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Relationship between sound signal and weld pool status in plasma arc welding①

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[**Abstract**] The sound features of the weld pool status in plasma arc welding were systematically investigated after the sound signal was collected with a microphone. The results show that it is difficult to extract information about the weld pool status directly in time domain although the sound signal varies with the weld pool behaviors to some extent. The frequency spectra of the sound signal contain plenty of information about the weld pool behaviors. It is shown from the analysis of the sound generation mechanism that the sound signal of plasma arc welding is mainly caused by the weld pool oscillation, the power source fluctuation and so on. R_S algorithm is designed to determine the weld pool status, and it is able to offer the feedback information for the closed-loop control of the penetration quality of plasma arc welding.

[**Key words**] plasma arc welding; weld pool status; sound feature; application
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1 INTRODUCTION

Plasma arc welding (PAW) is characterized by easy operation and low cost among the high-energy-density-beam processing techniques (for example, electron beam, laser and plasma). PAW is widely used in welding of stainless steel, high-nickel alloys, carbon steel, copper, copper-nickel alloys, titanium alloys, aluminum and magnesium alloys[1~5]. In plasma arc welding, the control of the keyhole behaviors is a crucial technique to achieve good quality welds, which attracts many scholars' attention. Sound wave is generated by solid vibration and fluid pulsation. During welding, the oscillation of the weld pool, the pulsation of the arc plasma jet and so on are all able to emit sound wave. Therefore, it is possible to detect the behaviors of the keyhole in the weld pool by the investigation of sound features during plasma arc welding.

The sound signal of plasma arc was preliminarily studied. Hu et al[6] detected the sound signal inside the welded pipe with a microphone mounted at one end of the pipe to determine whether the weld pool was penetrated. However, the sound signal is difficult to reach the back of the welds of complex structures in the welding. Futamata et al[7,8] analyzed the sound signal of the non-transferred plasma arc welding, and discovered the frequency range of the sound wave was large, moreover had a certain orientation. Manz[9] deemed that the plasma arc sound like jet engines. The above methods simply analyzed the penetration signal of welding in some respects, and it is difficult to apply in practice.

In this work, the investigation of the sound spectra of transferred plasma-arc keyhole welding is presented. The features of the sound signal are analyzed in time domain and frequency domain. A technique is developed to detect the weld pool status during welding, which is used in monitoring of the penetration quality and controlling of the plasma arc welding.

2 EXPERIMENTAL SYSTEM

The collect system of the sound signal is shown in Fig. 1, which consists of a microphone, a data acquisition card, a computer and so on. The sound signal during welding is measured by a microphone with a bandwidth up to 20kHz, which is mounted near the welding torch.

In the experiments, a phototriode is attached to the plasma torch and positioned on the back of the

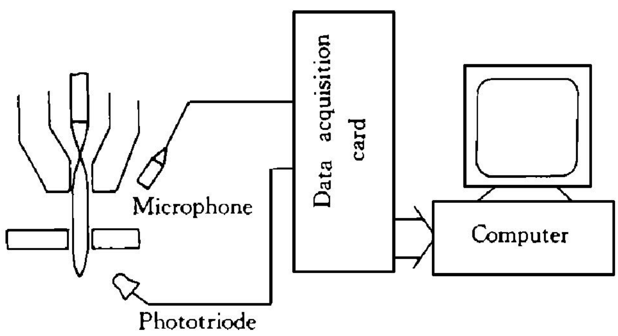

Fig. 1 Collecting system of sound signal

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weld so as to obtain the light signal of the efflux plasma. When the keyhole status varies, the output potential of the phototriode can generate a step change and offer a reference signal of the weld pool status.

The light signal and the sound signal are simultaneously recorded at a collecting frequency of 50 kHz. The data are transferred to the computer and processed.

3 SOUND SIGNAL

The welding process parameters were as follows. The welding current and voltage were 120~ 150 A and 29~ 31 V respectively. Pure argon was used as the shielding gas and the plasma gas. The flow velocity of the plasma gas was 80~ 120 L/h, and the welding speed was 28~ 34 cm/min. The flow velocity of the shielding gas was 700~ 900 L/h. The thickness of the samples varied from 6 mm to 4 mm, as shown in Fig. 2. When the plasma arc passed on the 6 mm-thick plate, a keyhole was not produced in the samples, but on the 4 mm-thick plate a keyhole was produced by using the above welding parameters.

The variations of the sound signal and light signal with time during welding are shown in Fig. 2. It can be seen from Fig. 2 that the process of the plasma arc welding can be roughly classified into two stage: non-keyhole stage (before 7.8 s) and keyhole stage (from 7.8 s to 15.8 s). During the non-keyhole stage, the amplitude of the sound signal is smaller (−2.0~ 2.0 V) and there is low frequency vibration to some extent. On the keyhole stage, the output potential of the phototriode has a step change and the overall amplitude of the sound signal becomes larger (−3.0~ 3.0 V). After welding for 15.8 s, the welding process is on the non-keyhole stage again.

As described above, the sound signal includes information about the keyhole status of the weld pool. However, it is difficult to obtain the information directly and obviously from the raw sound signal under the conditions studied.

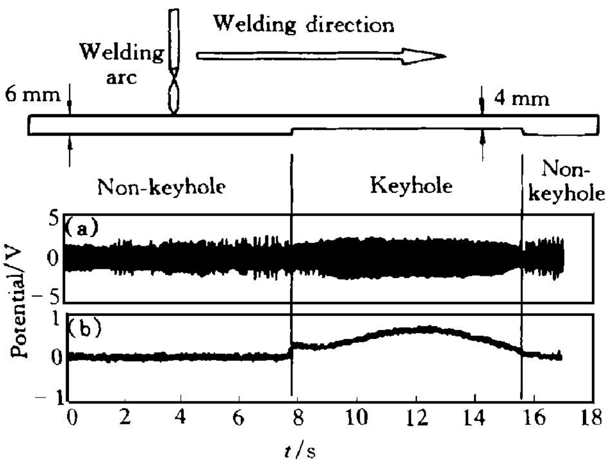

Fig. 2 Variations of sound signal and light signal with time during welding
(a) —Sound signal; (b) —Light signal

4 FREQUENCY DOMAIN CHARACTERISTICS OF SOUND SIGNAL

4.1 Frequency spectra of sound signal

A frequency domain analysis (Fast Fourier Transform, FFT) was performed to study the features of the sound signal. The typical results of the frequency spectra during two different stages are shown in Fig. 3, in which the analyzed data are obtained from the sound signal of welding for about 5 s and 12 s in Fig. 2.

It can be seen from Fig. 3 that there are several dominant peaks in the frequency spectra. The dominant peak at 16~ 17 kHz is the highest, which is higher on the keyhole stage than that on the non-keyhole stage. There are also dominant peaks at about 2 kHz, 13~ 14 kHz, 15~ 16 kHz frequencies, the variation trends of which are similar to that of 16~ 17 kHz peak during welding. On the other hand, unlike the higher frequency band, in the frequency spectra of the lower frequency band (< 400 Hz), no obvious dominant peak is found. The areas below the curve of the spectra, of the lower frequency band on the two stages are different, which is larger on the non-keyhole than on the keyhole one.

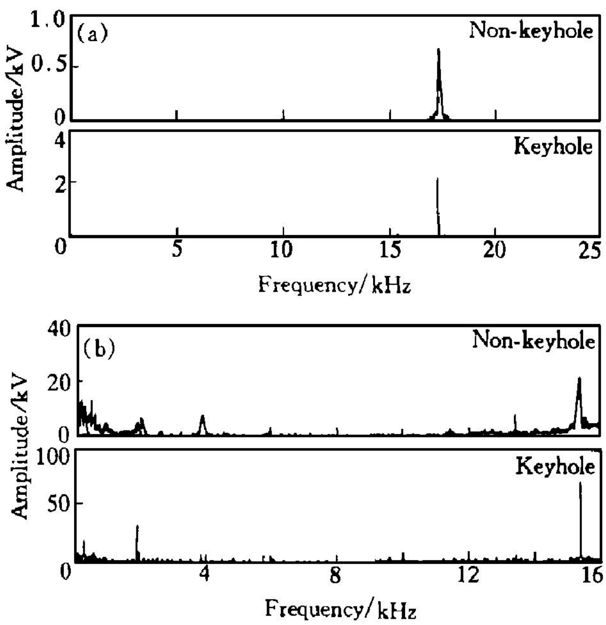

Fig. 3 Frequency spectra of sound signal
((b) is local magnification of (a))

4.2 Generation mechanism of sound signal

During welding, the pulsation of the arc plasma jet, the oscillation of the weld pool and so on are all the sources of the sound signal. The oscillation of the weld pool is the main source of the sound signal on lower frequency band, but it may have a slight influence on the higher-frequency-band sound signal. By observation and analysis, the weld pool during welding is divided into two types corresponding to the stages of welding process: non-keyhole weld pool and keyhole weld pool. When the weld pool belongs to the non-keyhole type, there is a layer of non-melted metal below the weld pool. The high-speed plasma jet reaches the weld pool, then is hindered by the weld pool and strongly stirred in the weld pool, so that the weld pool generates strong oscillation at low frequency. When the weld pool belongs to the keyhole type, there is a keyhole at the center of the weld pool and the stirring effect of the plasma jet is decreased due to the reducing force of the keyhole. As a result, the low frequency part of the sound signal is larger during non-keyhole weld pool than during keyhole weld pool, as shown in Fig. 3(b).

The plasma jet pulsation possibly caused by the power source fluctuation and so on is the main source of the dominant peaks at the higher frequency band of the sound signal. At non-keyhole stage, the plasma jet acts on the weld pool and the weld pool metal produces cushion effect on the pulsation of the plasma jet so that the plasma jet pulsation is suppressed to some extent. After the keyhole forms, part of the arc plasma pass through the weld pool and the cushion effect is decreased, therefore the amplitude of the plasma jet pulsation becomes larger. The inverter frequency of the power source used in the experiments is 32 kHz, and the 16~ 17 kHz peak is the highest among the dominant peaks. The amplitude of the 16~ 17 kHz is higher on the keyhole stage than that on the non-keyhole stage. The rest of the dominant peaks are also related to the inverter frequency and have similar in variation trend to the 16~ 17 kHz peak.

In summary, the variation trend of the area below the curve of the higher frequency band is opposite to that of the lower frequency band during plasma arc welding, which offers convenience to detect the keyhole status of the weld pool by using the sound signal.

5 SOUND DETECTION OF KEYHOLE STATUS

5.1 Short-time Fourier transform of sound signal

The frequency spectra of the sound signal comprise information about the keyhole behaviors of plasma arc welding. To extract the status information of the weld pool, a time-frequency domain analysis (short-time Fourier transform) is carried out. Let $s(n)$ denote the corresponding discrete-time sound signal after the continuous-time sound signal is collected at a rate T_s. By discussion, the analysis-window function is given

$$w(n-m) = \begin{cases} 1 & n = im, im+1, \cdots, im+N-1 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where i is the sliding step of the analysis-window, $i = 1024$; N is the data points of Fourier transform; $n = 0, 1, 2, \cdots$; $m = 0, 1, 2, \cdots$

In terms of the DSP (Digital Signal Processing) theory, the discrete short-time Fourier transform of $s(n)$ is given by

$$STFT_s(m, k) = \sum_{n=0}^{\infty} s(n) w(n-m) e^{-j\frac{2\pi}{N}nk} \quad (2)$$

where $k = 0, 1, 2, \cdots, N-1$.

It can be seen from the analysis of the frequency spectra that the low frequency part and high frequency part obviously changed with the keyhole status of the weld. To reduce the influence of random factors and increase the reliability of the processing results, the sound signal of some frequency band is integrated over frequency. An algorithm, called I_s algorithm, is designed as

$$I_s(m) = \sum_{K=f_1 T_s N}^{f_2 T_s N} |STFT_s(m, k)| \quad (3)$$

where f_1 and f_2 are the lower limit frequency and the upper limit frequency of the selected frequency band respectively. For example, at the lower frequency band, $f_1 = 0$ Hz, and $f_2 = 300$ Hz; at the higher frequency band, $f_1 = 1$ kHz, and $f_2 = 3$ kHz. The results of the I_s algorithm are shown in Fig. 4. It can be seen that when the keyhole status varies during welding, the results at lower and higher frequency bands considerably change. Moreover, the variation trend of the result at lower frequency band is opposite to that at higher frequency band. However, it is difficult to extract a steady threshold of the keyhole status by using I_s algorithm. Therefore, the relative

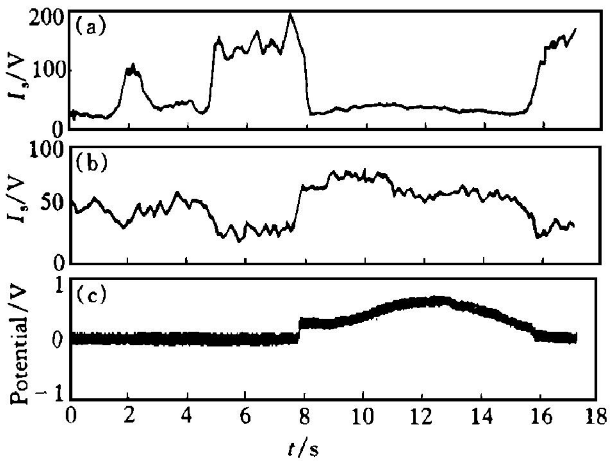

Fig. 4 I_s algorithm of sound signal and output potential of light signal

(a) —Sound signal ($f_1 = 0$ Hz, $f_2 = 300$ Hz);
(b) —Sound signal ($f_1 = 1$ kHz, $f_2 = 3$ kHz);
(c) —Light signal

variation of the spectra of the two bands is obtained by means of suitable algorithms, which may more steadily reflect the behaviors of the weld pool.

5.2 Detection of weld pool status

By the analysis of the data, an algorithm, R_s algorithm, is introduced, by which steady thresholds are obtained. R_s algorithm is given by:

$$R_s(m) = \frac{\sum_{k=f_3T_sN}^{f_4T_sN} |STFT_s(m, k)|}{\sum_{k=f_1T_sN}^{f_2T_sN} |STFT_s(m, k)|} \tag{4}$$

where f_1, f_2, f_3, f_4 are the frequency of sound signal, $f_1 = 0$Hz; $f_2 = 300$Hz; $f_3 = 600$Hz; $f_4 = 8000$Hz. The results of R_S algorithm are depicted in Fig. 5. It can be seen that the keyhole status can be clearly determined in numerical quantities by means of R_S algorithm. When the value of R_s is less than 3, there is no keyhole in the weld pool; when the resulting value is more than 4, the keyhole is formed and the normal plasma-arc keyhole welding is achieved.

The R_s algorithm is tested on several specimens and has better reliability, so it can be used in detecting the weld penetration status.

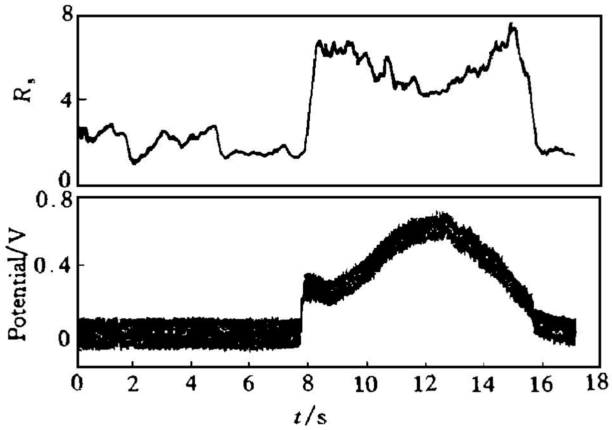

Fig. 5 R_s algorithm of sound signal and output potential of light signal
(a) —Sound signal; (b) —Light signal

6 CONCLUSIONS

1) The sound signal during plasma arc welding includes information about the keyhole status. However, it is difficult to extract the information directly in time domain.

2) The sound signal is mainly caused by the weld pool oscillation and the fluctuation of power source. It is shown from the frequency spectrum analysis that the lower frequency part and higher frequency part obviously vary and their variation trends are opposite when the weld pool status changes.

3) The R_s algorithm is able to reflect the keyhole status of the weld pool and has better reliability. It can offer the necessary feedback information for the closed-loop control of the penetration quality of plasma arc welding.

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