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Detection of irregularities on weld bead from the L-Statistic analysis of the acquired sound during pulse mode laser welding process

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Detection of irregularities on weld bead from the L- Statistic analysis of the acquired sound during pulse mode laser welding process

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Abstract. Since several past decades, many studies prove that the statistical or signal features extracted from the sound acquired from laser welding process was significantly giving information on the weld condition. However, a considerable amount of studies were only emphasizing on the use of common statistical features in which it is restricted to some limitation when dealing with non-stationary random sound signal. In this particular work, the main aim was set to detect the irregularities along the weld bead by way of implementing the L-Statistic analysis on the acquired sound during pulse mode laser welding process. To achieve the goal, pulse mode laser welding have been done onto 22MnB5 boron steel plate in butt joined configuration. During the process, sound signal was acquired using microphone and further analyzed by extracting L-statistic features from it. According to the findings, among all the L-statistic features analyze in this study, L-Cv (scale) was found giving a significant indicator of the weld bead surface condition. Larger value of L-Cv was recorded at the point where the large underfill occurred. On the other hand, it was also found that the L-kurtosis values could give remarkable information on the existence of the irregularities on bead width and depth. Hence, it could be drawn into conclusion that the irregularities on the weld bead during the pulse mode laser welding could be detected from the appropriate L-statistic features of the acquired sound signal. The finding in this work was believed to be essential in enhancing the capability of acoustic sound method to be developed as online monitoring system for pulse mode laser welding process.

Keywords. Weld irregularities; Sound Signal; L-Statistic; Pulse Mode laser welding

1. Introduction

Over many decades, the use of laser welding have increasingly popular owing to its advantageous in providing weld product with small heat affected zone, aesthetic appearance, less post-weld machining process and high production rate [1]. By the meantime, significant number of studies connected to the optimization of laser welding process has been reported over the past years [2-5]. In any type of industries, the irregularities of weld bead are intolerable and received a great concern because it could degrade the strength of weld product. Therefore, some scholars suggest that the robust monitoring method for the process is essential because it could promote greater control during the process [6]. Since many years, numerous methods for monitoring laser welding have been studied which inclusive of electrical, thermal, optical as well as acoustic method. Among those methods, acoustic sound method attracted some interest recently due to low cost, simple, high responsible speed and convenient features [7-9].

In recent times, many studies have been done to gain deeper understanding on how the acquired sound could be correlated with the weld condition. On one hand, weld condition was defined by its penetration status. For instance, in earlier research by Duly and Mao [10] have demonstrated the study of acoustic signal behavior from different depth of penetration in Aluminum 1100 based on its spectral amplitude features. Based from the study, peak within 9 kHz to 10 kHz was found increasing in its amplitude simultaneously with gaining laser intensity which concurrently increased the depth of penetration. Comparable work also has been reported by Farson et al [11] in which the experiment was done on 304 stainless steel plate. Unlike the previous work, the spectral energy was determined instead of its amplitude. In contrast with the aforementioned study, the significant range was recorded to be within 1 kHz to 2 kHz whereas its energy drops when insufficient penetration detected. In their extended study [12], the investigation was done in broader range of power and travel speed. Different with their previous work, the Root Mean Square (RMS) was used as a feature to identify whether the penetration status felt under full, moderately full, or partial penetration class. In another part of their research [13], the test was done up to the high power or keyhole welding regime. Supported by measured optical charged particle data, the depth of penetration status could be classified into full penetration, overheat penetration and half penetration. Unlike the other work, in recent study, Huang and Kovacevic [7, 14] have demonstrated the analysis of Sound Pressure Deviation (SPD) and Band Power (BP) to classify the weld penetration. Moreover, uniquely in their study, the depth of penetration could be quantitatively estimated from multiple regression and artificial neural network analysis on both sound signal features.

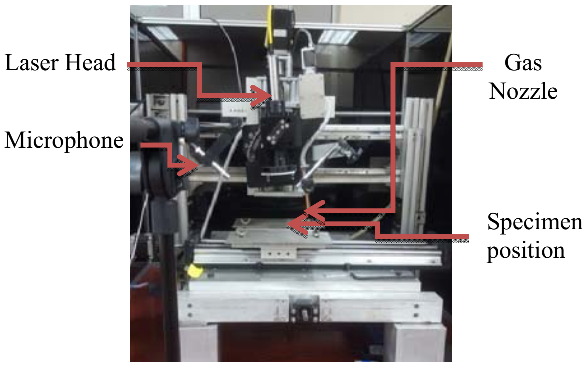
On the other hand, despite the weld penetration, the weld condition was also determined from the existence of defect or irregularities along the weld bead. In recent work, Luo et al., [8] exhibit the use of multiple number of microphone to detect and locate the burn through defect. Based from the illustrated result, it was noted that the detection and location of burn trough defect based on the sound pressure level and time delay recognition analysis was done with small error with an aided from sound proof equipment. In another work, the use of acoustic method was also reported to be used to detect other types of defect such as underfill and humping [15]. In this work, the effect of Zn coating thickness and gap between the lap joint to the degree of those defects was monitored based on the acquired sound signal. From the drawn result, the amount of spatter which influences the existence of both underfill and humping was found to be consistent between 0.08 to 0.2 mm gaps depending on the coating thickness. Simultaneously, within the same range, the recorded RMS of sound signal was significantly changed. Moreover, the analysis of frequency spectrums shows that the amplitude of frequency spectrum within 1 kHz appeared in descending pattern when coating thickness increased. This is due to the fact that the large thickness value contributes to high vapor pressure which consequently suppressed periodic motion of keyhole. In addition, the amplitude of time domain sound signal which was filtered at the dominant frequency have also show deviating values from 22V to 38V when the defect exist. In another unique study, Sansan et al., [16] implies blind source separation technique which combining principal component analysis (PCA) and independent component analysis (ICA). Through blind source separation analysis, acoustic signal was successfully decomposed into cooling and keyhole component and the existence of blowholes was detected.

As proven from wide variety of studies, there was one similar point could be made whereas the statistical or signal features extracted from the sound acquired from laser welding process significantly giving information on the weld condition. However, a considerable amount of studies were only emphasizing on the use of common statistical features. Owing to the fact that the pulse mode laser welding process possible emitted signal with outliers due to its cyclo-stationary non-linear random behavior, it is vital to explore other analysis that could overcome these drawbacks. Moreover, far too little attention has been paid to the study of sound behavior during the pulse mode laser welding which make it limited to find the appropriate statistical features which could give information with respect to weld condition for this particular type of welding process. In this work, the main aim is to study the L-statistic features trend of the acquired sound amplitude in order to detect the existence of irregularities on the weld bead during the pulse mode laser welding. Basically, L-Cv (Scale), L-Skewness as well as L-Kurtosis was determined from the acquired sound in attempt to identify the most significant features which will determined the weld condition.

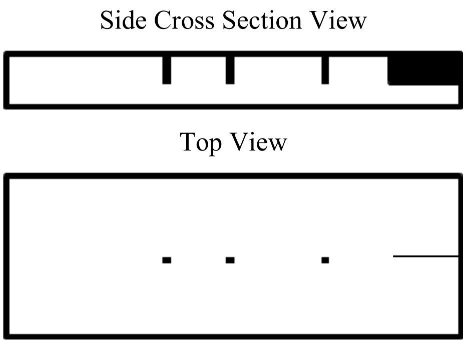
2. Methodology

2.1. Experiment & data acquisition setup

The setup of the experiment was depicted in figure 1(a). In this present work, butt joined weld were done onto the 22MnB5 boron steel plate with the variation of parameters set as shown in table 1. For all setup, welding process was done with the pulse width, speed and pulse repetition rate of 6 ms, 1.5 mm/s and 20 Hz respectively. Meanwhile, pure argon with flowrate of 15L/min was used as a shielding gas in this experiment. As stated in table 1, for some specimen, artificial non-uniformity on the surface of the specimen was set at several locations by creating small scratch at 9 mm, 13 mm and 17 mm as well as big gap from 21 mm further as shown in figure 1(b). This is intently done to create small gap to allow molten metal flow deep further into the weld pool which results in deeper penetration at such point.



(a)



(b)

Figure 1. Experimental setup (a) Test rig setup (b) Specimen non-uniformity location for specimen 3.

While the pulse mode laser welding process were in progress, the sound emitted from the process was acquired using microphone whereas the discretization of the signal engaged in National Instrument (NI) 9234 analog-to-digital converter connected to it with the rate of 25.6 k Sample/s. The discretized sound signal, x (i), for each experiment was analyze as one population of dataset in the next stage.

Table 1. Weld parameter set.

Specimen No.	Focal Length (mm)	Peak Power (W)	Surface Non-uniformity
1	+5	1000	No
2	+5	1600	No
3	-5	600	Yes

2.2. L-Statistical Analysis
Factually, in the analysis of time series signal, x(i) represent the amplitude at the specific time whereas i represent the ith acquired data at the specific time (i = 1,2,3,…,N). Therefore, extracting the statistical feature from x (i) more or less will revealed the trend of amplitude distribution as well as characterizing the signal. In order to avoid the influence of sample variation and local extreme or outliers that took place from the conventional statistical analysis, the L-Statistic analysis as proposed by Hosking [17] was applied in this study. In this work, L-Cv (Scale), L-Skewness and L-Kurtosis was determined from the acquired sound signal by the equation (1) to (3) respectively.

$$L-Cv(Scale)=\frac{2(\frac{1}{n}\sum_{j=2}^{n}x_j[\frac{j-1}{n-1}])-(\frac{1}{n}\sum_{j=1}^{n}x_j)}{(\frac{1}{n}\sum_{j=1}^{n}x_j)} \tag{1}$$

$$L-Skewness=\frac{6(\frac{1}{n}\sum_{j=3}^{n}x_j\left[\left(\frac{(j-1)(j-2)}{(n-1)(n-2)}\right]\right)-6\left(\frac{1}{n}\sum_{j=2}^{n}x_j\left[\frac{(j-1)}{(n-1)}\right]\right)+(\frac{1}{n}\sum_{j=1}^{n}x_j)}{2\left(\frac{1}{n}\sum_{j=2}^{n}x_j\left[\frac{j-1}{n-1}\right]\right)-(\frac{1}{n}\sum_{j=1}^{n}x_j)} \tag{2}$$

$$L-Kurtosis=\frac{20(\frac{1}{n}\sum_{j=4}^{n}x_j\left[\left(\frac{(j-1)(j-2)(j-3)}{(n-1)(n-2)(n-3)}\right]\right)-30\left(\frac{1}{n}\sum_{j=3}^{n}x_j\left[\frac{(j-1)(j-2)}{(n-1)(n-2}\right]\right)+12(\frac{1}{n}\sum_{j=2}^{n}x_j[\frac{j-1}{n-1}])-(\frac{1}{n}\sum_{j=1}^{n}x_j)}{2\left(\frac{1}{n}\sum_{j=2}^{n}x_j\left[\frac{j-1}{n-1}\right]\right)-(\frac{1}{n}\sum_{j=1}^{n}x_j)} \tag{3}$$

3. Results and discussion
As explained in the previous section, L-statistic analysis was done onto the time series of the sound signal which was acquired during pulse mode laser welding process. This was done in order to study the behavior of each of the statistical features with respect to the occurrence of irregularities during the process. On the other hand, this attempt intently made to achieve the main goal in this study which is to detect the irregularities in weld bead by the analysis of the acquired sound signal.

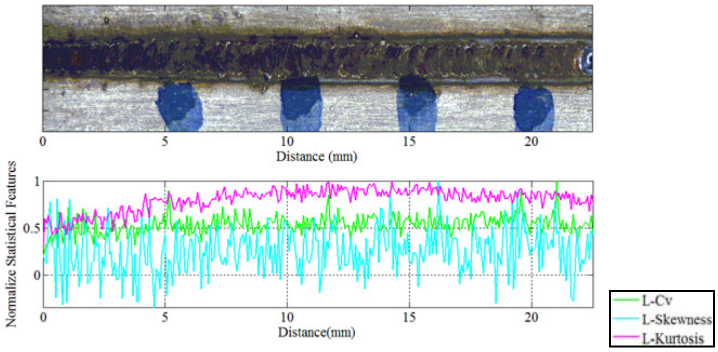


Figure 2. Sound amplitude L-statistic feature trend in respond to the bead surface irregularities during pulse mode laser welding process on specimen 1.

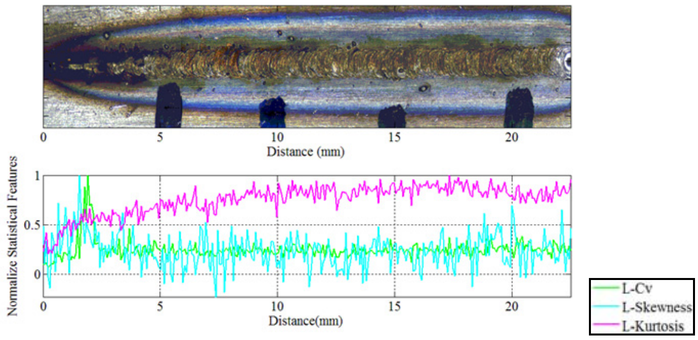


Figure 3. Sound amplitude L-statistic feature trend in respond to the bead surface irregularities during pulse mode laser welding process on specimen 2.

Figure 2 and 3 illustrate the image of weld bead from the top view of specimen 1 and 2 respectively. On the same figures, all the L-statistic features determined from each of the acquired pulse sound was plotted with respect to the weld distance. According to the figures, it was clearly illustrated that the bead diameter was lower at the early stage of welding process. The diameter reaches the steady-state value after it extents to certain value of weld distance. The rate of change in bead diameter was much more obvious for the case of weld process with peak power of 1600W on specimen 2. Moreover, it could be observe that there was large underfill at around 2 mm from the weld starting point on specimen 2. In recent studies, many scholars [18-21], comes into agreement that high laser power would cause an excessive metal evaporation. Simultaneously, the number of spatter would increase due to the large evaporated metal or plasma plume pressure which cause molten metal split out from the weld pool. In the present experiment, the occurrence of spatter might be the reason why the amplitudes of sound were higher at the point where the large underfill presence. Consequently, higher value of both L-Cv and L-Skewness were recorded.

Deep observation into the variation of L-statistic feature in both figure 2 and 3, revealed that the trend of L-kurtosis were much more align with trend of weld bead diameter. For both cases (specimen 1 & 2), L-kurtosis was found recorded small value at the point where the small bead diameter occur. Meanwhile, it reaches consistency in its value when the steady-state bead diameter value was achieved. Uniquely, unlike the L-kurtosis trend, both L-Cv (scale) and L-Skewness variation was found more likely following the condition of the weld bead surface. Results from the analysis show that at the good weld bead surface as obtained from the specimen 2 in figure 3, the variation of L-Cv (scale) were small. However, the L-Cv values spikily increase at the point where the large underfill occurs. On the other hand, when the bead surface was moderately smooth as obtained on the specimen 1 in figure 2, the dispersion of L-Cv value was found much higher. These trends also could be found on L-skewness values but the values variation was larger than L-Cv values.

Despite studying the behavior of sound amplitude with respect to the weld bead surface condition, analysis was also extended in order to study the trend of sound amplitude in respond to the irregularities on the depth of penetration. As described by figure 4, it was clear that L-kurtosis have recorded a significant respond with the change in the depth of penetration as compared to the other two L-statistic features. Based from trend of the plotted L-kurtosis values, it was figured out that the kurtosis value dropped at the point where the irregularities on penetration depth were occurred. According to the findings from several studies in the past [6, 22-24], the amplitude of sound would increase as the depth keep larger. This is due to the reason that high penetration emerged from high power laser which simultaneously increase the amount of evaporated metal. As a result, the amplitudes of sound were also increase and any of its statistical features would literally increase. However, in this study L-Kurtosis was found recorded a small values when deeper penetration was logged at certain point along the weld bead. As explained in the previous section, the artificial gap was created onto the specimen intently to create irregularities on the depth of penetration during welding process. Unfortunately, it was believe that this gap have create the cavity which results in deeper location of weld pool position due to small diameter of laser beam. Consequently, the evaporated metal was oscillating inside the cavity which acts as a sound damper. Hence small amplitude of sound was recorded in this case which results in small value of L-Kurtosis.

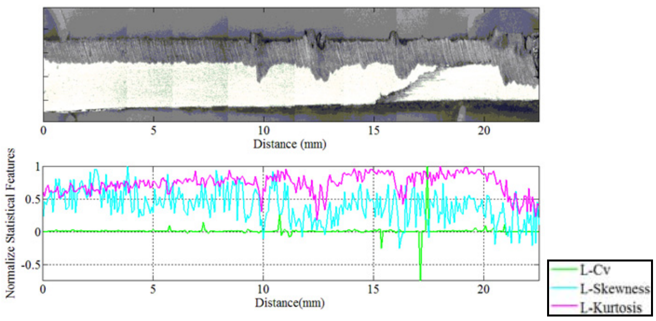


Figure 4. Sound amplitude L-statistic feature trend in respond to the irregularities on penetration depth during pulse mode laser welding on specimen 3.

4. Conclusions

In this particular work, sound signal was acquired during the pulse mode laser welding in attempt to study its L-statistical feature trend with respect to the occurrence of irregularities on the weld bead. As summary of this work, L-Cv (scale) was found giving a significant indicator of the weld bead surface condition. Meanwhile, L-kurtosis values could give noteworthy information on the existence of the irregularities on bead width and depth. Hence, it could be conclude that the irregularities on the weld bead during the pulse mode laser welding could be detected from the acquired sound signal. This could be done from the L-statistical analysis onto the acquired sound. However, the selection of appropriate L-statistical features is vital due to the findings which show that different feature will give different type of information regarding the irregularities on the weld bead.

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