

Defect Identification During Pulse Mode Laser Welding Process Through the Pattern Recognition Analysis of the Acquired Sound Frequency Spectrum



M. F. M. Yusof , M. Ishak, M. N. Salleh, and M. F. Ghazali

Abstract Problems on laser weld quality still remain as vital issue even though the process was done with optimized condition which results the demand on robust monitoring method during the process. Until recently, many methods have been explored and air-borne acoustic are among of methods that have been proven to be able to detect the presence of defect. However, despite detection, it is essential if the type of defect could be identified as it gives different severity level to the development of failure. This work presents the identification of defect during pulse mode laser welding through the analysis of sound. In achieving the goal of this study, bead on plate weld have been done onto the 22MnB5 boron steel plate repeatedly based on 3 different set of experiment with the variation in the level of parameters. Simultaneously, time-series sound signal was acquired along the process before it was converted into frequency spectrum before further analysis. According to the result, it was recorded that the variation of parameters level in pulse mode laser welding process lead to the presence of porosity and crack. Relatively, the trend of sound frequency spectrum were also significantly changes its trend in respond to the parameters level variation. It was discovered that the dominant frequency for the signals acquired from the process which produce good quality weld, porosity and crack recorded the same range which was between 5 to 7 kHz. Uniquely, the existence of porosity could be identified by the occurrence of peak at around 9 kHz while the presence of crack could be recognized by the occurrence of peak at 8 kHz and 11 kHz. This trend was proven to be consistent in repeated experiment according to the result from principal component analysis. Based from the result in this study, it could be conclude that the identification of defect could be done by the analysis of the acquired sound during the process. Significantly, this would expand the ability

M. F. M. Yusof · M. Ishak (✉) · M. N. Salleh · M. F. Ghazali
Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang,
Pekan, Pahang, Malaysia
e-mail: mahadzir@ump.edu.my

M. Ishak
Centre for Research in Advanced Manufacturing, University Malaysia Pahang, Pekan, Pahang,
Malaysia

of acoustic method for quality monitoring purpose as the identification of defect is also important in quality control.

Keywords Defect identification · Pulse mode laser welding · Sound frequency spectrum

1 Introduction

Increasing trend on the use of laser welding process could be seen since past decades. This was owing to its advantageous in giving a small heat affected zone, aesthetic appearance, high production rate as well as reducing the post-weld processing [1]. Due to this fact, numerous studies associates to the laser welding process on wide variety of materials have been reported over the past years [2–5] which more or less could be apply many type of industries. However, the problems on weld quality still remain as vital issue even though the process was done with optimized condition. It is well known that the existence of defects in weld product is intolerable and become a massive concern since it could degrade the strength of weld product. To address on this issue, the implementation of robust monitoring method has been suggested as it promote greater control during the process [6]. Since past decades, numerous methods which inclusive of electrical, thermal, optical as well as acoustic method have been applied in laser welding process. Among those methods, acoustic sound method gained attention lately due. It was due to its high responsible speed, low cost and simple setup [7–9].

Since past decades, many studies have been done to comprehend the relation between the sound characteristic and weld condition. In earlier research, the characteristic of sound frequency spectrum was reported to be strongly related to the weld penetration [10]. The investigation was done on Aluminum 1100 and according to the result, the peak of sound spectrum at the bandwidth of 9–10 kHz recorded an increment simultaneously with laser intensity gain. Concurrently, the depth of penetration is also increasing. Unlike the aforementioned work the spectral energy was reported to drop in its value when insufficient weld penetration was detected [11]. In this work, the study was done on 304 stainless steel plate and different range of active frequency bandwidth was found within 1–2 kHz. In another work which involved broader range of power and travel speed [12], it was reported that the Root Mean Square (RMS) of the acquired sound recorded distinguished pattern in separating full-, moderately full-, or partial-penetration weld joint. In another part of this research [13], the study was extended into the high power or keyhole welding regime. As results from the combination analysis of the acquired sound and optical charged particle signal, the penetration status could be divided into three different classes which were full penetration, overheat penetration and half penetration. In recent study, other sound features were also reported to gives a significant trend with the change in penetration status. Huang and Kovacevic [7, 14] investigate the trend of

Sound Pressure Deviation (SPD) and Band Power (BP) to classify the weld penetration. Uniquely, despite of giving a distinctive pattern, the weld penetration estimation models were successfully developed using multiple regression and artificial neural network by learning the trend of these features.

Apart from penetration condition, other defects or irregularities along the weld bead was reported to be able to detected from the analysis of the acquired sound during the laser welding process. In recent work [8], it was reported that the sound pressure level trend significantly giving information with respect to the existence of burn through defect. Moreover, with the use of arrays of microphones and sound proof equipment, the location of defect could also been identified with reasonable error through time delay recognition analysis. Acoustic method was also reported to be able to detect underfil and humping. In the previous work [15], the effect of Zn coating thickness and gap between the lapped specimens to the degree of those defects was accessed based on the acquired sound signal. Based on the results, it was found that the amount of spatter was consistently appeared between 0.08 to 0.2 mm gap. Accordingly, the existence of spatter influenced the existence of both humping and underfil. Simultaneously, it was found that the RMS of sound signal recorded a significant change at the same gap. Moreover, the amplitude of frequency spectrum at around 1 kHz appeared to be inversely proportional to the coating thickness. This phenomenon happen because of high vapor pressure produced from the thicker coating which results in the suppression of keyhole oscillation. In addition, the amplitude of the bandpass-filtered time domain signal show deviating trend from 22 to 38 V at the presence of defects. Different from the other studies, Sansan et al. [16] combined principal component analysis (PCA) and independent component analysis (ICA) to decompose the acquired acoustic signal into cooling and keyhole component in order to detect the existence of blowholes.

As established by the above studies, it could be generally summarized that the analysis of the acquired sound during laser welding process could lead to the detection of defect by in-situ basis. However, up to this point, many existing studies were only underlining on the detection of several type of defect. In order to establish this method for the purpose of monitoring laser welding process, it is important to study on how the behaviour of the acquired sound responds to the occurrence of the many other type of defect such as crack and porosity which could lead to the crack nucleation and degrade the fatigue life of the component. Moreover, it is essential if the type of defect could be identified as it gives different severity level to the occurrence of failure. In this work, the main aim is to identify type of defect from the analysis of the frequency spectrum of the acquired sound during pulse mode laser welding process. At the first stage of this work, the behaviour of both time domain and frequency domain in respond to the occurrence of different type of defects will be discussed. In the next part, the significant use of principal component analysis to recognize the different in sound spectrum pattern and simultaneously identify the different type of defect will be presented.

2 Methodology

2.1 Experimental and Data Acquisition Setup

The setup of the experiment was illustrated in Fig. 1. In this study, bead on plate weld were done on 22MnB5 boron steel with the variation of parameters set as shown in Table 1. Basically, focal length, peak power, pulse width and pulse repetition rate was set to be varied in this work in attempt to produce both intact weld and weld with defect. In all cases in this work, the speed of weld was set to constant at 1.5 mm/s. Meanwhile, pure argon shielding gas flowrate was set to 15 L/min it was also constant along the entire experiment. On the other hand, each set of experiment was repeated 5 times and sampled at 5 different points to gives total of 75 set of sound signal for the analysis purpose. This was done in order to observe the consistency of both defects occurrence as well as the sound signal trend.

During the pulse mode laser welding process, the sound signal emitted from the process was acquired using microphone. The acquired analog signal was discretize using National Instrument (NI) 9234 analog-to-digital converter with the rate of 25.6 k Sample/s. The digital signal was then converted into digital frequency spectrum using analyser before further analysis was done. Meanwhile, the microphone was located at 25 cm and 300 angle from the weld spot to ensure that the spatter that produced during the process was not damaging the sensor.

Fig. 1 Experiment and data acquisition setup

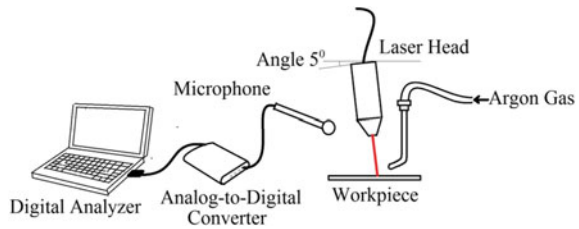


Table 1 Pulse laser welding parameters setup

Experiment No	Focal length (mm)	Peak power (W)	Pulse width (ms)	Pulse repetition rate (Hz)
1	+ 5	1600	6	20
2	- 5	1200	6	16
3	0	1200	2	50

2.2 Experiment and Data Acquisition Setup

As briefly explained in the earlier section, analysis of frequency spectrum will be done in order to identify the type of defect occurs during the laser welding process with the parameters as shown in Table 1. Basically, the frequency spectrum was obtained from the Fast Fourier Transform (FFT) of the time-series of the acquired sound. In order to reveal the different in spectrum pattern due to the occurrence of different type of defect, principal component analysis (PCA) was applied in this study.

In principal, PCA was applied based on theory explained by Jolliffe [17] which considering all the collected spectrum as a big population of data. In this case, each observation represents a single frequency spectrum with the variation of amplitudes x_f along the band as stated in Eq. 1 whereas m and n were the number of observation and samples respectively.

$$Xf_m = xf_{m1}, xf_{m2}, xf_{m3}, \dots, xf_{mn}, \quad (1)$$

By gathering all the spectrum in $m \times n$ size matrix, the covariance between all spectrums was determine by Eq. 2 which gives $m \times m$ covariance matrix $[C_{xf}]$.

$$[C_{xf}] = [Xf_{mn}].[Xf_{mn}]^T \quad (2)$$

In order to determine how each of the spectrum trends was different from the others, the projection of their covariance need to be determined. This could be done through the eigenvalue decomposition of the obtained covariance matrix as shown in Eq. 3 in which \vec{v} and γ represent eigenvector and eigenvalues respectively.

$$[C_{xf}].\vec{v} = \gamma.\vec{v} \quad (3)$$

Theoretically in PCA, eigenvectors is the principal component which was sorted in descending order of its variance value shown by eigenvalue matrix. The different in amplitude pattern along the entire band in frequency spectrum could be observed from the principal component.

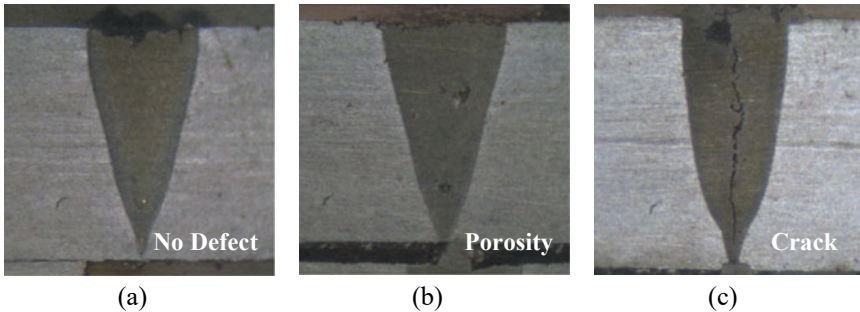
3 Result and Discussion

3.1 Type of Defects Emerged from Pulse Mode Laser Welding Process

Recalling back to the previous section, it was explained that the experiment was done based on the set of weld parameters represent in Table 1. Table 2 summarized the defects that occur during each set of experiment. Based from the table, it could be

Table 2 Defect occurred from different set of experiment

Experiment No	Focal length (mm)	Peak power (W)	Pulse width (ms)	Pulse energy (mJ)	Pulse repetition rate (Hz)	Type of defect occurred
1	+ 5	1600	6	9600	20	No defect
2	- 5	1200	6	7200	16	Porosity
3	0	1200	2	2400	50	Crack

**Fig. 2** Cross section image of the selected sample in each of experiment **a** Experiment 1 **b** Experiment 2 **c** Experiment 3

clearly observed that intact weld was produced from experiment set 1. In contrast, set 2 and set 3 of experiment was found consistently produce porosity and crack respectively. To get clearer picture, the weld bead cross section of each one of the experiment was depicted in Fig. 2.

In order to understand the phenomena occurs in this study, the physical theory on the defect formation mechanism need to be look into. According to Dawes [1], hot crack and porosity could occur during laser welding due to uncertainty during solidification process. In pulse mode laser welding the tendency of crack to occur is quite larger [18] and investigating the optimum cooling time to reduce the critical strain which could initiate crack might solve this issue [19]. As could be observed in Fig. 2, the occurrence of crack was found in set 3 of the experiment. Compared to the parameters from set 1 experiment which produces pristine weld condition, it was recorded that the pulse repetition in experiment set 3 was more than 2 times larger. Moreover, the pulse width was 3 times smaller. This factor might affect the cooling behaviour which emerged the crack in this study. On the other hand, the formation of porosity was explained by the trapped bubbles emerged from the instability of keyhole and molten metal during backfilling process [20, 21]. Some scholars, [22, 23] suggest that the overlapping factor could suppressed the formation of porosity in pulse mode laser welding. In principal, the overlapping factor is influenced by the laser spot diameter and pulse repetition rate and the smaller pulse repetition rate in experiment set 2 might explain the existence of porosity in that experiment.

3.2 Behaviour of the Acquired Sound Signal

Owing to the fact that the existence of defect was influenced by the variation of parameters as prior presented, it is important to understand how the generated sound respond to the different set of parameters in the experiment. Figure 3 depicts the time series of sound signal acquired from different set of experiment. Due to the nature of pulse mode laser welding which emit the laser periodically, all the acquired sound shows the pulse behaviour as illustrated in the figure. In more detail observation, it was clear that the duration of sound pulse was influence by the pulse width value during the laser welding. For instance, pulse sound acquired from experiment 3 recorded the shortest pulse duration as a result from lowest pulse width setup. Meanwhile, the pulse duration of sound captured in Fig. 3a and b both were slightly similar due to the same value of pulse width during the experiment. On the other angle, the maximum amplitude of the acquired sound seems to be influences by the amount of energy during laser welding process. The average maximum amplitude of all the acquired sound for experiment 1, 2, and 3 was recorded to be 6.37 mV, 3.71 mV and 2.21 mV respectively.

Apart from time series of the acquired sound, it is important to observe the trend of frequency spectrum with respect to the change in weld parameters which influenced the occurrence of defect. Basically, frequency spectrum gives information on both frequency and amplitudes as illustrated in Fig. 4. According to the result shown in the figure, it could be generally summarized that the amplitude trend was similar to the trend recorded in time-series in Fig. 3. Meanwhile, in all set of experiment, it was found that the dominant frequency of the acquired sound lies between 5 and 7 kHz which emerged from the plasma plume oscillation explained by [24]. Uniquely, small peak was recorded around 9 kHz for the case of experiment 2 while it was found around 8 and 11 kHz in experiment 3. This trend shows that the change in parameters will influence the entire structure of the frequency spectrum in this study which could possibly give a significant result in identification or clustering analysis.

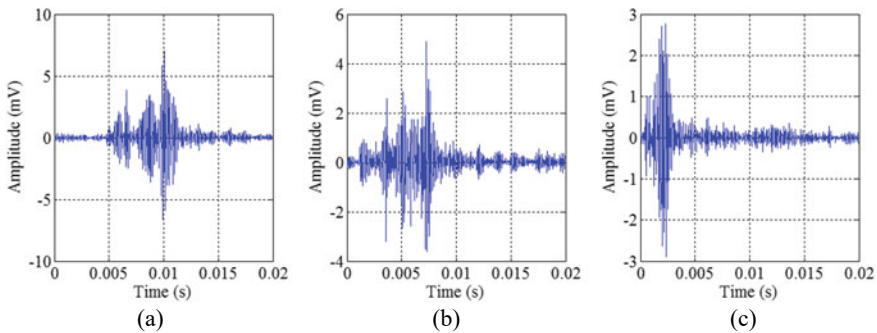


Fig. 3 Time series of pulse sound signal acquired from different set of experiment **a** Experiment 1 **b** Experiment 2 **c** Experiment 3

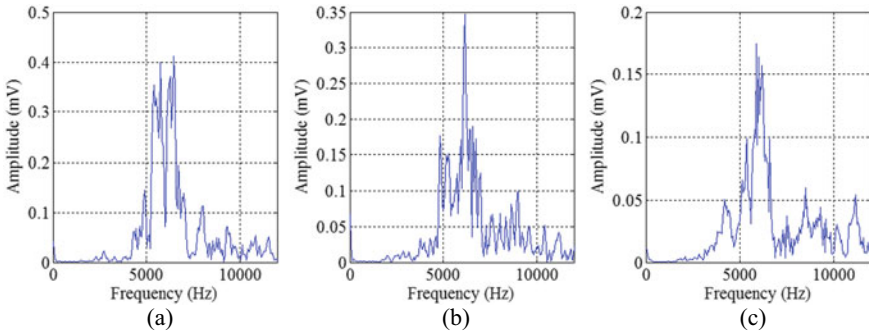


Fig. 4 Frequency spectrum of pulse sound signal acquired from different set of experiment **a** Experiment 1 **b** Experiment 2 **c** Experiment 3

3.3 Defect Identification Through the Principal Component Analysis

As previously presented, the formation of defect was influenced by the set of parameters which results in the change of frequency spectrum behaviour. In prior section, it was explain that the pattern recognition analysis of the frequency spectrum will be done using PCA in attempt to identify the sound signal from different type of defect. Figure 5 shows the principal component plot of the analysed sound frequency spectrum.

As could be observed in Fig. 5, all the spectrums were classify into 3 different groups based on weld condition. In order to determine the precision of scattered point for each group, the centroid was determined by k-mean method. From the result, it was found that the spectrums from crack weld was scattered in more precise pattern

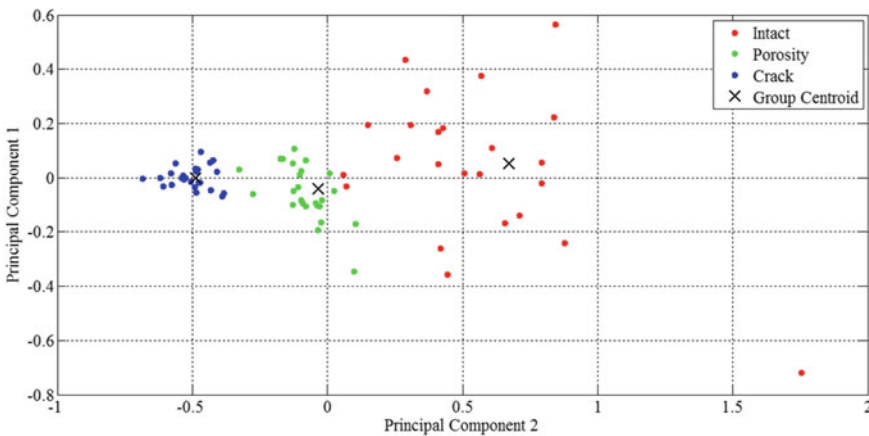


Fig. 5 Principal component plot of the analysed frequency spectrum by PCA

followed by spectrum recorded from porosity and intact weld. This show that all the frequency spectrum for the case of crack and porosity weld recorded a consistent trend in every repetition of the experiment which could allow ones to identify the type of defect from the captured sound signal.

4 Conclusion

According to the result presented in this work, it could be summarized that the formation of defect was influence by the set of parameters during pulse mode laser welding process. Simultaneously, the frequency spectrum of the captured sound was also found significantly changes its pattern. Moreover, principal component analysis revealed that different trend was recorded for different type of defect and it was quite consistent for every repetition of experiment which allows the identification of defect. As conclusion, the identification of defect could be done by the analysis of frequency spectrum acquired during pulse mode laser welding. This could promote an alternative way for monitoring the weld condition by in-situ basis.

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