to acquire optical spectrum data derived from the emission spectra generated during welding operations. Spectral analysis plays a pivotal role in discerning the composition of the plasma generated in laser-induced welding and provides essential insights into the welding process. Spectrometer-derived optical spectrum information has been effectively employed in diagnosing defects encountered in laser beam welding processes.

Notably, researchers have extensively studied spectrometer signals to advance research on welding processes. Jadidi et al. [1] demonstrated the potential of spectrometers in establishing correlations between spectral emissions and beam offsets, enabling the monitoring and optimization of welding parameters. Lee et al. [2] illustrated the capacity of spectrometers to effectively classify welding imperfections by analyzing emission spectra, thereby aiding in the identification and categorization of defects including underfill and bead separation defects. The incorporation of this technology enables real-time monitoring and data acquisition of welding defects. Yu et al. [3] presented findings on the utilization of a spectrometer featuring an extensive response range, facilitating the analysis of reflected light within the welding region. This approach provided comprehensive insights into weld penetration conditions. Subsequently, Zhang et al. [4] employed a spectrometer to capture real-time data pertaining to welding defects, such as hump, blowout, and undercut occurrences during high-power disc laser welding. Furthermore, Chen et al. [5] achieved successful identification and categorization of laser welding defects, including porosity and bead separation, by implementing a cost-effective computational methodology. The integration of a spectrometer in laser beam welding operations not only enhances process control and weld quality but also augments our comprehension of the welding process and supports optimization efforts. The studies clearly underscore the efficacy of spectrometers in the detection and classification of defects in laser welding, thereby furnishing valuable insights while incurring minimal computational expenses. However, certain scholars have opted to employ multiple sensors to overcome the limitations associated with the restricted coverage of the target area.

There are several benefits to using multiple optical sensors in laser beam welding procedures. Through data verification and cross-validation, researchers can improve the precision and uniformity of measurements obtained with various sensors [6]. Various aspects of the welding process are captured by different sensors, allowing for more in-depth analysis. These sensors enable the measurement of a wide range of parameters that are helpful in assessing welding parameters and identifying defects, such as wavelengths, emission spectra, and spatial resolutions [7]. The use of numerous sensors increases coverage of the welding region, allowing for the detection of spatial differences, localized defects, and subtle alterations that may occur [8]. The extensive collection of data enhances a deeper understanding of welding dynamics and facilitates the optimization of welding parameters.

However, it is important to recognize that the use of multiple optical sensors may have certain drawbacks. A drawback of using multiple sensors is the higher complexity and cost involved in their implementation and management. The process of installing, calibrating, and maintaining each sensor can require considerable time and resources. Additionally, the utilization of multiple sensors necessitates supplementary equipment and infrastructure, thereby augmenting the overall expenses of the system. These factors require careful consideration during the process of system design and implementation. Wang et al. [9] used a high-speed CCD camera and image processing techniques to observe and measure the characteristics of keyhole entrances in laser beam welding. Zhang et al. [10] conducted a study where they used multiple sensor systems, such as an auxiliary illumination visual sensor, a UVV band visual sensor, a spectrometer, and a photodiode, to collect data on the high-power disc laser welding process. Gao et al. [11] designed a multisensory detection system for monitoring high-power disc laser welding. The system includes sensors such as an AI-sensing camera, UVV-sensing camera, X-ray TV system, visible light-sensing photodiode, reflected laser-sensing photodiode, and spectrometer. Liu et al. [12] used five sensors, including photodiode sensors, a spectrometer sensor, a UV and visible light sensing camera, and an auxiliary illumination sensing camera, to extract features related to the keyhole, plasma, and spatters.

Previous research has focused on the use of sensors to detect and identify several forms of welding defects, including as porosity, underfill, undercut, humping, and blowout. Nonetheless, there has been limited research on monitoring welding penetration, particularly in the context of Tailor Weld Blanks (TWBs). TWBs are made by pulse laser welding, which entails putting together many layers of sheet metal with varied thicknesses and compositions. These TWBs are crucial in the manufacture of lightweight parts with remarkable performance, particularly in industries such as aerospace and automotive. In TWBs, the extent of penetration obtained during welding has a major impact on the quality and performance of the weld joint [13]. During the welding process, adequate penetration is critical for generating a strong and long-lasting link between materials. Welded joints with insufficient penetration might have compromised structural integrity, making them more prone to fracture or distortion when stressed. This reduces fatigue resistance and raises the probability of premature failure in welded components. Inadequate penetration can have a negative impact on dimensional accuracy, jeopardizing the form and integration of the welded components. The mechanical characteristics, structural integrity, and overall performance of welded materials must be preserved by adequate penetration.

Yu et al. [3] conducted a study to prove the effectiveness of a spectrometer-based quality prediction model in evaluating the weld penetration conditions of laser welding. It is crucial to acknowledge that this model's scope is limited to the parameters investigated in the study, including the use of a Deep Neural Network (DNN) and materials. DNNs have shown impressive performance across various domains, but they have inherent limitations. Training deep neural networks with multiple layers and parameters requires significant computational resources and can be time-consuming. Deep neural networks often require high-performance hardware and extensive computational resources due to their computational demands and memory requirements. As a result, their applicability is limited to devices with limited memory capacity. Additional research is necessary to develop comprehensive monitoring techniques for welding penetration in TWBs, considering the unique characteristics and requirements of this welding process. These advancements would improve weld quality, optimize welding parameters, and enhance the overall performance of TWBs in diverse industries.

This study aimed at classifying penetration types in pulse laser welding processes, emphasizing its notable computational efficiency. The methodology employs laser technology to create plasma during welding, and then collects spectral information using a spectrometer. The spectral data is compressed by identifying important emission lines and extracting relevant features related to their temporal evolution. Principal Component Analysis (PCA) is used to condense large data tables into a concise set of informative indices, enabling comprehensive analysis and visual representation. The proposed model can efficiently train using pre-processed spectral data as input, allowing for effective summarization through the application of appropriate pre-processing techniques to the training data. The efficacy of this method has been confirmed through a sequence of welding experiments conducted on boron steel, demonstrating its successful implementation and potential for future progress in the discipline.

2. Methodology

The experimental setup included an IPG YLM 200/2000-QCW fiber laser and a precision 3-axis movement worktable, as shown in Figure 1. The fiber laser used in this study produced an average power of 0.2 kW, with a peak power of 2 kW in Pulse Wave mode. The study aimed to establish a correlation between the geometric characteristics of penetration and the optical emissions generated during pulse laser welding. The experiments were conducted using a bead-on-plate technique on a boron steel specimen with dimensions of 53 x 38 x 1.8 mm. Before the experiments began, the specimens were prepared by sanding their surfaces with 120-grit sandpaper. This was done to improve their ability to absorb energy from laser irradiation. Table 1 was a pivotal reference for manipulating important parameters, including peak power, pulse duration, and pulse repetition rate. During the experiment, a focal length of 155 mm and an angle of 5 degrees were consistently maintained. In addition, a continuous supply of argon gas at a rate of 15 L/min was used as a shielding gas to create a protective environment for the laser-induced fusion during the welding process.

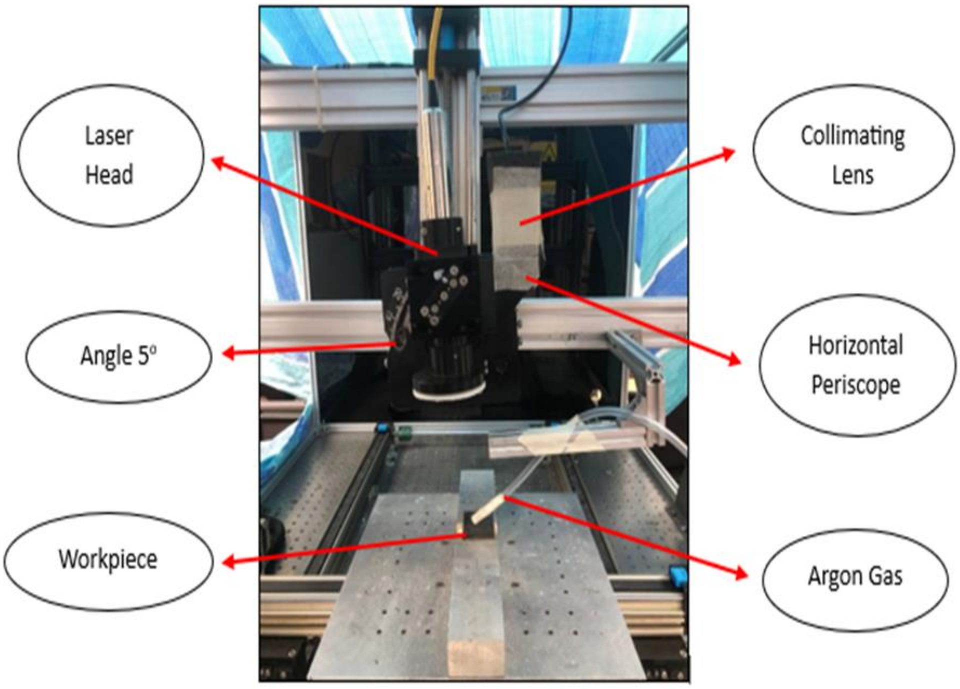


Figure 1. Experimental setup of pulse laser welding (a).

The data acquisition setup consisted of a scanner laser head equipped with a horizontal periscope, which was linked to two optical fibers. One fiber was a round-to-linear fiber optic bundle, connected to the spectrometer, while the other fiber transmitted the laser beam input from the laser source. To accomplish this, the scanner laser head and the fiber optic bundle were connected using a horizontal periscope, as shown in Figure 2. This periscope also served to concentrate the reflected light from the welding area. The laser light from the welding area was directed to the spectrometer using a horizontal periscope that included a partially transmitting mirror and an optical fiber. The laser beam was gathered using a collimator after reflection, and the collected data was then displayed and stored using computer software.

Table 1. Group of parameter variation in pulse laser welding.

Group	G1	G2
Peak power, kW	1000	1200
Pulse duration, ms	2	4
Pulse repetition rate, Hz	50	25
Focal length, mm	155	155

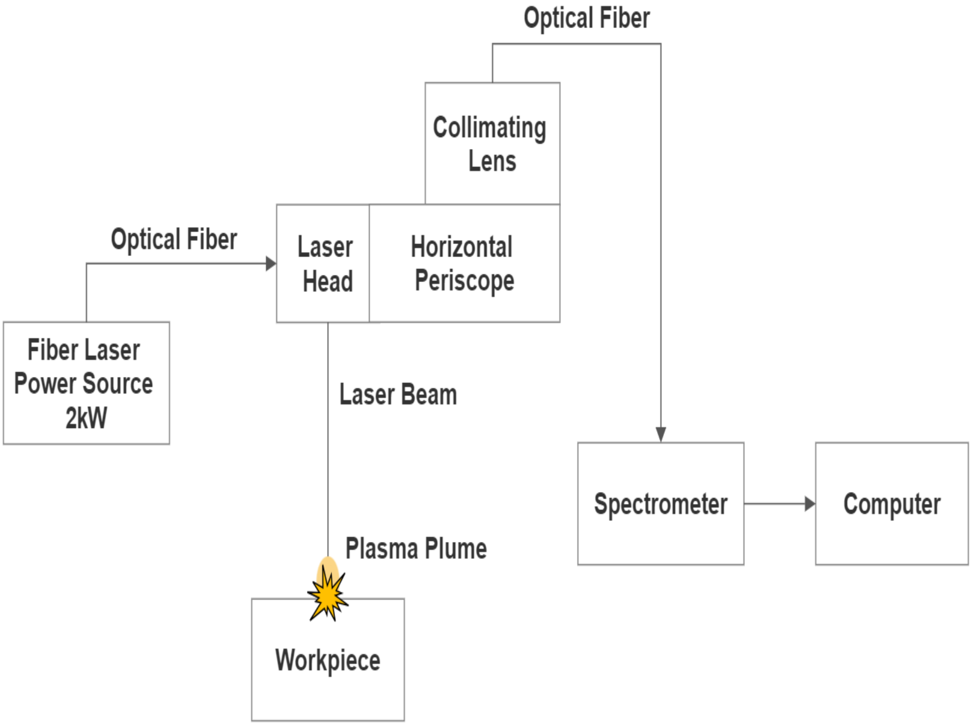
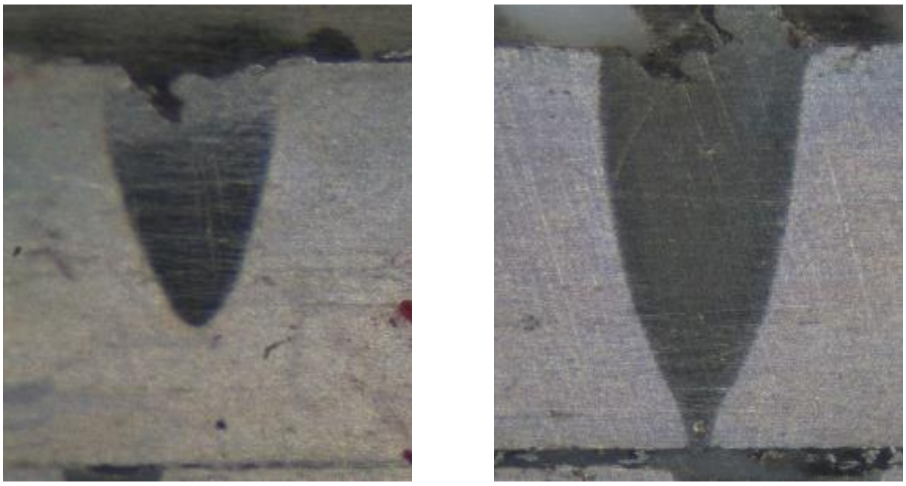


Figure 2. Schematic diagram of data acquisition setup.

3. Results & Discussion

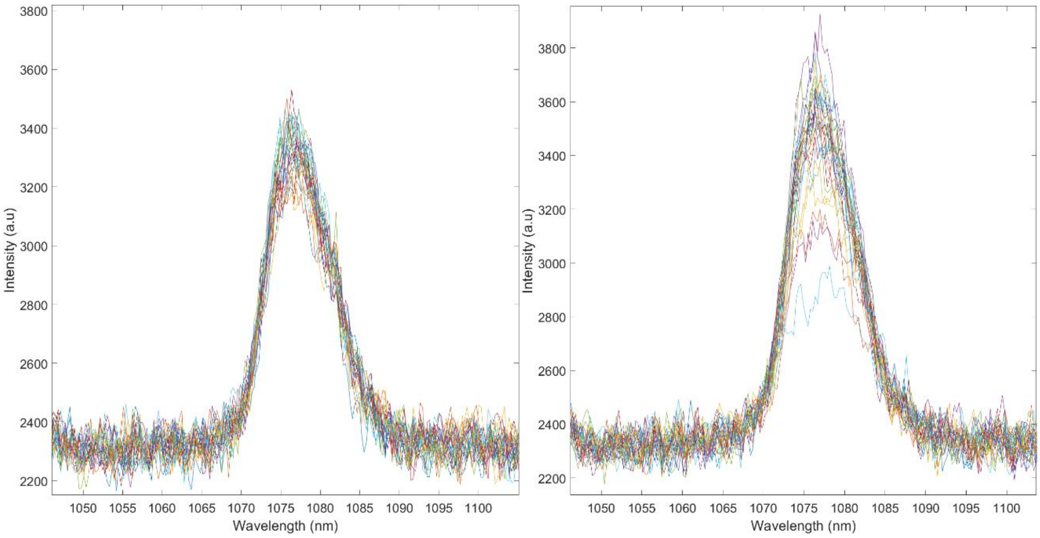
The quality assessment of welding was undertaken through a meticulous evaluation of the weld joint geometry, as elucidated in Figure 3. This study discerned two distinctive categories of joints, distinguished by disparities in peak power, pulse duration, and pulse repetition rate, specifically referred to as half penetration and full penetration. The former group, characterized by a pulse duration of 2 ms, manifested partial penetration, while the latter group, with a pulse duration of 4 ms, demonstrated complete penetration. These categorizations provide crucial insights into the weld joint characteristics and serve as a foundation for further analysis and interpretation of the welding process.



(a) (b)

Figure 3. Cross-sectional analyses of the welded joint based on distinct parameter group, (a) Half Penetration from G1 and (b) Full Penetration from G2.

The analysis of Figure 3 reveals a significant inference about the impact of peak power and pulse width on welding penetration depth. Group 1, which had the lowest penetration depth, also had the lowest peak power. The empirical observations support the conclusion that Group 1 weld joints had incomplete penetration, as the fusion zone did not fully form. A significant correlation was observed between the increase in peak power and the corresponding increase in penetration depth. The analysis of the pulse optical signal, shown in Figure 4, demonstrates that the magnitude of the spectrum depends on the peak power of the laser. The noticeable difference in the overall intensity behavior of Group 1 and Group 2 highlights distinct patterns in their optical signal profiles. The optical signal intensity from Group 2 is significantly higher, which corresponds to the peak power variation of the laser as shown in Table 1. Ruutiainen et al. [14] confirmed a correlation between laser output and radiation intensity in their study. The study found a positive linear relationship in the moderate to high power range. This data is essential for understanding the relationship between laser energy and weld penetration, highlighting the importance of controlling laser parameters to achieve desired welding results. Increasing laser energy levels can result in deeper welds, but it is crucial to strike an appropriate equilibrium to prevent negative effects such as excessive heat or damage to the material.



(a) (b)

Figure 4. Pulse optical signal acquired during pulse mode laser welding with parameters set as in (a) Group 1 (b) Group 2.

Both spectra were analyzed using Principal Component Analysis (PCA), a linear technique that reduces the dimensionality of datasets while retaining the essential information and reducing the number of variables [15]. The main goal of Principal Component Analysis (PCA) is to identify a linear combination of variables that effectively represents the variability present in the dataset. PCA effectively reduces the impact of variance and identifies a linear combination that explains the largest portion of the remaining variance [16]. This approach simplifies the dataset and allows researchers to uncover important patterns and insights in the welding process, leading to a thorough understanding of the spectral characteristics and their implications.

Figure 5 provides compelling evidence for the efficacy of PCA in distinguishing dissimilar spectra and weld conditions, even though there are some overlapping areas between the data of Group 1 and Group 2. This suggests that PCA is a reliable method for identifying significant differences and patterns that contribute to distinctions in welding. According to Beattie et al. (17), Principal Component Analysis (PCA) can decrease intricate spectral variations to a smaller set of variables that demonstrate enhanced statistical properties. PCA enables a direct relationship to be established between data and principal components, making it easier to extract valuable insights from linear combinations of spectral patterns. The overlapping phenomena is attributed to the constraints of a limited dataset. However, this problem can be resolved by increasing the sample size through augmentation. Expanding the dataset allows for a comprehensive analysis, improving the reliability and robustness of the findings.

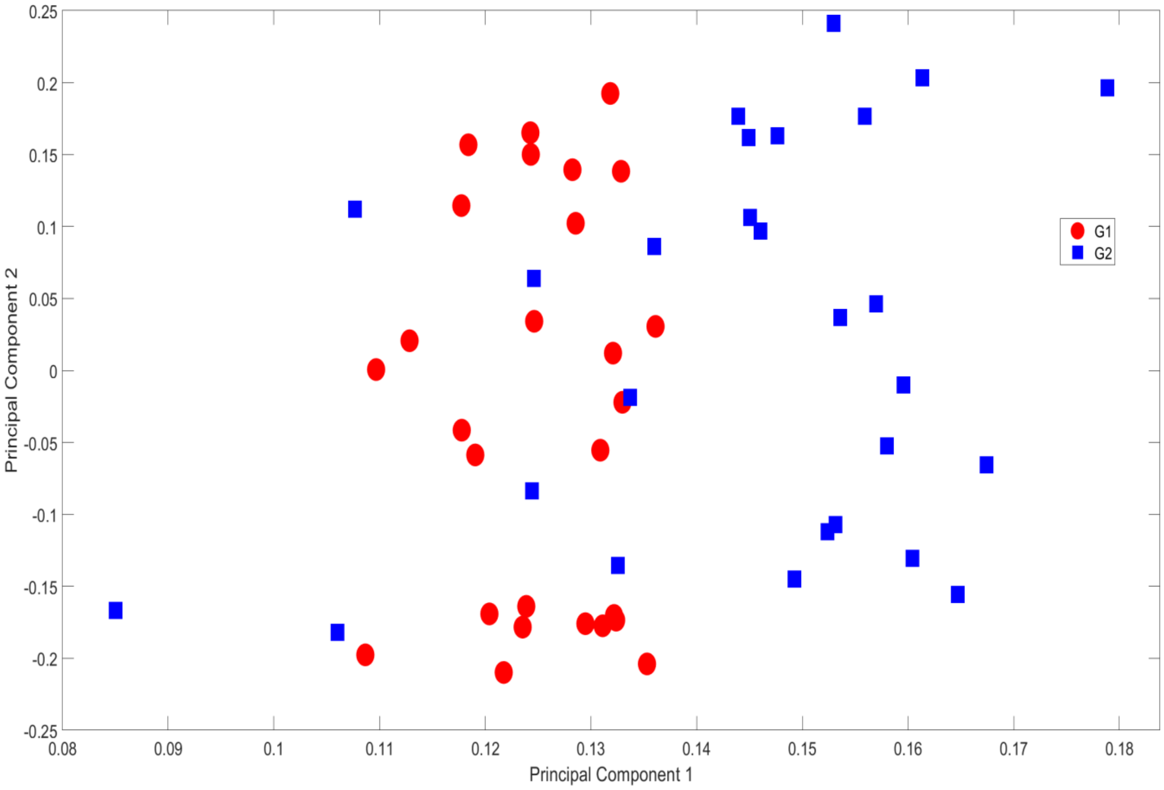


Figure 5. Scatter diagram resulting from the employment of PCA.

These findings highlight the importance of effectively managing laser parameters in welding processes. The direct influence of controlling peak power on penetration depth and weld quality is significant. Additionally, optical signal analysis offers valuable insights into the relationship between laser energy and spectral characteristics. Leveraging PCA enables researchers to extract important patterns and distinctions in spectral data, thereby enhancing their understanding of the welding process. With these insights, welders and engineers can optimize laser parameters to improve welding practices, resulting in increased efficiency, reliability, and enhanced weld quality and performance.

4. Conclusion

This study establishes a clear relationship between peak power and penetration depth in the field of pulse laser welding. Empirical evidence supports a positive correlation between higher peak power and increased penetration depth in welding. This relationship offers valuable insights into the characteristics of welded joints. By conducting a comprehensive examination of optical pulse signals and employing Principal Component Analysis (PCA), it is feasible to distinguish and categorize different weld conditions, particularly those pertaining to half penetration and full penetration classifications. The results indicate that Principal Component Analysis (PCA) is effective in reducing spectral variations and extracting meaningful patterns and insights from linear combinations of spectral data. Additionally, increasing the dataset size in this analysis has the potential to improve the accuracy and reliability of the findings. Increasing the sample size improves the reliability of the findings by enhancing the comprehensiveness and detail of the analysis. These findings offer valuable insights for optimizing welding parameters and are relevant in various domains, including Tailor Weld Blanks. They could improve both the field of welding technology and its practical application in industries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of competing interest

S A A Aleem: Conceptualization, Experiment & Analysis, Writing-Original draft preparation. **M F M Yusof**: Supervision, Data Validation, Writing-Reviewing and Editing. **M Ishak**: Visualization, Supervision.

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