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Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 2009 223: 343
DOI: 10.1243/09544054JEM1320

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The manuscript was received on 5 August 2008 and was accepted after revision for publication on 18 December 2008.

DOI: 10.1243/09544054JEM1320

Abstract: It is a trend to use high-strength steels in the automobile industry because of their good formability, weldability, and high strength–volume ratio. In order to achieve quality control, it is necessary to monitor the welding process online. In this paper, acoustic signals generated during the laser welding process of high-strength steel DP980 were recorded and analysed. A microphone was used to acquire the acoustic signals. A spectral subtraction method was used to reduce the noise in the acoustic signals, and a Welch–Bartlett power spectrum density estimation method was used to analyse the frequency characteristics of the acoustic signals. The results indicate that good welds with full penetration (FP) could be clearly distinguished from bad welds with partial penetration (PP). An algorithm based on the different sound pressures between FP and PP was developed to identify the penetration state in the time domain. Another algorithm based on the different frequency characteristics from 500 to 1500 Hz between FP and PP was also developed to differentiate the penetration state. The results show that these two algorithms can effectively distinguish FP from PP. In addition, the mechanisms of the different characteristics of the acoustic signal generated from different penetration depths and modes were also analysed and discussed. This study shows that it is feasible to use acoustic signals to achieve online monitoring of the penetration states during the laser welding of high-strength steel DP980 in a noisy environment by applying proper digital signal processing methods. The acquired acoustic signal could be used as a feedback signal to control the depth of weld penetration in the laser welding process.

Keywords: laser welding, acoustic signal, noise reduction, depth of weld

1 INTRODUCTION

In recent years, more and more applications for high-strength steels have been found in the automotive industry. Compared with common steels, high-strength steels not only have greater strength, which can significantly improve a vehicle's crash performance and service life, but also have better formability and weldability. The laser welding of high-strength steels, instead of arc welding, has also attracted the attention of the automotive industry because it has several advantages such as deep penetration, a high depth–width ratio, a high welding speed, and low distortion. However, during the laser welding process, different types of weld defect are produced, and as a result the overall quality of the welds is greatly degraded. Therefore, it is necessary to identify the presence of defects at their inception by monitoring the process online and to achieve quality control during the laser welding process of high-strength steels.

As a primary concern in industry, the detection of defects by online monitoring must be fast, reliable, flexible, and cost effective in a hostile industrial environment [**1**]. Different online monitoring systems in the laser welding process are being developed to inspect weld defects and achieve quality control. Laser welding emits strong radiation which can partially indicate the state of the welding process

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with the use of optical sensors. Infrared (IR) photodiodes and ultraviolet (UV) photodiodes were used by Park *et al.* [**2**] to investigate the plasma and spatter during CO_2 laser welding. Zhang *et al.* [**3**] also used optical sensors to investigate the relationship between the IR/UV signals and the weld quality during underwater laser welding. UV radiation is strongly correlated with plasma, so studying plasma through UV sensing can help to gain a better understanding of the inside mechanisms of keyhole formation and effectively monitor the weld penetration. Rockstroh and Mazumder [**4**] used UV spectroscopic analysis to study plasma during laser–material interaction. While optical sensors are capable of detecting keyhole formation and weld penetration, there are also some other sensor systems that have been developed for online monitoring of the laser welding process, such as the electromagnetic acoustic transducer [**5**], polyvinylidene fluoride sensors [**6**], and the CMOS camera [**7**]. Among the different sensors, acoustic sensors draw the most attention both from academia and from industry owing to their non-contact and low-cost features.

Acoustic sensors include a structure-borne acoustic emission (AE) sensor and an airborne acoustic sensor. A structure-borne AE sensor, usually a piezoelectric transducer, can be used for those AE signals in the frequency range 50–900 kHz. Although the structure-borne AE sensor has a high sensitivity to detect interior macroscopic flaws such as cracks, porosity, spatters, and weld penetration [**1**], its requirement to be attached to the workpiece greatly limits its broader application. In contrast, the airborne acoustic sensor, which is typically a microphone mounted near the welding zone, does not have such a limitation. Generally, airborne acoustic sensors can detect acoustic signals with a human audible frequency range from 20 Hz to 20 kHz. The acoustic signals detected by airborne acoustic sensors contain the sound pressure and frequency information of a sound wave, produced by vibration and then transmitted from the source of the vibration to the airborne acoustic sensor through the air. The pressure and frequency information of the sound wave is detected by the acoustic sensor and then transformed into an electric signal. As shown in Fig. 1, during the laser welding process, the airborne acoustic signal, which contains the sound pressure and frequency content of the sound wave from the welding zone, reflects the changes in pressure produced by molten pool pulsation, plasma generation, thermal stress, metal vapour, and keyhole oscillation [**1**]. By monitoring the acoustic signals produced during the laser welding process, the status of the molten pool, the generated plasma, the vaporized metal, and the keyhole, reflecting the status of the weld, can be obtained.

Previous work on the acoustic signal from laser welding can be traced back to Shimada *et al.* [**8**]. They used a microphone to inspect and evaluate the penetration in laser welding and drew the conclusion that penetration can be monitored by measuring the sound pressure level. Mombo-Caristan *et al.* [**9**] were the first to use a frequency method to analyse acoustic signals. Gu and Duley [**10–12**] investigated the acoustic signals from laser welding in depth. They found that a strong energy emission was observed at the high-order harmonics of the laser modulation frequency that corresponds to the eigenmodes of a keyhole. A statistical approach was also developed by them to predict weld quality, based on a comparison between real-time acoustic spectra during laser welding of mild and galvanized steel sheets. Gu and Duley also found that different locations of microphones gave different accuracy in predicting the quality of welds, while acoustic monitoring alone had difficulty in identifying the change in keyhole penetration depth. Farson *et al.* [**13**] investigated the

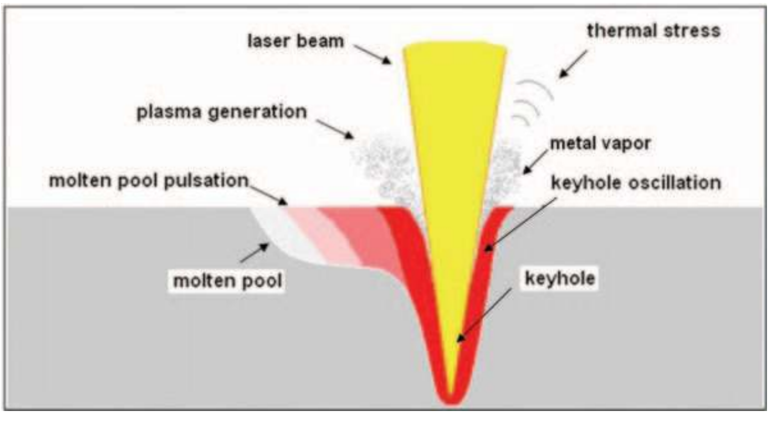


Fig. 1 Mechanisms of sound pressure generation during laser welding

acoustic signals from laser lap welds in stainless steel sheets and concluded that poor-quality welds and good-quality welds can be distinguished on the basis of the acoustic energy in the frequency range 1–2 kHz. In addition to researches on acoustic monitoring for laser welding, the acoustic signals from the gas–metal arc welding (GMAW) process have also been investigated in depth. Grad *et al.* [**14**] studied the acoustic waves produced by GMAW, and the results indicated that the arc sound exhibited distinct characteristics for each welding situation and that the main source of acoustic waves in short-circuit metal transfer mode was arc reignition. Cudina and Prezelj [**15**] investigated two noise-generating mechanisms during the GMAW process, and a new algorithm based on the measured welding current was developed to calculate the emitted sound during the welding process. The calculated values were in good agreement with the measured values of the sound signal. However, in terms of laser welding, although previous studies have shown that acoustic signals can be effectively used to monitor the laser welding of mild steel, stainless steel, and galvanized steel, there is limited literature on the study of acoustic signals during the laser welding of high-strength steels. In addition, approaches developed by previous researchers did not consider or analyse the effects of noise, which is the greatest obstacle to broader application of microphones in the welding industry. Because acoustic sensors are very difficult to use in a noisy and hostile environment [**16**], it is necessary to apply noise reduction methods in order to overcome this limitation. By applying a noise reduction method, the quality of the acoustic signal is greatly improved. Thus, a more accurate analysis of the acoustic signal and effective quality control of laser welding become possible.

The objective of this study was to investigate the feasibility of using the signatures of acoustic signals for the online monitoring of the laser welding process. A microphone was used to acquire the acoustic signals during the laser welding of high-strength steel DP980 in a lap-joint configuration. By applying the spectral subtraction noise reduction method [**17**], the signals of interest were purified in a noisy environment, and their characteristics in the time domain were analysed. Meanwhile, by using the Welch–Bartlett power spectrum density estimation method [**18**], the frequency properties of the acoustic signals were also analysed. Based on these analyses, two algorithms, one in the time domain and the other in the frequency domain, were developed to process the denoised acoustic signals and extract useful information pertaining to the penetration state of the welds.

2 EXPERIMENTAL SET-UP AND EXPERIMENTAL METHOD

2.1 Experimental set-up

The experimental set-up for the laser welding system used in this study to record, process, and analyse the acoustic signals is shown in Fig. 2. A 4 kW fibre laser mounted on a six-axis robot was used for the heat source. A free-field microphone was set at a distance of 22 cm from the incident position of the laser beam, with an inclination of 45° with respect to the worktable. A data acquisition (DAQ) system coupled with the Sound and Vibration Assistant software kit was used to record the acoustic signals. The sampling rate of the DAQ system was set at 50 kHz so that the frequency content of the acoustic signals between 20 Hz and 20 kHz could be recorded and studied according

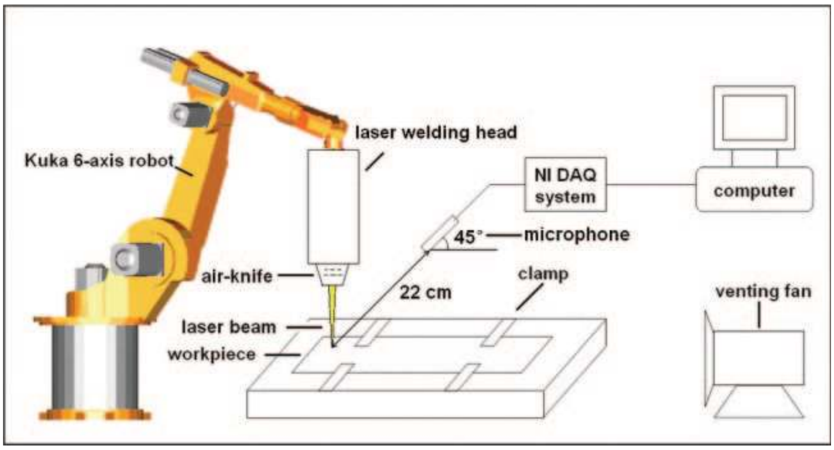


Fig. 2 Schematic diagram of the experimental set-up

to the Nyquist–Shannon sampling theorem. The workpiece in this study was galvanized high-strength dual-phase steel DP980 with a thickness of 1.5 mm. The workpiece was arranged in a lap-joint gap-free configuration, while the zinc coating at the interface was mechanically removed to avoid instability during the welding process. Argon with a flowrate of 30 SCFH was used as the shielding gas, while compressed air was used as an air-knife to protect the lens from spatters in the laser welding head. To vent the fume and vapour produced during the laser welding process, a venting fan was placed in the vicinity of the worktable. The noise from the background is the main obstacle to successful use of a microphone in a hostile industrial environment. In this experimental set-up, the venting fan and the air-knife were the main sources of noise that contaminated the acoustic signal generated from the laser welding of high-strength steel DP980.

2.2 Experimental method

To investigate different characteristics of the acoustic signals between good welds with full penetration and bad welds with partial penetration, different welding parameters were set in five experiments. The heat input, the most important factor deciding the welding results, is determined by laser power and welding speed. Therefore, these two parameters were varied to achieve welds with different penetration states. The parameters for the five experiments are shown in Table 1.

Both experiment 1 and experiment 2 were designed to achieve full penetration and partial penetration separately by setting different laser powers and welding speeds. Experiment 3 investigated the relationship between the depth of weld penetration and the acoustic signals. In experiment 4, full penetration and partial penetration were achieved under the same laser power but different welding speeds in a single laser welding procedure. Experiment 5 consisted of 28 experiments carried out under different laser powers and welding speeds. By analysing the results of these 28 experiments, the mechanisms of the different characteristics of the acoustic signals generated from different penetration depths and modes were determined.

3 DIGITAL SIGNAL PROCESSING OF ACOUSTIC SIGNALS

3.1 Noise reduction method

As an important subject that has been researched in many different fields, noise reduction draws much attention from both academia and industry. The noise reduction method can be used to reduce noise of the signal acquired in a noisy environment while enhancing the signal-to-noise ratio (SNR). The improvement in the quality of desired acoustic signals can bring sizable benefits to many fields. In the welding industry, which is usually a noisy environment, a noise reduction method is of great importance to online monitoring and quality control if airborne acoustic sensors are used. In order to investigate the effects of noise on the acoustic signals of interest during the laser welding of DP980 steel, the noise produced by the venting fan, the air-knife, and the robot was studied in this study. Spectral subtraction, as a traditional noise reduction method, can be traced back to 1979 when Boll [**17**] used it to suppress acoustic noise in speech by estimating the noise spectrum from regions that were noise only and subtracting that noise spectrum from the spectrum of the noisy signal. The algorithm of the spectral subtraction method can be briefly described by the equations below.

1. Let $x(k)$, $s(k)$, and $n(k)$ denote respectively the original signal, desired signal, and noise signal in the time domain

$$x(k) = s(k) + n(k) \tag{1}$$

2. Transform the original signal $x(k)$ into the frequency domain by fast Fourier transform (FFT)

$$X(\mathrm{e}^{\mathrm{j}w}) = S(\mathrm{e}^{\mathrm{j}w}) + N(\mathrm{e}^{\mathrm{j}w}) \tag{2}$$

where

$$X(\mathrm{e}^{\mathrm{j}w}) = |X(\mathrm{e}^{\mathrm{j}w})|\mathrm{e}^{\mathrm{j}\theta_X} \tag{3}$$

$$S(\mathrm{e}^{\mathrm{j}w}) = |S(\mathrm{e}^{\mathrm{j}w})|\mathrm{e}^{\mathrm{j}\theta_S} \tag{4}$$

$$N(\mathrm{e}^{\mathrm{j}w}) = |N(\mathrm{e}^{\mathrm{j}w})|\mathrm{e}^{\mathrm{j}\theta_N} \tag{5}$$

Table 1 Laser welding parameters in different experiments

	Laser power (W)	Welding speed (mm/s)	Workpiece dimensions (mm × mm × mm)
Experiment 1	3500/2500	30	200 × 40 × 1.5
Experiment 2	3000	20/40	200 × 40 × 1.5
Experiment 3	3000	30	200 × 40 × 1.5
Experiment 4	3500	30/35/40/45	300 × 50 × 1.5
Experiment 5	2500/2750/3000/3250/3500/3750/4000	30/40/50/60	200 × 40 × 1.5

$|X(e^{jw})|$, $|S(e^{jw})|$, and $|N(e^{jw})|$ are the magnitudes of the transformed signals, and θ_X, θ_S, and θ_N are the phases of the transformed signals.

3. To obtain an estimate of the noise spectrum, the magnitude $|N(e^{jw})|$ is replaced with its average value $|\mu(e^{jw})|$, which can be measured during the time of noise only. In this study, the average magnitude of the transformed noise signal is calculated from the acquired noise signal before laser welding. The phase of the transformed noise signal θ_N is replaced with θ_X. Therefore, in equation (2), the transformed noise signal can be represented as $|\mu(e^{jw})|e^{j\theta_X}$.
4. According to equation (2), the desired signal in the frequency domain can be written as

$$S'(e^{jw}) = |X(e^{jw})|e^{j\theta_X} - |\mu(e^{jw})|e^{j\theta_X} = (|X(e^{jw})| - |\mu(e^{jw})|)e^{j\theta_X} \quad (6)$$

5. Transform $S'(e^{jw})$ back into the time domain by inverse FFT and the denoised signal is obtained

$$s'(k) = \frac{1}{2\pi}\int_{-\pi}^{\pi} S'(e^{jw})e^{jwk}dw \quad (7)$$

By applying spectral subtraction, the main errors committed by the approximations come from the replacement of $|N(e^{jw})|$ with its average value $|\mu(e^{jw})|$ and the subtraction of $|\mu(e^{jw})|$ from $|X(e^{jw})|$. For the spectral subtraction method, the property of the noise is always assumed to remain relatively stationary during the data acquisition process. Therefore, $|N(e^{jw})|$ can be replaced with its average value $|\mu(e^{jw})|$ if this assumption holds. This assumption was tenable in the present experiments because the background noise did not change. However, this method may have limitations in an industrial environment with complex and unstable noise sources, where $|N(e^{jw})|$ cannot be accurately replaced with its average value $|\mu(e^{jw})|$. The other error could come from the subtraction of $|\mu(e^{jw})|$ from $|X(e^{jw})|$. When $|X(e^{jw})|$ is smaller than $|\mu(e^{jw})|$ at some frequencies, then the estimated $|S(e^{jw})|$ is negative, which is impossible. In this case, the output at these frequencies is set to zero. This non-linear operation will bring in some spike-like sound called a 'musical noise effect'. This effect will influence the audibility of speech when SS is applied to it. However, in this study, which applied the spectral subtraction method to noisy signals from the laser welding process, audibility to the human ear was not a main concern.

Although spectral subtraction has its limitations under the assumption that the noise should be relatively stationary, which may be problematic in an industrial environment with complex and unstable sources of noise, it can still greatly improve the quality of the acquired acoustic signals during the laser welding process by effectively lowering the noise floor. In addition to its effectiveness, the spectral subtraction method is easy to implement and requires only a small computation, which qualifies this method for application in real-time control systems.

3.2 Frequency analysis method

The frequency analysis of a signal is of great importance to gaining a better understanding of the signal itself and to choosing an efficient digital signal processing method. In this study, investigating the frequency properties of the acoustic signals was helpful in finding out the frequency distributions of the signal of interest as well as the noise and in correlating the frequency properties of the signals with the quality or defects of the welds. In addition, based on the frequency analysis, other DSP algorithms could be developed and applied. Therefore, in this respect, the application of a proper frequency analysis method is significant to further study. In this research, the Welch–Bartlett method [**18**] was used to estimate the power spectrum density (PSD), which denotes the power of a signal versus its frequency. This is based on the periodogram method which transforms the signal from the time domain to the frequency domain. It also improves this method by the time averaging of individual periodograms, thus reducing the variance of individual power measurements. To illustrate the basic concept behind the Welch–Bartlett PSD estimation method, a pictorial description is shown in Fig. 3. As seen in Fig. 3, the signal is first divided into segments of equal length, which is also termed the window length. Two

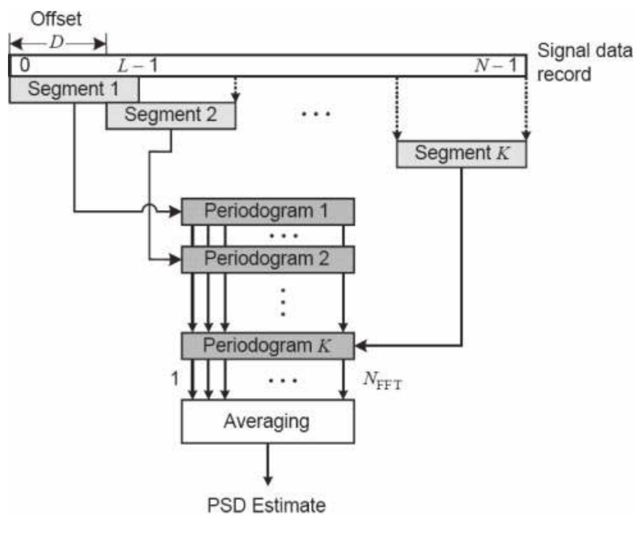


Fig. 3 Pictorial description of the Welch–Bartlett method [**18**]

successive segments are overlapped to a certain percentage of the window length. By applying the proper window function to these segments of the signal, the periodograms are then calculated for each segment by the *N*-point discrete Fourier transform. To average all these periodograms afterwards, a more precise PSD estimation is attained. In this study, the parameters of the Welch–Bartlett method were set as a rectangular window with a length of 1000 sampling points and 50 per cent overlap. The discrete Fourier transform was calculated at 4096 points. By choosing a rectangular window, a high frequency resolution as well as magnitude resolution was possible.

4 RESULTS AND DISCUSSION

4.1 Analysis and processing of noise

As mentioned above, noise is the biggest obstacle to acquiring clean acoustic signals during the laser welding process. In this study there were two main noise sources: the venting fan and the air-knife. Before using the spectral subtraction method to reduce the noise from the desired signals, the properties of the noise had to be analysed both in the time domain and in the frequency domain. The noise from the venting fan and air-knife was recorded separately before the welding process was performed. The overall noise during welding was also acquired. Figure 4 shows the recorded noise from the venting fan and air-knife and the overall noise.

From Fig. 4 it can be seen that the noise from both the venting fan and the air-knife had a sound pressure of around ± 1 Pa, which is equal to 94 dB. Long-term exposure to this level of noise would be harmful to the operator. According to the recorded noise signals in the time domain, the frequency properties of the noise can also be analysed by the Welch–Bartlett PSD estimation method. Figure 5 shows the frequency characteristics of the noise signals. Because the power spectrum densities of the noise from the venting fan and the air-knife were relatively small above 2000 Hz, only the frequency contents between 0 and 2000 Hz were analysed (Fig. 5). From the PSD estimation of the noise it can be observed that the main frequency distribution of the noise from the venting fan was around 230 Hz with a magnitude of

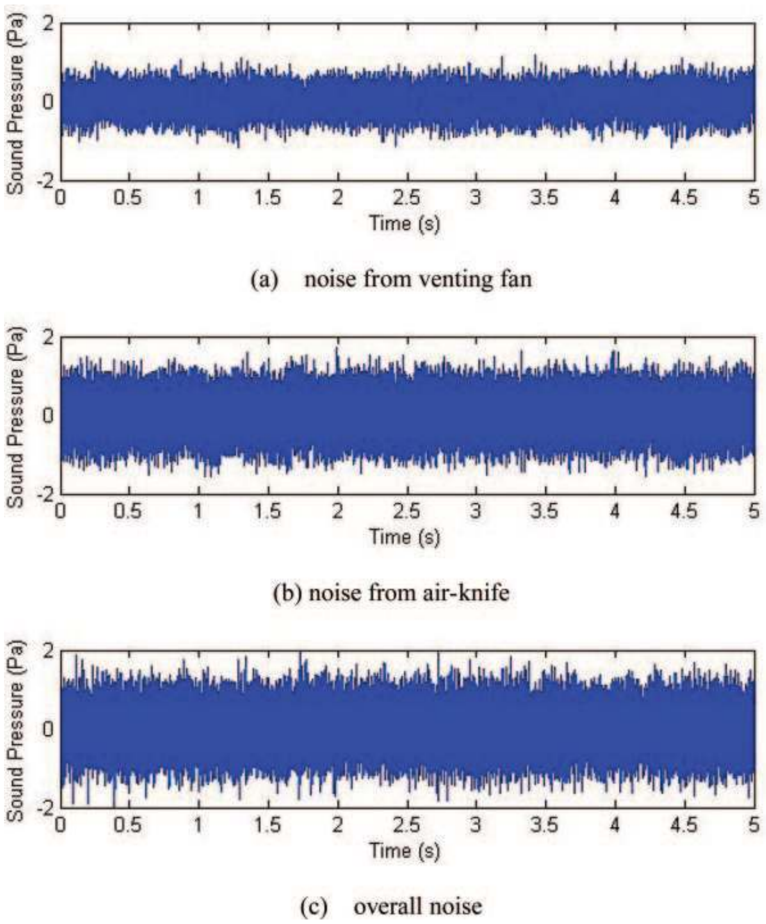
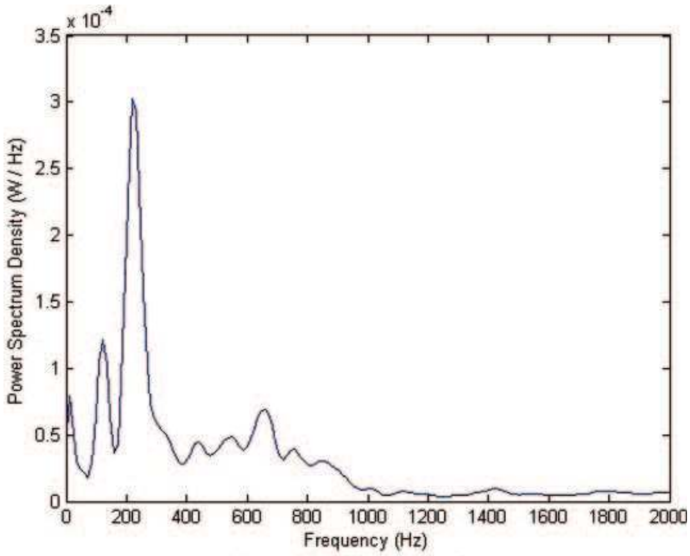
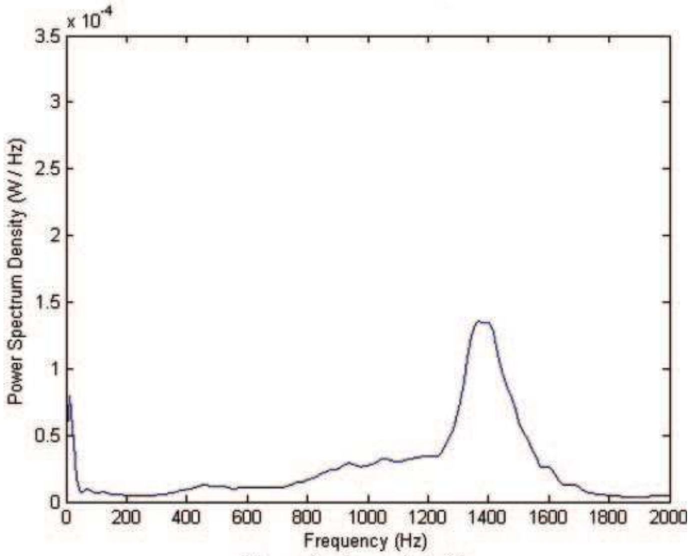


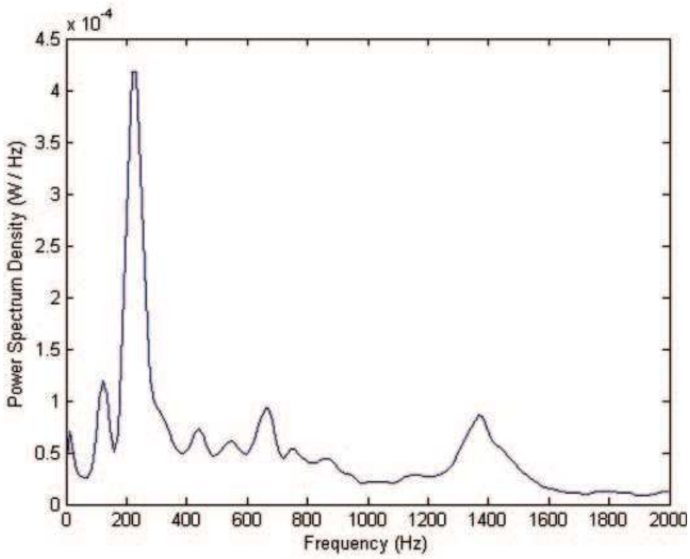
Fig. 4 Sound pressure of noise signals



(a) noise from venting fan



(b) noise from air-knife



(c) overall noise

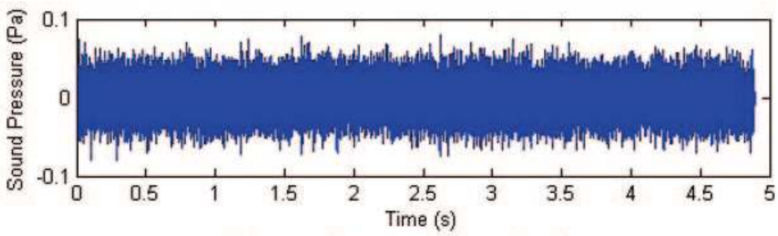
Fig. 5 Power spectrum density of noise signals

3×10^{-4} W/Hz, while the noise from the air-knife was around 1385 Hz with a magnitude of 1.3×10^{-4} W/Hz. From Fig. 5(c) it can be seen that the PSD of the overall noise was approximately the summation of the PSD of the venting fan and air-knife. This illustrates that other noise sources had a very small influence on the overall PSD estimation of noise. By applying the aforementioned spectral subtraction method, the sound pressure of the overall noise can be suppressed from ± 1 Pa to only ± 0.05 Pa, as shown in Fig. 6(a). From Fig. 6(b) it can be observed that the spectral subtraction method also greatly reduced the magnitude of the PSD of the overall noise from 10^{-4} W/Hz to 10^{-7} W/Hz.

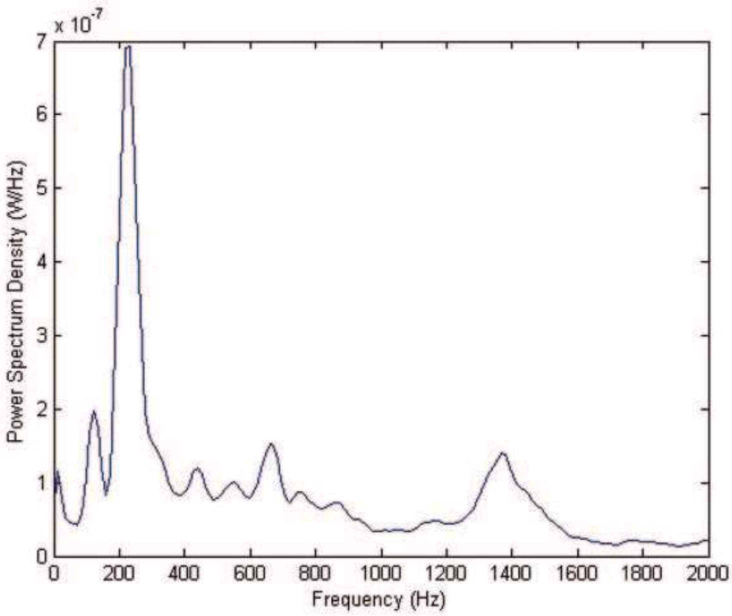
From this analysis of noise using the Welch–Bartlett method it can be concluded that the noise present in this study could be effectively reduced to a negligible level by using the spectral subtraction method. As a result, a quite clean acoustic signal could be obtained during the laser welding process. This result is of great significance to gaining a better understanding of the relationship between the acoustic signals and the penetration state and quality of the welds, allowing effective online monitoring of the laser welding process to be achieved.

4.2 Analysis and processing of the experimental results

In order to achieve good welds with full penetration and bad welds with partial penetration, experiments 1 and 2 were carried out by setting different welding parameters. In experiment 1, full weld penetration was achieved by setting a higher laser power at 3500 W, while partial weld penetration was obtained with a laser power of 2500 W. From Figs 7(a) and (b) it can be seen that the geometries of the transverse cross-sections in two welds were totally different. The first weld was fully penetrated because of a keyhole formed during the laser welding process. A similar welding result was also achieved in experiment 2. The laser beam with a lower welding speed of 20 mm/s produced more heat input; thus, it fully penetrated the workpiece. The other workpiece was only partially penetrated because of a higher welding speed of 40 mm/s. According to Fig. 8, which shows the noise-reduced acoustic signals from experiment 1 and

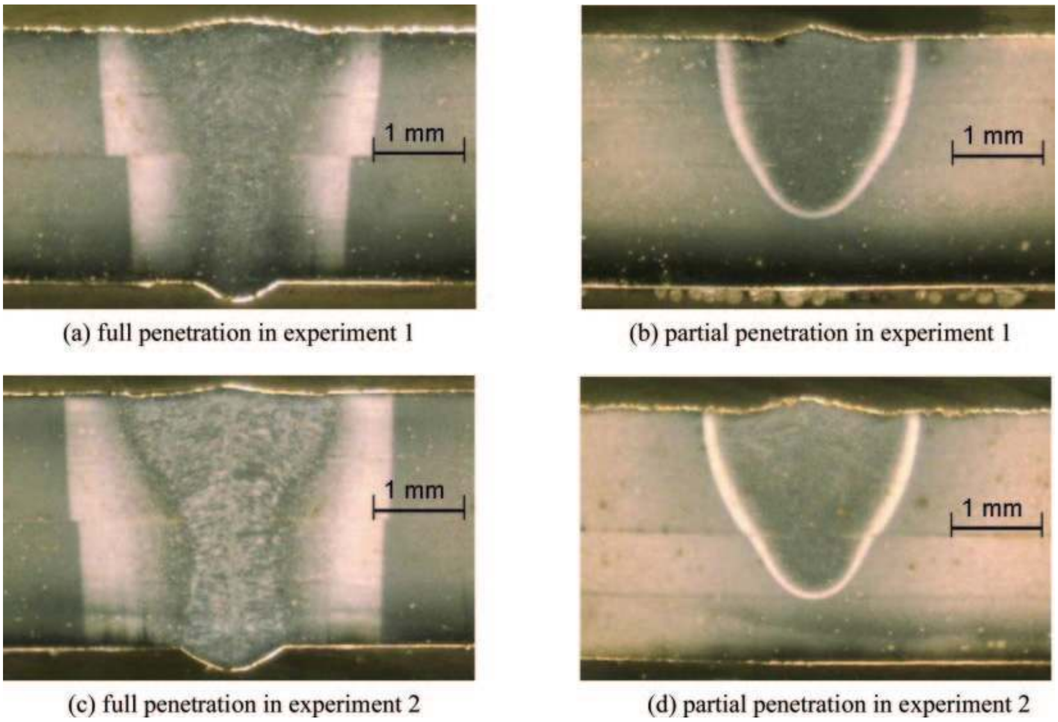


(a) sound pressure of overall noise



(b) power spectrum density of overall noise

Fig. 6 Analysis of the overall noise signal after spectral subtraction



(a) full penetration in experiment 1
(b) partial penetration in experiment 1
(c) full penetration in experiment 2
(d) partial penetration in experiment 2

Fig. 7 Transverse cross-sectional view

experiment 2, it can clearly be seen that the sound pressure from welds with full penetration is higher than that from partially penetrated welds. This implies a rough relationship between the depth of the penetration and the sound pressure of the acoustic signals.

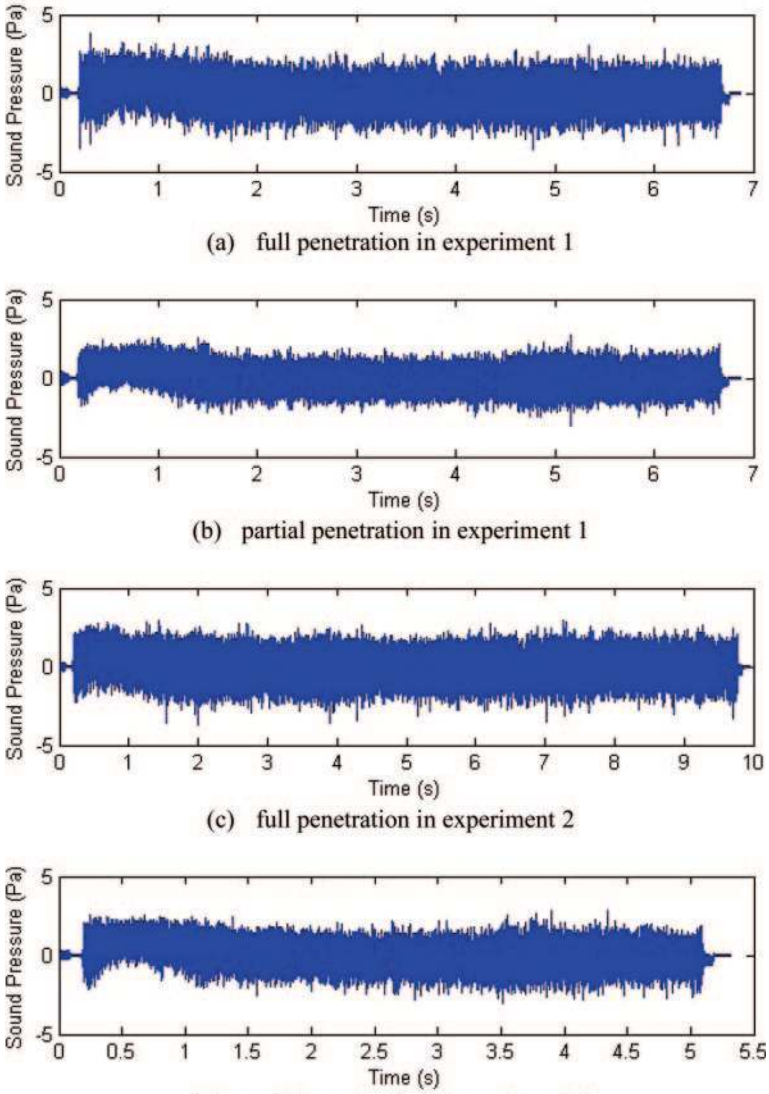
By applying the power spectrum density estimation method, the differences in the PSD between acoustic signals from full penetration and partial penetration were also analysed in experiments 1 and 2. Figure 9(a) shows the PSD estimation in a full frequency range of 0–20 000 Hz for the results from experiment 1. From Fig. 9(a) it can be observed that the main difference in the PSD between the FP and PP lies in the frequency range of 0–2000 Hz. Therefore, the following frequency analysis will only focus on this frequency range. As can be seen in Figs 9(b) and (c), the welds with full penetration generated acoustic signals with higher power spectrum densities in the frequency range 500–1500 Hz than the welds with partial penetration. This frequency characteristic both in experiment 1 and in experiment 2 suggests that, not only in the time domain but also in the frequency domain, a difference is evident between acoustic signals from full weld penetration and partial weld penetration.

The performed analyses of the acoustic signals both in the time domain and in the frequency domain clearly showed the difference between the signals representing full penetration and partial penetration. Based on these observations, two algorithms, one in the time domain and the other in the frequency domain, were developed to distinguish full weld penetration from partial weld penetration. In the time domain, the differences lie in the sound pressure. Therefore, the sound pressure deviation algorithm, which calculates the absolute difference between the sound pressure at each sampling point and the mean value of the sound pressure in a segment of the whole acoustic signal, can be carried out in four steps in the time domain as shown below.

1. Divide the denoised acoustic signal into segments of equal length.
2. Calculate the mean value of the sound pressure for each segment.
3. Calculate the sound pressure deviation with respect to the mean value of the sound pressure calculated in step 2 for each sampling point.
4. Integrate the sound pressure deviation along the timeframe of each segment.

Besides this algorithm, another was also developed on the basis of the different PSD distributions between signals representing full penetration and partial penetration. This band power algorithm can be described by the following three steps.

1. Divide the denoised acoustic signal into segments of equal length.
2. Calculate the PSD of the signal for each segment by the Welch–Bartlett method.
3. Integrate the PSD in the frequency range 500–1500 Hz for each segment.



(a) full penetration in experiment 1

(b) partial penetration in experiment 1

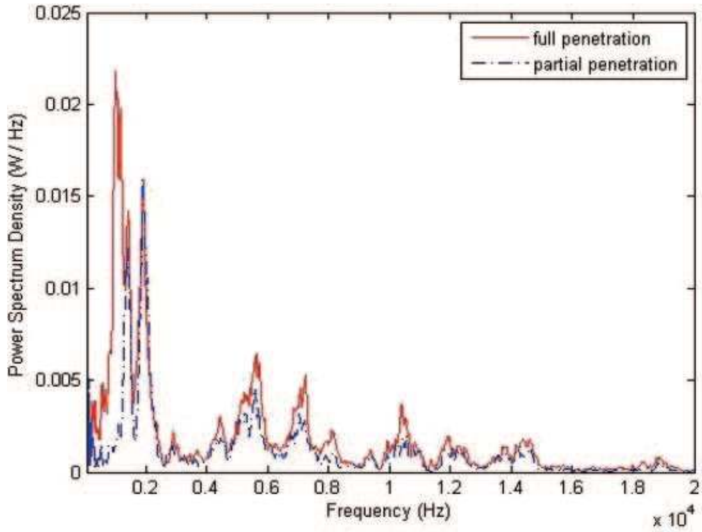
(c) full penetration in experiment 2

(d) partial penetration in experiment 2

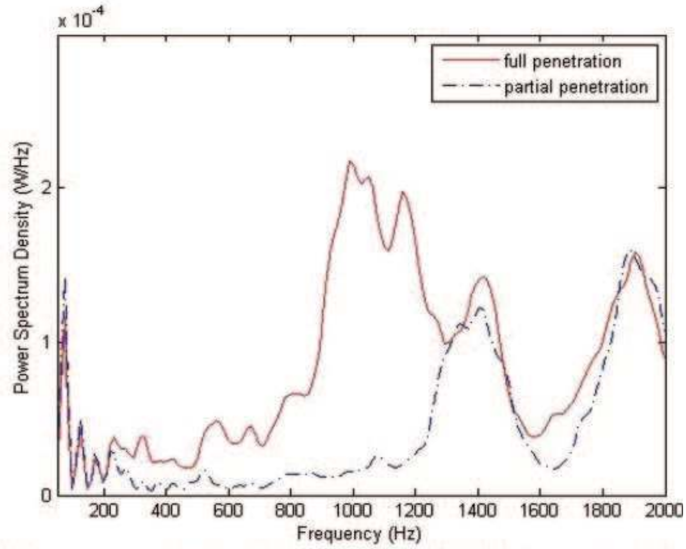
Fig. 8 Sound pressure of acoustic signals after spectral subtraction

When applying these two algorithms to the denoised acoustic signals, the equal length of each segment is chosen to be 5000 sampling points. Since the sampling rate of data is set at 50 kHz, a segment with a length of 5000 sampling points contains acoustic information acquired in 0.1 s. This length of segment offers a high time resolution of the acoustic signal, which is significant to achieve a fast and accurate quality control for future study. The analysis results based on these two algorithms are shown in Fig. 10. It can be seen that both algorithms can differentiate well between full weld penetration and partial weld penetration by setting a proper threshold.

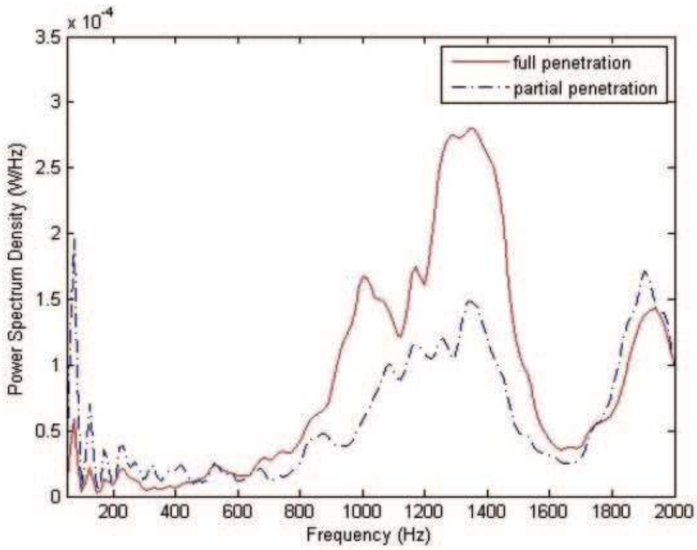
Experiment 3 investigated the relationship between the penetration depth and the acoustic signal during the laser welding of DP980 steel. In order to study this relationship, the laser power was set at 3000 W and the welding speed at 30 mm/s. With these welding parameters, the laser beam generated a series of unstable penetration depths along the weld seam. The penetration depths were not so stable because these welding parameters represented the transition phase from PP to FP. A part of the as-welded workpiece was longitudinally cut to show the penetration depth variation (see Fig. 11(a)). The penetration depth was measured numerically under a microscope. The measured data are plotted in Fig. 11(b). Figures 11(c) and (d) show the results of applying the two different algorithms to the acoustic signal from the weld. The band power in the frequency range 500–1500 Hz agrees with the variation in the penetration depth, while the sound pressure deviation roughly shows the trend of the variation in the penetration depth.



(a) power spectrum density between 0 and 20000 Hz in experiment 1

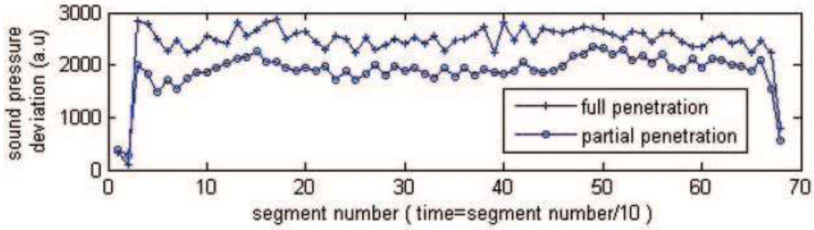


(b) power spectrum density between 0 and 2000 Hz in experiment 1

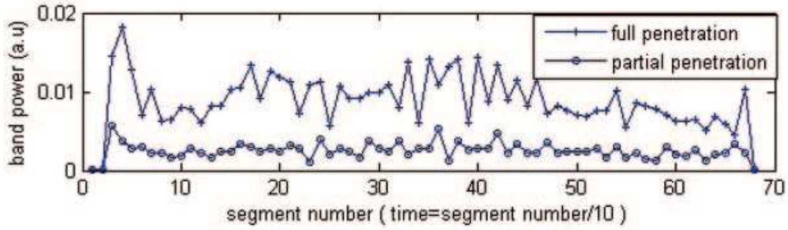


(c) power spectrum density between 0 and 2000 Hz in experiment 2

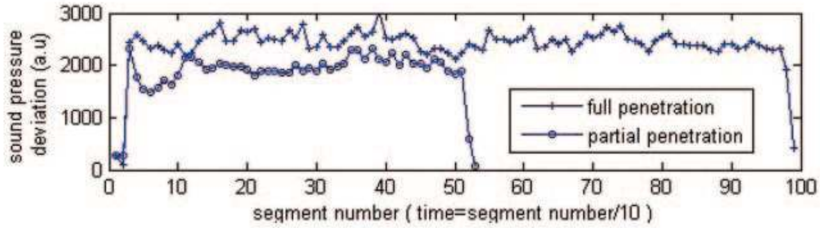
Fig. 9 Comparison of the PSD of acoustic signals from FP and PP



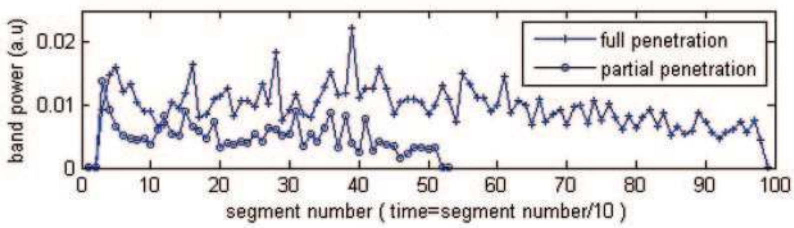
(a) sound pressure deviation of acoustic signals in experiment 1



(b) band power of acoustic signals in experiment 1



(c) sound pressure deviation of acoustic signals in experiment 2



(d) band power of acoustic signals in experiment 2

Fig. 10 Results of analysing acoustic signals on the basis of the two algorithms

The acoustic signal analysis and processing methods applied in the first three experiments were applied to the acoustic signal in experiment 4, which was designed to achieve different penetration states in a single welding procedure with the same laser power but different welding speeds. Figures 12(a) and (b) show the top view and bottom view of the as-welded sheet. As can be seen from Figs 12(e) and (f), there is a clear relationship between the penetration state of the weld and the processed acoustic signals based on the two proposed algorithms. By setting a proper threshold, the full weld penetration and partial weld penetration can be differentiated. For instance, as shown in Fig. 13, a result can be obtained when thresholds (the upper threshold is 2750 and the lower threshold is 1450) are set for the sound pressure deviation as shown in Fig. 12(e). In Fig. 13, 0 represents a partial weld penetration, 1 represents a full penetration, and 2 represents an overpenetration which is caused by a pause of the laser beam to change the welding speed in experiment 4. By comparing the processed results shown in Fig. 13 with the actual penetration states shown in Fig. 12(b) it can be seen that the results agree well.

4.3 Discussion

Based on the analyses of the processed acoustic signals, it can be concluded that there are evident differences between the acoustic signals representing full penetration and the acoustic signals representing

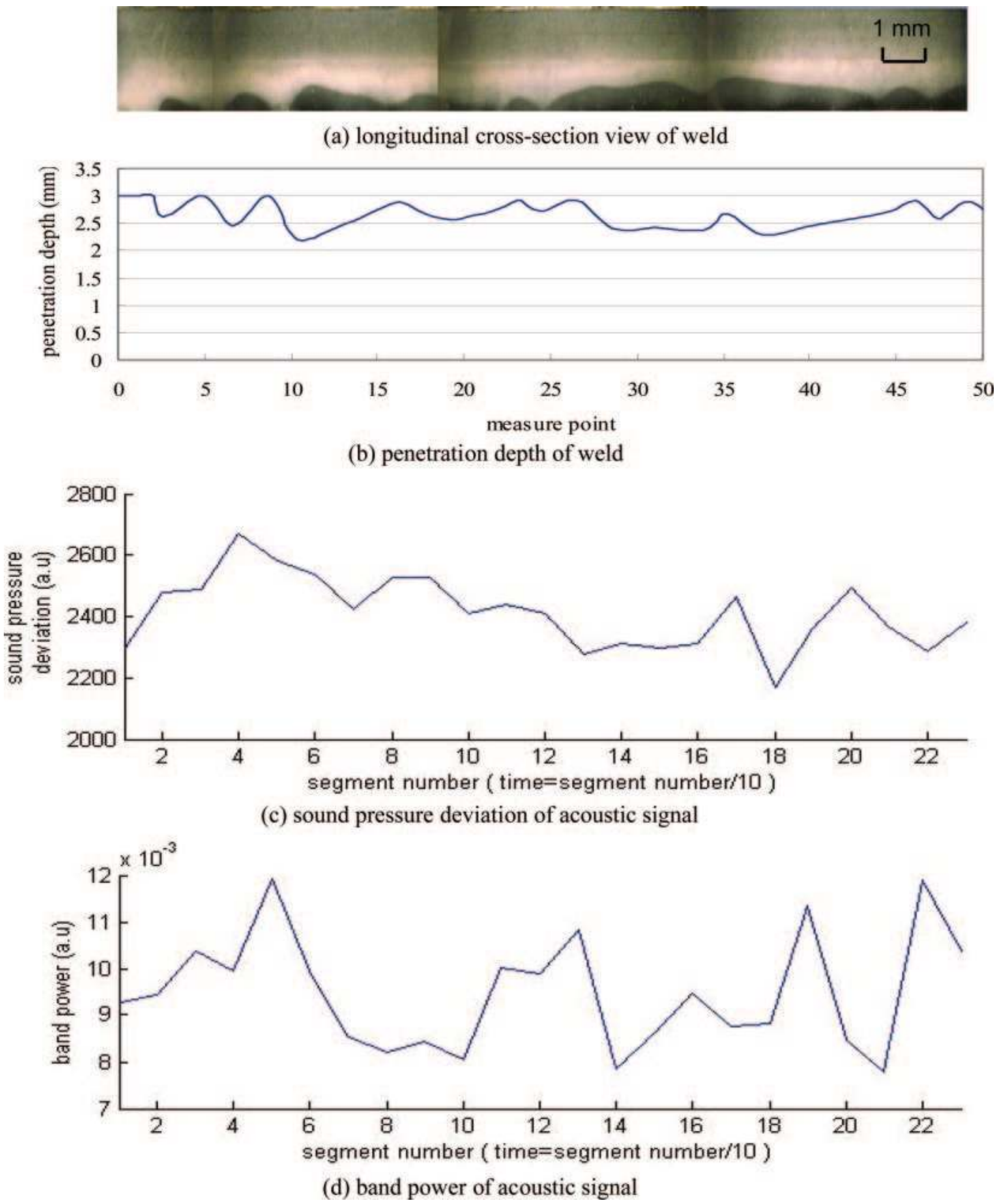
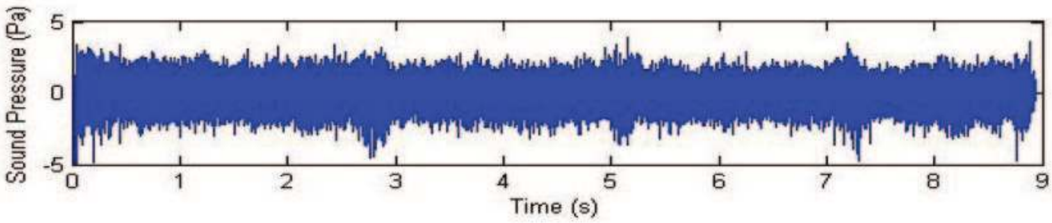


Fig. 11 Results of analysing the acoustic signals in experiment 3

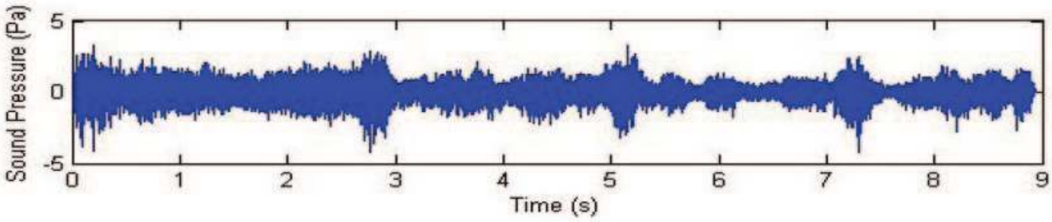
partial penetration both in the time domain and in the frequency domain. The two algorithms developed above can differentiate well between full weld penetration and partial weld penetration. To explain the differences in the acoustic signals from FP and PP, the information contained in the acquired acoustic signals should be analysed. As mentioned in the introduction, the acoustic signal produced during the laser welding process, which reflects the sound pressure and frequency content of the sound wave from the welding zone, contains important information about the molten pool pulsation, plasma generation, thermal stress, metal vapour, and keyhole oscillation. The reason why the acoustic signals from full penetration and partial penetration are different in sound pressure deviation can be explained as follows. When full penetration is achieved by adequate heat input, a higher thermal stress is produced, a higher intensity of plasma is generated, more molten metal is vaporized through the keyhole, and the oscillation behaviour of the keyhole is intensified. Consequently, the pressure produced by the combined effects of these factors increases, resulting in a larger sound pressure deviation. In contrast, when partial penetration is present, the ejection of plasma, the thermal stress, the mass of the vaporized metal,

(a) top-view of weld

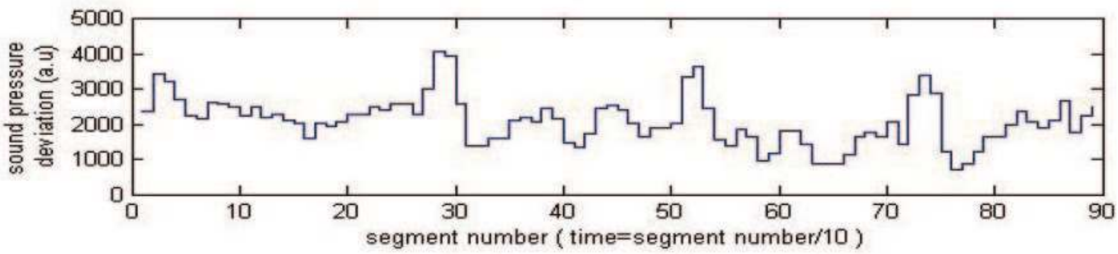
(b) bottom-view of weld (magnified)



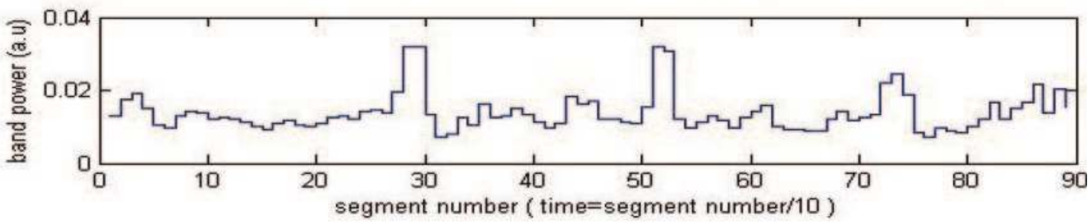
(c) original acoustic signal



(d) denoised acoustic signal



(e) sound pressure deviation of acoustic signal



(f) band power of acoustic signal

Fig. 12 Results of analysing the acoustic signals in experiment 4

and the magnitude of the keyhole oscillation are lower. In the case of partial penetration, a keyhole is not formed or it is formed but remains unstable during the welding process. In this so-called heat conduction mode, the sound pressure is further weakened. Therefore, the results shown in Figs 10(a) and (c) can be explained by the analyses given above. Besides the difference in the sound pressure, the acoustic signals

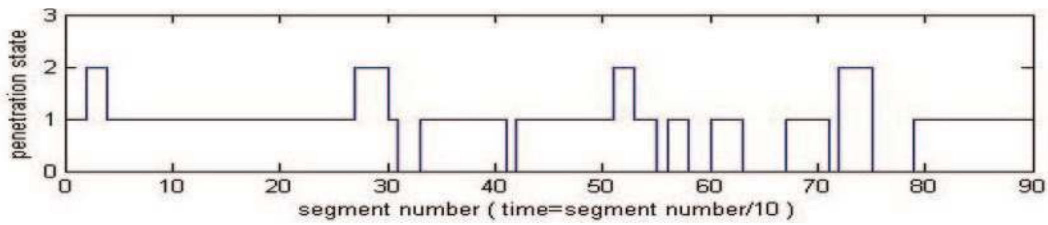


Fig. 13 Processed results of the penetration states in experiment 4

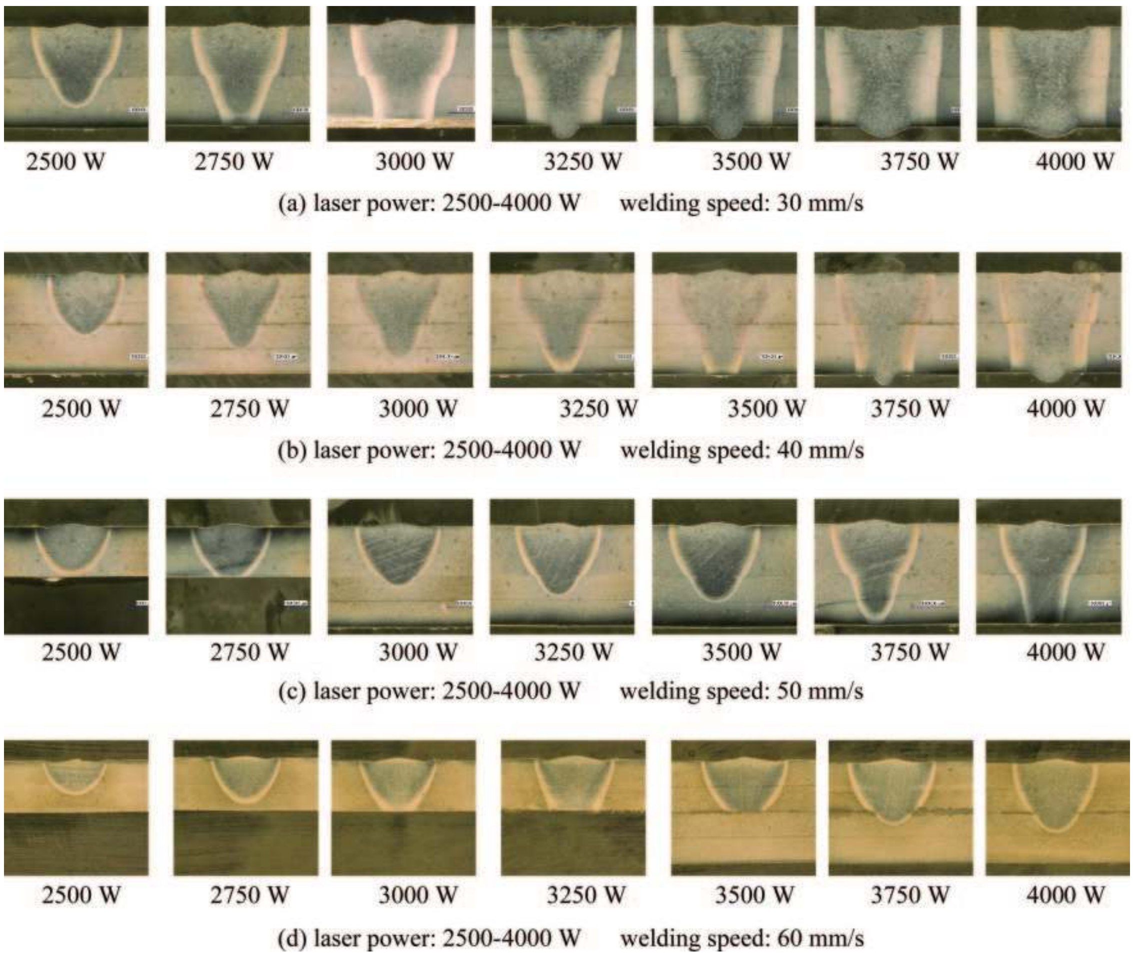
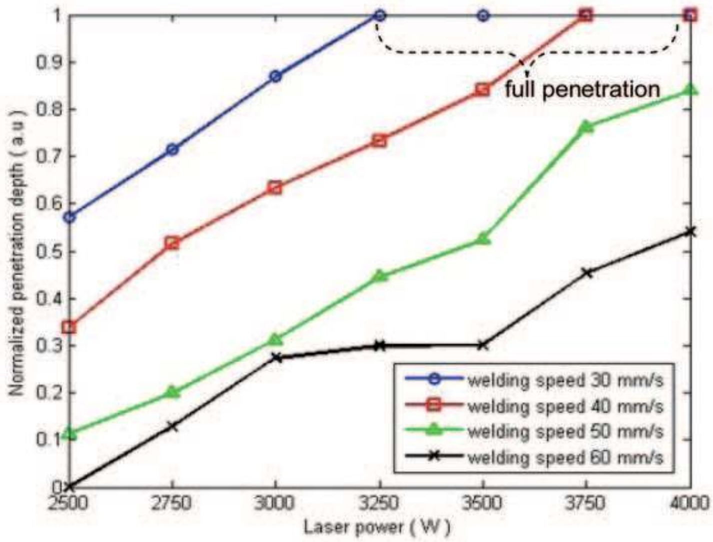
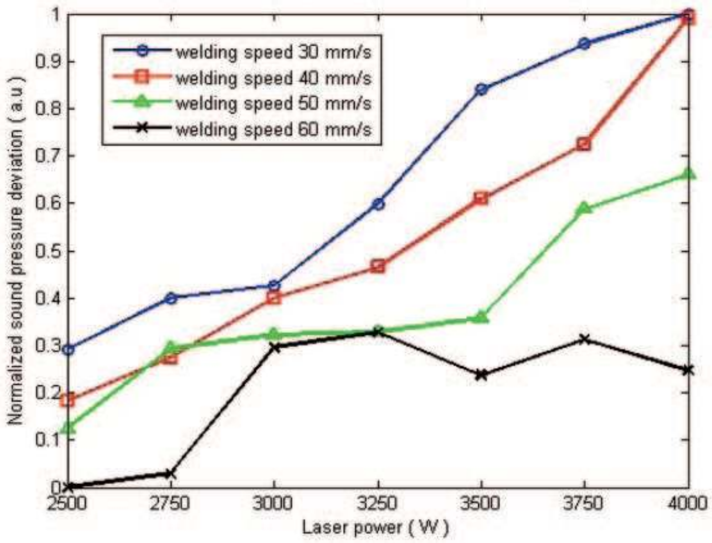


Fig. 14 Cross-sectional view of the penetration depths with different laser welding parameters (magnification 4×)

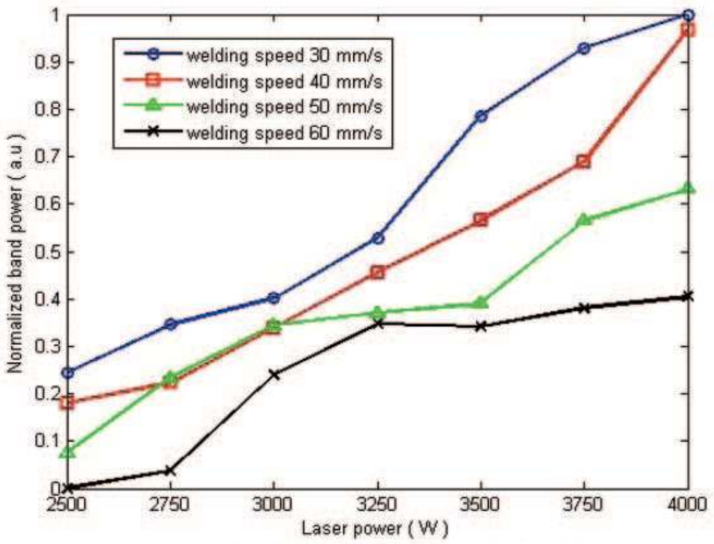
also have different frequency characteristics. The power spectrum densities of acoustic signals from full penetration and partial penetration are different in the frequency band 500–1500 Hz. To illustrate this phenomenon, the dynamic behaviour of the keyhole should be taken into consideration. Usually, keyhole oscillation has several eigenfrequencies that are mainly determined by the physical and thermal properties of the material. There are three modes of keyhole oscillation: radial, axial, and azimuthal, but only the radial mode received a full investigation by Simon's group [**19**, **20**]. By studying different materials such as aluminium, iron, and copper, they concluded that the typical frequency of keyhole oscillation is about 1.5 kHz, and, if the gas flow within the keyhole is not taken into consideration, the typical frequency of keyhole oscillation is around 600 Hz. Although these results relate to different materials rather than to high-strength steel DP980, they could still be helpful in justifying the findings in this study that the frequency band 500–1500 Hz closely correlates with the dynamic behaviour of keyhole oscillation.



(a) normalized penetration depth



(b) normalized sound pressure deviation of acoustic signals



(c) normalized band power of acoustic signals

Fig. 15 Results of analysing the acoustic signals in experiment 5

When full penetration was formed in the keyhole mode, as shown in Figs 7(a) and (c), the power of the signals increased in the frequency band relating to the eigenfrequencies of keyhole oscillation. When a keyhole was not formed and only partial penetration was achieved, as shown in Figs 7(b) and (d), the power of the acoustic signals in this frequency band was much lower. Furthermore, the same analyses can be used to explain the results in experiment 3, as well as in establishing a relationship between the penetration depth and the sound pressure level or the power in the corresponding frequency band.

To verify further the relationship between acoustic signals and penetration state, and to investigate the mechanisms of the different characteristics of acoustic signals generated from different penetration depths and modes, experiment 5, which consisted of 28 experiments, was carried out using different welding parameters. The acoustic signals produced during the laser welding process with these different welding parameters were processed and analysed by the spectral subtraction method and the two algorithms developed above. As shown in Fig. 14, different penetration depths were achieved by different welding parameters. By applying seven different laser powers of 2500, 2750, 3000, 3250, 3500, 3750, and 4000 W at four different welding speeds of 30, 40, 50, and 60 mm/s, different penetration depths were obtained. To establish the correlation between the acoustic signals and the penetration depths, the average of the sound pressure deviation and band power was calculated for the acoustic signal from each welding result, and the penetration depths were measured by microscope. Because the units of the penetration depth and the average of the sound pressure deviation and band power were different, they were linearly normalized. The linear normalization equation is as follows

$$X_{\text{normalize}} = \frac{X_{\text{original}} - X_{\min}}{X_{\max} - X_{\min}} \tag{8}$$

where X denotes a set of values that can represent the penetration depth or the average of the sound pressure deviation and band power, $X_{\max}$ and $X_{\min}$ are the maximum and minimum values in the dataset, and X_{original} and $X_{\text{normalize}}$ denote the original value and normalized value in the dataset respectively. By applying linear normalization, the correlation between the penetration depth and the average of the sound pressure deviation and band power can be better analysed.

As shown in Figs 14 and 15(a), the normalized penetration depth increases linearly with increase in laser power and decrease in welding speed before full penetration is achieved. Once full penetration is achieved, the penetration depth will not change much with increase in laser power. By observing the trends of the average of the sound pressure deviation and band power at welding speeds of 30 and 40 mm/s, as shown in Figs 15(b) and (c), it can be seen that the sound pressure deviation and band power increase with increase in penetration depth. When full penetration is achieved, the sound pressure deviation and the band power continue to increase with increase in laser power. This is because, when full penetration is achieved, although the penetration depth will not change much with increase in laser power, a larger mass of molten metal will be formed owing to further increase in laser power, which will be accompanied with greater generation of plasma and metal vapour, consequently producing a higher sound pressure in the welding zone. For the experiments carried out at a welding speed of 50 mm/s, the sound pressure deviation and the band power do not increase much when the laser power is between 2750 and 3500 W. This trend of change in the acoustic signals can be explained by observing the cross-sectional view of the weld shown in Fig. 14. When the welding speed is set at 50 mm/s and the laser power is under 3500 W, the penetration depths are very shallow. In this mode, which is called the heat conduction mode, a keyhole is not formed and the mass of molten metal increases slowly with increase in laser power. Consequently, the sound pressure deviation and band power, which reflect the pressure from the generated plasma, molten pool pulsation, metal vapour, and keyhole oscillation, do not increase much with slow increase in penetration depth. However, when the laser power is increased to 3750 W, the sound pressure deviation and band power dramatically increase when the keyhole mode has just formed, as shown in Fig. 14. For the experiments carried out at a welding speed of 60 mm/s, the lower level of sound pressure deviation and band power, which do not change much when the laser power increases, can also be explained by the presence of the heat conduction mode without keyhole formation. From these results it can be concluded that the sound pressure deviation and the band power of the acoustic signals are closely correlated with the penetration depth and the penetration mode. In the heat conduction mode, the sound pressure deviation and the band power are at a lower level owing to less generated plasma and metal vapour, weaker molten pool pulsation, and lower thermal stress. Once the keyhole mode is formed, the sound pressure deviation and the band power of the acoustic signals will be much higher than those in the heat conduction mode, and they will increase with increase in penetration depth owing to greater generation of plasma and metal vapour, as well as to the stronger oscillation behaviour of the keyhole formed. From these experiments, the correlation between acoustic signals and penetration depth and penetration mode has been established. The mechanisms of the different characteristics of acoustic signals from full weld penetration and partial weld penetration have also been discussed.

5 CONCLUSIONS

In this study, the acoustic signals during the laser welding of high-strength steel DP980 were recorded, processed, and analysed. The main objective was to study the feasibility of using these acoustic signals for online monitoring of weld quality during laser welding. Based on the results of experiments, the following conclusions can be drawn.

1. The application of noise reduction methods, such as the spectral subtraction method, greatly suppresses the noise, and consequently an improvement in the quality of the desired acoustic signal can be obtained.
2. The sound pressures of the acoustic signals from full penetration and partial penetration are different in the time domain. The sound pressure tends to increase with increase in penetration depth. The full penetration achieved by the keyhole formed generates a higher sound pressure than partial penetration.
3. In the frequency domain, the acoustic signal from full penetration has a stronger power density in the frequency band 500–1500 Hz than that from partial penetration. This can be explained by the eigenfrequency of the oscillation behaviour of the keyhole.
4. Based on analyses both in the time domain and in the frequency domain, two algorithms were developed and applied to the denoised acoustic signals. The results show that these two algorithms can differentiate well between full penetration and partial penetration by setting a proper threshold.
5. The relationship between acoustic signals and penetration depth can also be established from the processed signals. Therefore, it is feasible to use the acoustic signals to achieve online monitoring of the laser welding process. Furthermore, a feedback control system can be developed to control the laser power to achieve a weld with full penetration.

ACKNOWLEDGEMENTS

This research was supported financially by the National Science Foundation under Grant EEC-0541952 and General Motors Corporation. Thanks to Mr Andrew Socha, research engineer of the Research Center for Advanced Manufacturing at SMU, Shanglu Yang, a PhD candidate, and Dr Dechao Lin for their assistance in the experiments.

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