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Detection of defects on weld bead through the wavelet analysis of the acquired arc sound signal

M.F.M. Yusof*, M.A. Kamaruzaman, M. Zubair and M. Ishak

Faculty of Mechanical Engineering, Universiti Malaysia Pahang,
26600 Pekan, Pahang, Malaysia
*Email: fadhlan@ump.edu.my
Phone: +6094246319; Fax: +6094246222

ABSTRACT

Recently, the development of online quality monitoring system based on the arc sound signal has become one of the main interests due its ability to provide the non-contact measurement. Notwithstanding, numerous unrelated-to-defect sources which influence the sound generation are one of the aspects that increase the difficulties of applying this method to detect the defect during welding process. This work aims to reveal the hidden information that associates with the existence of irregularities and porosity on the weld bead from the acquired arc sound by applying the discrete wavelet transform. To achieve the aim, the arc sound signal was captured during the metal inert gas (MIG) welding process of three API 5L X70 steel specimens. Prior to the signal acquisition process, the frequency range was set from 20 Hz to 10 000 Hz which is in audible range. In the next stage, a discrete wavelet transform was applied to the acquired sound in order to reveal the hidden information associated with the occurrence of discontinuity and porosity. According to the results, it was clear that the acquired arc sound was not giving an obvious indication of the presence of defect as well as its location due to the high noise level. More interesting findings have been obtained when the discrete wavelet transform (DWT) analysis was applied. The analysis results indicate that the level 8 of the approximate and detail wavelet coefficient have given a significant sign associated with the presence of irregularities and porosity respectively. Moreover, despite giving the information on the surfaces pores, the detail wavelet coefficient was found to give a clear indication of the sub-surface porosity formation during welding process. Hence, it could be concluded that the hidden information with respect to the occurrence of discontinuity and porosity on the weld bead could be obtained by applying the discrete wavelet transform.

Keywords: MIG welding, sound signal, discrete wavelet transform.

INTRODUCTION

In the oil and gas industries, welding is one of the major joining processes which received a lot of attention. This process is vital because many catastrophic failures in the gas pipeline system were reported to initiate from the welding defect [1-3]. For that reason, the advancement of welding technology has been increasing rapidly since the past few decades in order to improve the strength of the joined part, reduce risk as well as increase productivity. This was made through the studies related to the optimization of welding parameter as well as the strength analysis of the welded part [4-9]. In industries, welding is done according to the general procedures and standard in order to avoid the welding defect. However, the welding defect could still exist due to the uncertainties that occur during the process. Due to that reason, many studies were done to find the potential development of the online welding monitoring system due to the fact that it could offer a greater control during the process. According to Grad et al., the online quality monitoring is believed to be an influential factor contributing to higher productivity, lower cost and greater reliability of the welded components even though it is still not established in industries. Literally, many studies have been conducted in attempt to find the potentially fast and robust method to detect and localize the defect during welding process. Based on previous studies, defects such as cavity, linear porosity, gas pores and slag inclusion could be detected using methods such as the ultrasonic testing [10, 11], acoustic emission [12], x-ray radiography [13-16], and arc spectroscopy [17, 18]. In spite of the ability of these methods, it also has some limitations. For instance, the application of ultrasonic testing can only provide information on the vicinity of the scanned area, and when it comes to measuring the whole area, it is definitely time consuming. Meanwhile, the application of the acoustic emission technique might be laborious due to the structure-borne nature of the signal which consequently makes it difficult to be applied on a hardly-accessed area. Comparing to the ultrasonic and acoustic emission methods, the x-ray radiography and arc spectroscopy have shown greater potential in detecting defect during welding process. However, in some cases, the application of x-ray radiography could be subjective and time consuming [15] while the accuracy of the arc spectroscopy method depends on the process behaviour [19]. Unlike other methods, the detection of defect using the arc sound can be considered as a more unique method because it is simple and promotes a non-contact measurement. This factor increased the researcher’s interest to obtain a deeper understanding of this method.

Based on the past studies, the detection of defect from sound signal was done based on the understanding of several phenomena such as the weld pool metal vibration [20, 21], arc plasma jet pulsation [22], change in arc intensity [20] and metal transfer [23] because these are the possible sources of the sound generated during the welding process. However, it is important to understand that the sound signal is not only created from these sources but also non-damage-related sources. You et al. [19] in their study reported that the limitation in applying this method is the harsh surrounding where it contributes to the higher noise in the acquired signal. Previously, many studies show that the signal processing method was able to reveal the defect-related information from the acquired arc sound. For example, Wang et al. [21] used the short time Fourier transform in order to decompose the acquired arc sound signal and select the related decomposed component for further analysis. They reported that this method was significant in monitoring the keyhole status and the analysis results show a good agreement with the presence of irregularities on the weld bead. In another study, Hong Luo et al. [24] used wavelet transform to analyse the acquired sound from laser welding. In that study, the intensity of the decomposed signal was found to give a clear relation with the existence of defects. On the other hand, signal processing is applied to extract the signal features instead of decomposing it. In works related to this approach [20, 22, 23], the extracted features were found to show a clear correlation to the phenomena that occur during the process. According to the findings, it could be summarized that the use of sound signal can provide a significant result in detecting several types of defect, as well as monitoring some phenomena during the welding process in order to prevent the formation of defect. However, in most of the reported findings, the exploration of this method was limited to several types of defect. Moreover, only small number of studies highlighted the identification of defect based on the arc sound signal pattern. To ensure that this method can be further developed, it would be more significant if a wide variety of defects can be detected and identified through this method, especially the more severe types such as porosity and inclusion underneath the weld bead. Thus, the application of the signal processing method is helpful due to its ability to remove the unwanted noise which consequently hides the information associated with the existence of defect. This has been proven by some researchers. Nonetheless, the signal processing approach is still not broadly applied in this case. The study of the signal analysis method as the pre-processing technique is important in the attempt to optimize the capability of detecting and localizing multiple types of defect in a single measurement.

In this paper, the aim is to study the application of the discrete wavelet transform in revealing the hidden information associated with the existence of irregularities and porosity in the weld bead from the acquired arc sound. In the first stage, the arc sound signal was acquired during the welding process of an API 5L X70 gas pipeline steel using a Metal Inert Gas (MIG) welding. Then, the DWT was applied on the acquired arc sound and the selected decomposition product in the form of detail and an approximate coefficient which was found relatively related to the presence of irregularities and porosity will be discussed.

EXPERIMENTAL SET UP

Experimental Procedures

The arrangement of instruments in this experiment is shown in Figure 1. Basically, the instrumentation system in this project consists of the PCB Electronics microphone with the bandwidth from 20 Hz to 10,000 Hz. Based on previous findings [21-25], the information of defect could be obtained within this range. To acquire the signal the National Instrument Analogue-to-Digital Converter Model NI9234 was used due to its ability to provide suitable sampling frequency for this experiment. Meanwhile, a PC was used as a signal analyser unit. Prior to the experiment stage, the sampling frequency of data acquisition was set to be 25.6 kSamples/s. Welding parameters were set according to the values shown in Table 1. These parameters were based on the recommendation in the technical specification sheet from the filler wire manufacturer. The filler wire used in this experiment was E70RS-6 carbon steel. The selection was made based on the chemical composition in which it was slightly similar to the based metal (specimens) used in this experiment. The specimen used in this project was API 5L X70 grade carbon steel with the dimension of 40 mm x 70 mm x 4 mm each side.

Table 1. MIG welding parameters.

Specimen	Voltage	Current	Welding Speed (mm/s)	Shielding Gas (pure Argon) Flow rate (L/min)
1	24	200	5	15
2	24	170	3	7.5
3	23	165	4	10

In an attempt to avoid human error, the automated MIG welding was used in this experiment. During the welding process, the specimen on the railed clamp was moved in accordance with the welding speed which was set in the prior stage and a microphone was attached to the welding torch to ensure the distance from the area of metal transfer was kept constant.

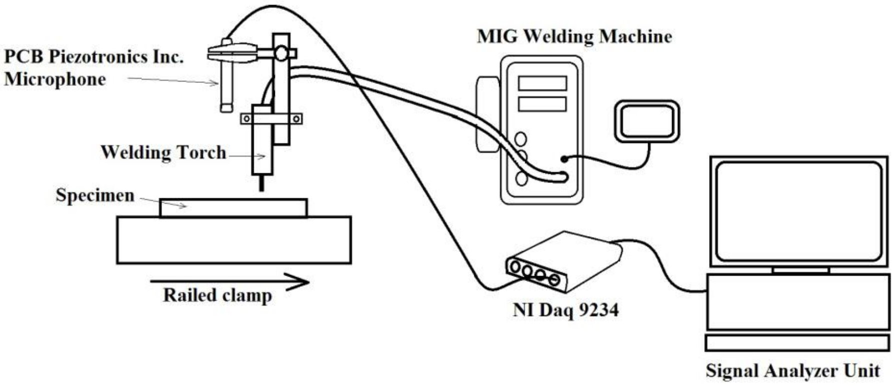


Figure 1. Experiment setup.

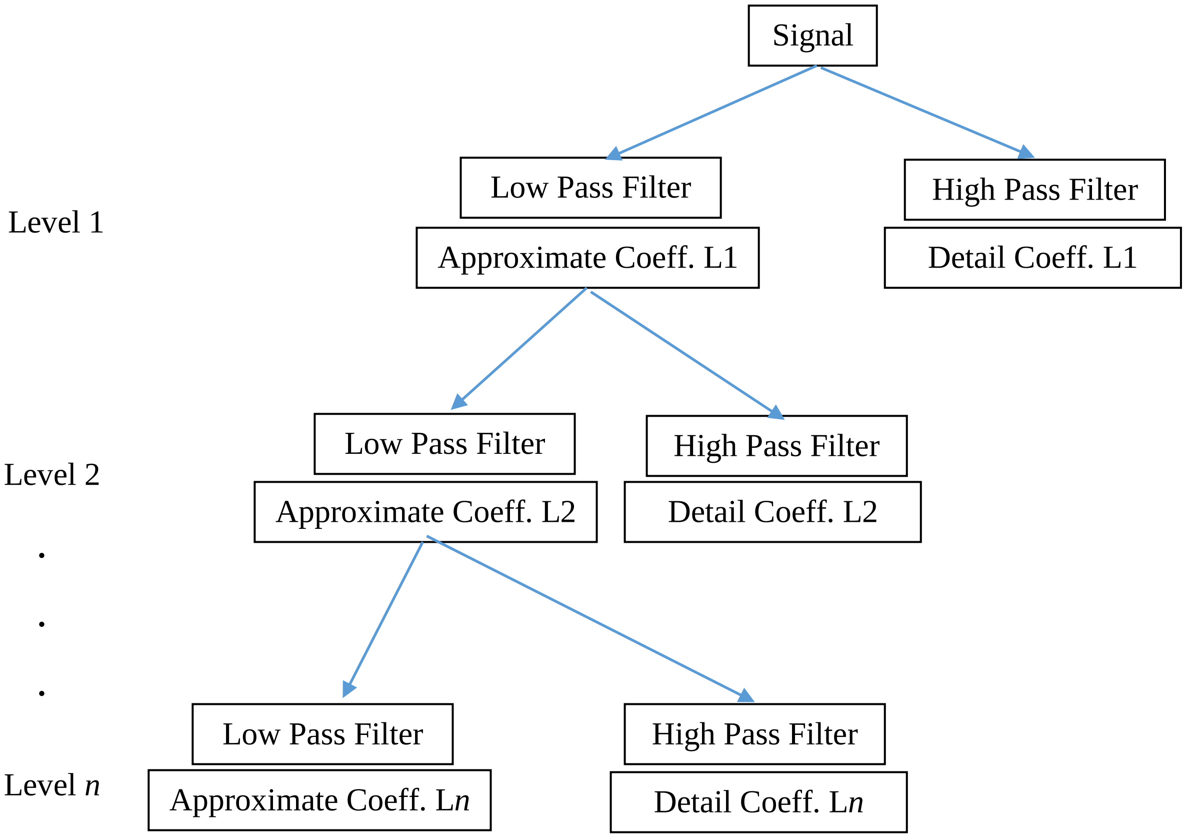


Figure 2. Discrete wavelet transform.

Discrete Wavelet Transform

Basically, the wavelet transform (WT) turn out to be one of the best decomposition methods because it can cater time scale information of a signal enabling the extraction of features that vary in time. This feature makes wavelet an ideal tool for analysing the signal of a non-stationary nature [26]. As proposed by [27] and represent in Eq.(1), the continuous wavelet transform (CWT) of $f(t)$ is the sum over all time of the signal multiplied by scale, shifted versions of the wavelet functions $\Psi(t)$.

$$CWT\ (a,b) = \frac{1}{\sqrt{|\alpha|}} \int_{-\infty}^{\infty} f(t)\Psi^{*}\left(\frac{t-b}{a}\right) dt \tag{1}$$

where *Ψ (t), α,* and *b* denotes the mother wavelet, scale index and time shifting respectively. Meanwhile, the DWT was derived from the discretization of CWT (*a, b*) and the most common discretization was dyadic given by [26] as,

$$DWT\ \ (j,k) = \frac{1}{\sqrt{2^{j}}} \int_{-\infty}^{\infty} f\ (t)\Psi^{*}\left(t - \frac{2^{j}k}{2^{j}}\right) \tag{2}$$

Whereas [26] proposed a and b to be replaced by 2^{j} and 2^{k}. In 1989, [28] found a persuasive way to apply this method using filters. The $f(t)$ passed through two complementary filters and emerged as the low- and high-frequency signals. The decomposition may be iterated with the successive approximations began to decompose in turn, so that the signals may be broken down into the lower resolution components as illustrated in Figure 2.

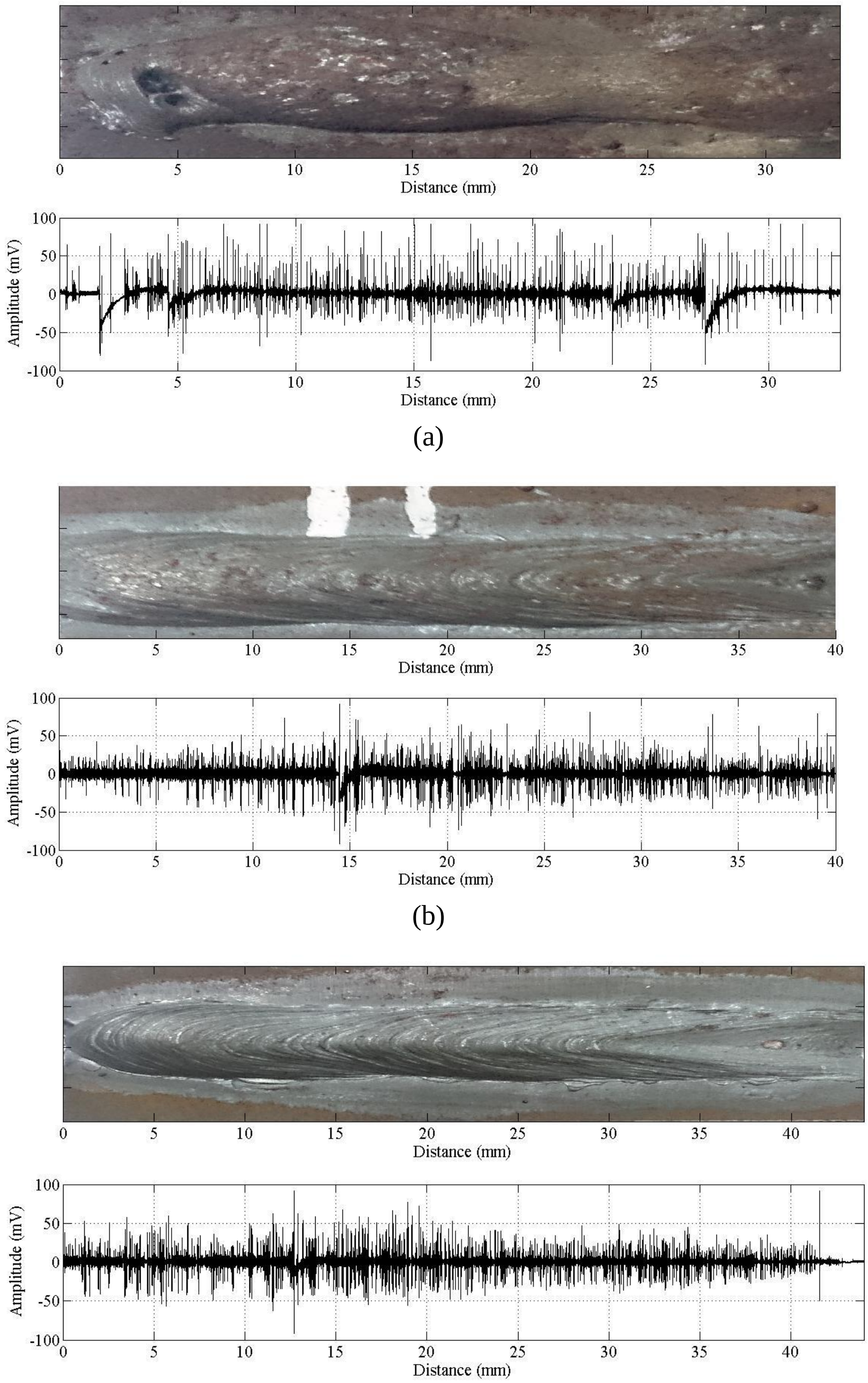
RESULTS AND DISCUSSION

Acoustic Signatures Acquired During Welding Process

The captured acoustic signatures in the distance domain from the welding process for all specimens are shown in Figure 3. Basically, the time domain series was converted into distance domain according to the welding speed for each of the specimen. Based on the result in Figure 3(a), it was clear that there were uncertainties in the pattern of the acquired arc sound at around 2mm to 5mm and 27mm from the initial point. Conforming to the image of the weld bead in the same figure, the uncertainties occurred at the region where irregularities in the weld bead shape exist. Moreover, the surface pores were found at around 2 mm from the initial point. In Figures 3(b) and (c), the same pattern of arc sound could be observed when the irregularities in the weld bead shape existed though no porosity was found for both cases. Overall, even though the acquired arc sound signal gave a sign of the existence of irregularities on the weld bead, the signal itself was influenced by the high amount of noise. As a result, the uncertainties in the signal were barely clear to be seen. As explained in the earlier literatures, this phenomenon commonly occurs if sound is used as a medium to monitor the welding process due to the fact that the process itself undergoes harsh surrounding [19, 21]

Detection of Irregularities of the Weld Bead

Based on the results in the previous section, it was observed that the physical patterns of the arc sound at the location where the defect existed were unclear. Hence, it was significant to decompose the signal into several frequency components to entirely reveal the hidden signal abnormalities associated with the defect formation during welding process. The decomposition result from the discrete wavelet transform (DWT) is shown in Figures 4 and 5. Figures 4(a), 4(b), and 4(c) present the plot of approximate wavelet coefficients level 8 over the distance for specimens 1, 2, and 3, respectively.

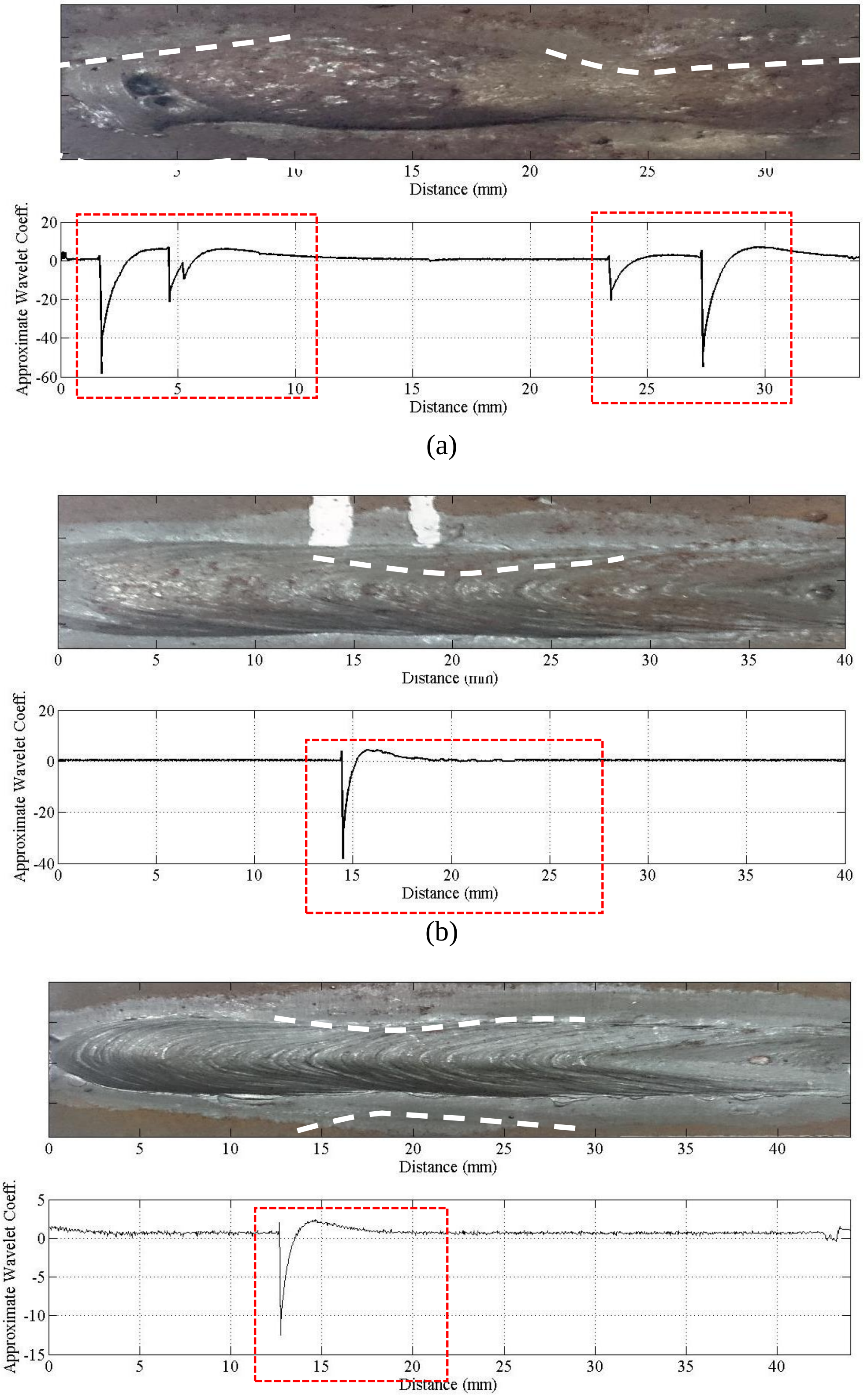


(a)

(b)

(c)

Figure 3. The acquired sound signal during welding process
(a) Specimen 1 (b) Specimen 2 (c) Specimen 3.



(a)

(b)

(c)

Figure 4: Level 8 approximate wavelet coefficient of a decomposed arc sound signal during welding process of (a) Specimen 1, (b) Specimen 2, and (c) Specimen 3

Overall, it was found that the level 8 approximate wavelet coefficient gave a better trend with respect to the irregularities of the weld bead shape as compared to the raw signal. For instance, the decomposition result of the acquired sound from specimen 1 showed that there was a clear transient-shape trend from 1.65 mm to 4.28 mm, 4.6 mm to 15mm, 23.35 mm to 26 mm, and 27.3 mm to 33 mm. Comparing to the trend of the arc sound before the decomposition, the uncertainties were not found at around 23mm. This showed that the decomposition process was significantly aided in revealing the hidden information with respect to the defect. Similar result trend also were recorded in Figures 4(b) and (c) whereas the transient shape signal was found from 14.43 mm to 23.7 mm, and 12.68 mm to 20.45 mm respectively. The weld bead irregularities were also found as the result was compared to the weld bead image in the same figure. Overall, the results presented in Figure 4 obviously show that the irregularities on the weld bead shape can be significantly correlated with the occurrence of the transient shape of the decomposed sound signatures. It was estimated that the transient shape signal produced by the arc sound was associated with the instability of weld pool oscillation due to the existence of surface tension force or Marangoni force. According to the previous finding [29], it was reported that this force has led to the irregularities in the weld bead. This happens because the exerted force tends to make the molten metal flow away from the desired area and cause discontinuity to occur [30]. Mendez [29] defined this as the split bead. As illustrated by Figure 2, the approximate coefficient obtained from the discrete wavelet transform was from the lower frequency component. This shows good agreement with what reported by Wang et al. [21]. In a previous study, Wang et al. [21] summarized that the weld pool status could be significantly monitored from the lower frequency component of the acquired arc sound signal.

Detection of Porosity

As illustrated in Figure 3(a), the result for specimen 1 shows the presence of several numbers of porosity on the surface. Unlike discontinuity, in this study, the porosity phenomenon was found to be highly related with the detail wavelet coefficient level 8. This was evident whereas the plot of level 8 details wavelet coefficient in Figures 5 and Figure 6 show a significant correlation with the presence of both surface and sub-surface porosity. Basically, the image of subsurface porosity was obtained after the specimen was grounded. As shown in Figure 5(a), the small burst signatures were found at around 3 mm, 5 mm, 23 mm and 27 mm from the starting point. Comparing to the weld image in Figure 5(b), the surface porosity was found at around 3 mm and 5 mm which were the same spots where the burst signature occurred. In contrast, there was no clue to the existence of porosity at around 23mm and 27mm. However, the subsurface pores were found around both spots after the specimen was grounded by 2.84 mm and 4.15 mm. The similar trends were also recorded for the decomposed signal for specimen 2 in Figure 6. In Figure 6(a), it could be observed that the burst signatures appeared at the spot where the small sub-surface was found after the specimen was grounded by 4.87 mm. This was confirmed by the grounded weld image shown in Figure 6(b). In contrast with other specimens, no porosity was found in specimen 3. Overall, it could be summarized that the burst signatures appeared in the detail wavelet coefficient gave a significant sign of the existence of both surface and sub-surface porosity. The detail observation led to the findings that the spot where the burst signatures appeared in the detail wavelet coefficient were actually the same spots where the transient shape signature occurred. According to [30], both the surface and sub-surface porosities could occur from the entrapped insoluble air during the welding process. This entrapment happened when the convection pattern was in the downward direction as the Marangoni force occurs. As explained in the previous section, the transient shape signatures are believed to be relatively associated with the weld pool instability due to the existence of Marangoni force. Hence, it was estimated that the burst type signal occurred due to the Marangoni force itself which consequently caused the high energy amplitude to occur instantly.

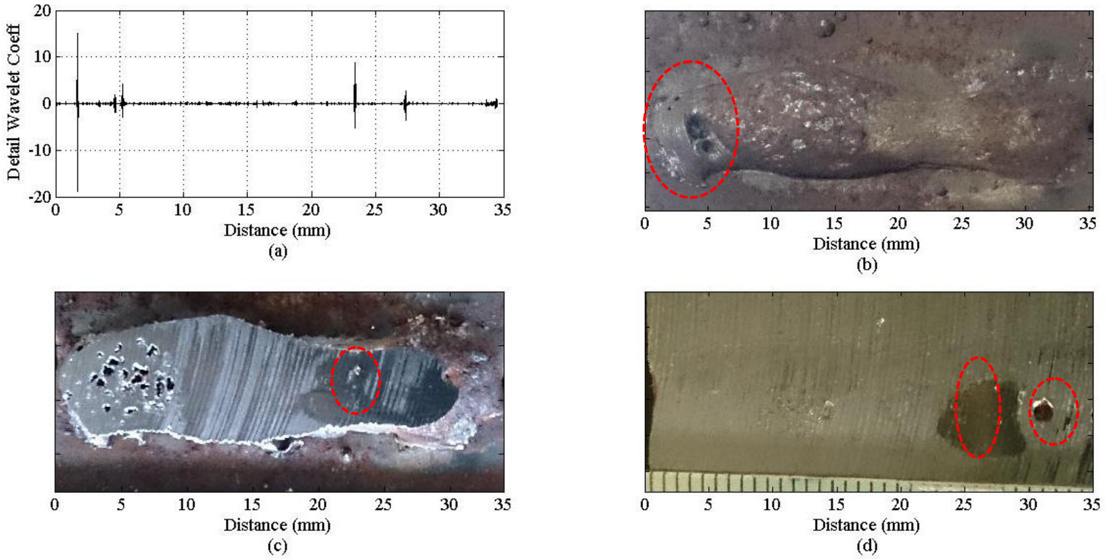


Figure 5. Level 8 detail wavelet coefficient of a decomposed arc sound signal during welding process of Specimen 1 (a) Level 8 detail wavelet coefficient, (b) Weld bead image, (c) Specimen grounded by 2.84 mm, and (d) Specimen grounded by 4.15 mm.

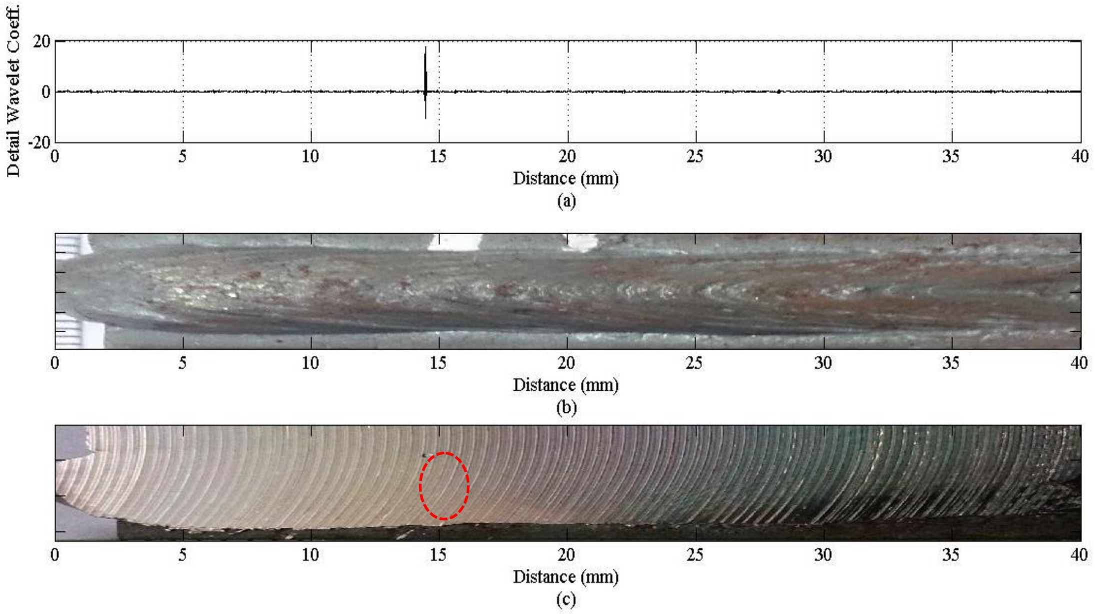


Figure 6. Level 8 detail wavelet coefficient of a decomposed sound signal during the welding process of Specimen 2 (a) Level 8 detail wavelet coefficient, (b) Weld bead image, and (c) Specimen grounded by 4.87 mm.

CONCLUSIONS

In accordance with the results, the sound signal was successfully acquired from the welding process of the API 5L X70 steel. As illustrated in the beginning part, the acquired arc was influenced by the high amount of noise which caused the noticeable sign of defect almost hidden. After applying the discrete wavelet transform, it was clearly shown that the approximate wavelet coefficient gave obvious significant pattern related to the weld pool instability which led to the irregularities in the weld bead shape. Meanwhile, the small burst appeared in the detail wavelet coefficient plot gave a significant alarm of the existence of both surface and sub-surface porosities. Thus, it could be concluded that the application of discrete wavelet transform was significant in revealing the hidden information associated with the existence of discontinuity and porosity of the acquired sound signal. However, several limitations need to be improved in future. In this work, the estimation of the phenomena leading to the defect formation during the welding process was from both literature and result trend basis. Nevertheless, it is more significant if the image from the high speed camera could be used to confirm the estimation. Moreover, the development of the mathematical model for the sound generation from the phenomena that occur during the welding process might be useful to get earlier estimation of the result.

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