Signature Analysis for Quality Monitoring in Short-Circuit GMAW

An effective method has been developed to identify the process stability and weld quality of short-circuit GMAW

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ABSTRACT. An efficient approach is presented to identify the stability and quality of short-circuit gas metal arc welding (GMAW) by using power spectral analysis and time-frequency spectral analysis methods. A systematic analysis based on experimental data shows that the short-circuiting frequency is a determining factor on weld process stability. The relationship between the short-circuiting frequency and the process stability is established. Moreover, using the time-frequency analysis method, some disturbances and unpredictable variation of welding conditions, which contributes to an instable process, can be easily identified and weld defects can be located. A set of experiments with designed disturbances was conducted to verify the method. The results show that it is possible to evaluate the process stability and detect weld defects automatically during the welding process. The time-frequency analysis method is also useful in tuning or refining a welding procedure to obtain the greatest level of stability.

Introduction

Gas metal arc welding (GMAW) is widely applied in various industries because of its high productivity, flexibility, and low cost. It can be operated in semiautomatic and automatic modes and can be utilized particularly well in a high-volume production environment. In GMAW, there are three major modes of metal transfer from the electrode wire to the weld pool: globular transfer, spray transfer, and short-circuiting transfer. Short-circuit GMAW employs the lowest range of welding current, low voltage, and small wire diameters, thus producing low heat input and a small, fast-freezing weld pool. The low heat input minimizes distortion of the welded structure. Therefore, short-circuit GMAW is highly suited for welding thin sheet metals. Recent trends toward fabricating hydroformed parts for vehicle structures have led to the implementation of short-circuit GMAW for thin sheets in the automotive industry.

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Short-circuit GMAW is characterized by periodic contacts between the electrode wire and the weld pool. This causes periodic changes in its welding current and voltage. Therefore, there must be a relationship between the electrical signals, welding process stability, and weld quality (since the weld joint with good quality can only be produced by a stable welding process). Signal processing and analysis techniques, which are widely used in process monitoring and control, may be employed to analyze the complex short-circuit processes of GMAW. Using these methods, weld joint quality and welding stability corresponding to different short- circuit welding processes can be investigated.

The stability of the arc in the short-circuit process affects the quality — such as surface finish, penetration, and amount of spatter — of the weld. This means that stable arcs can result in stable welding processes and good weld quality. But even given a set of good welding parameters, the process may be disturbed by some unpredictable variation of welding conditions, causing unstable welding processes and leading to a greater probability of spatter, nonuniform weld bead, and other fusion defects. Thus, the goal of industrial welding to consistently produce high quality is quite difficult. However, traditional methods of monitoring welding processes and weld quality are heavily dependent on the knowledge, skill, and experience of welders. This is typically labor intensive, may be unreliable, and may also increase manufacturing cost. Therefore, a method of on-line monitoring of weld stability and weld quality by analyzing the signatures of the GMAW process would be highly desirable.

KEYWORDS

GMAW
Process Stability
Short-Circuiting Frequency
Quality Monitoring
Defect Detection

In the last few years, much effort has been put into the study of weld stability and weld quality. The related research (Refs. 1–8) uses the welding voltage and current to analyze the stability or regularity of metal transfer in welding processes. Standard deviation is computed with arc and short-circuiting time, short-circuiting peak current, mean current, and voltage to assess the process stability. However, little research attention has been paid to the frequency domain or the time-frequency analysis of the welding processes to consider time-varying frequencies corresponding to unstable welding processes. Most existing studies have been focused on the time domain. There is no systematic study on the relationship between short-circuiting frequencies, welding process stability, welding parameters, and weld quality. It was reported (Refs. 1, 2) that in the short-circuiting welding mode, optimal stability occurs when the short-circuit frequency equals the oscillation frequency of the weld pool and reaches its maximum. But measuring the weld pool oscillations is not practically possible in GMAW, in particular because of the impact of droplets entering the weld pool. Some monitoring systems are based on the visual analysis of weld quality after welding and normally employ visual information from the weld joint geometry, weld pool, and/or from the weld bead geometry (Ref. 9). However, visual systems are not always reliable where used in a production environment because the intensive disturbance from the electric arc interferes with the visual sensor system.

The objective of this paper is to analyze the signatures of a welding process for welding stability and weld quality using power spectral density and time-frequency analysis methods. By analyzing the welding voltage and current in the frequency domain, the relationship between short-circuiting frequency and process stability and other welding parameters,

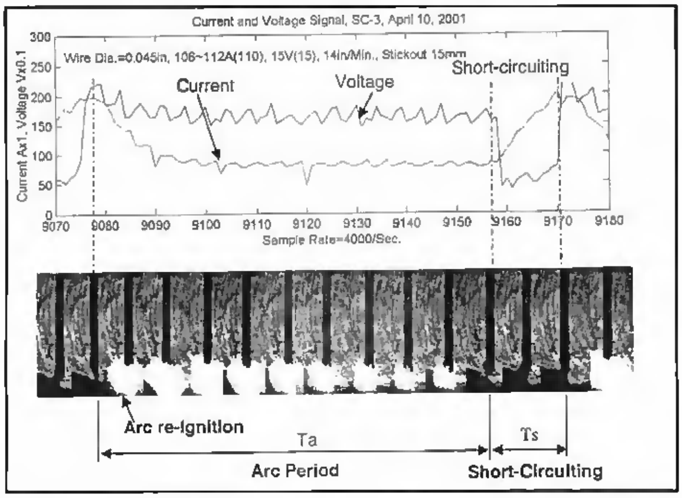


Fig. 1 — The captured images of a metal transfer in short-circuit GMAW and the corresponding welding current and voltage.

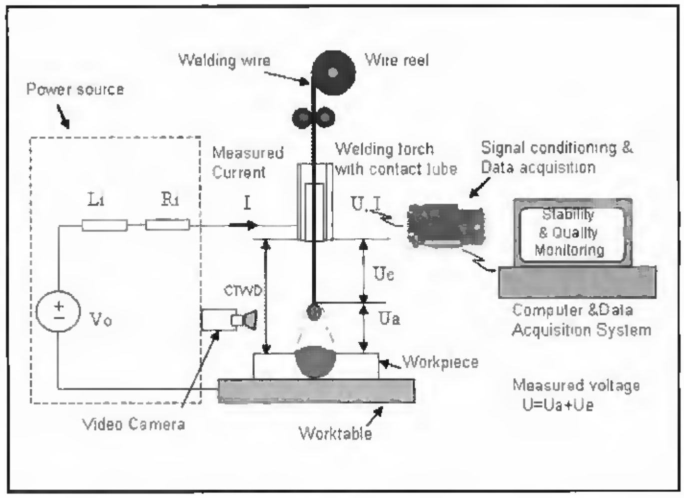


Fig. 2 — Schematic diagram of GMAW principle with data acquisition.

such as travel speed, wire feed rate, and welding voltage, is discussed and established. Signatures of welding processes for weld quality are analyzed and identified. The time-frequency analysis is used to identify the stability of a process at a specific time (or point). A systematic study based on experimental data shows that the power spectral analysis and time-frequency analysis methods are efficient approaches for stability and quality analysis of the GMAW process. This paper is organized as follows: the next section describes the short-circuit GMAW process, while the subsequent section presents signature analysis methodology, results and discussion, and a final summary.

Short-Circuit GMAW Process

Short-circuit GMAW is characterized by periodic contacts between the electrode wire and the weld pool. As shown in Fig. 1, the electrode wire melts and the molten droplet is formed at the electrode tip during the arcing period T_a. When the molten droplet touches the surface of the weld pool, short-circuiting transfer occurs, which extinguishes the arc. During the short-circuiting period T_s, the welding voltage decreases to its minimum value, and the current increases to its maximum value. Once the contact bridge breaks, the arc is reignited, and another short-circuiting cycle starts. Therefore, the short-circuiting frequency of the welding voltage and current corresponds to the characteristics of the molten metal transfer of a short-circuiting process.

The GMAW process employs a consumable wire electrode passing through a copper contact tube, as shown in Fig. 2. The welding voltage is measured between the electrode wire applied to the contact tube and the conducting worktable that serves as a reference. A Hall sensor is used to measure the welding current. After signal conditioning, the current and voltage are sampled by a data acquisition system with the sample frequency 4.0 kHz. The data are transferred to and stored in the computer. While the computer starts collecting current and voltage signals, a trigger signal is sent to a high-speed video camera to take images of the short-circuiting transfer process in a synchronous way. Thus, the real image description of a short-circuiting transfer process, as shown in Fig. 1, can be observed to correspond with the periodic changes with current and voltage signals.

Signature Analysis of Welding Processes

In this research, the welding voltage and current are used as main characteristic signals for signature analysis of the welding process. Since one cycle of welding current or voltage waveform corresponds to the transfer of one molten droplet in the short-circuiting process, the variation of the short-circuiting frequency of the current and voltage represents irregularity of metal transfer (i.e., the stability of the process). The following subsections will discuss the relationship between the short-circuiting frequencies, process stability, and weld quality by the power spectral density analysis and time-frequency analysis methods. First, the power spectral density and time-frequency functions are described. Next, the experimental results and computational analyses are presented.

Power Spectral Density Function

Power spectral density is a frequency-domain function. It is most directly interpreted as a measure of the frequency distribution of the mean square value of the data. For the sequence of a sampled signal with a finite interval N, $x(n)$, $n=0,1,\ldots,N-1$, the power spectral density is the discrete Fourier transformation of the autocorrelation function as follows (Ref. 10):

$$P_{xx}(f)=\sum_{k=-N+1}^{N-1} r_{xx}(k)e^{-j2\pi fk} \qquad (1)$$

where f is the frequency, $r_{xx}(k)$ is the autocorrelation function of a signal $x(n)$ given by

$$r_{xx}(k)=\frac{1}{N}\sum_{n=0}^{N-k-1} x(n)x(n+k),$$
$$k=0,1,\cdots,N-1. \qquad (2)$$

It can also be viewed in terms of direct Fourier transformation of the original data by

$$P_{xx}(f)=\frac{1}{N}\left[\sum_{k=0}^{N-1} x(k)e^{-j2\pi kf}\right]^2 \qquad (3)$$

The function $P_{xx}(f)$ defined in Equation 1 is equivalent to the corresponding function defined in Equation 3. Thus, spectral density functions can be estimated either through finite Fourier transformations of the correlation's functions, or through finite Fourier transformations of the original time history signals.

Time-Frequency Spectrum Function

The time-frequency analysis describes

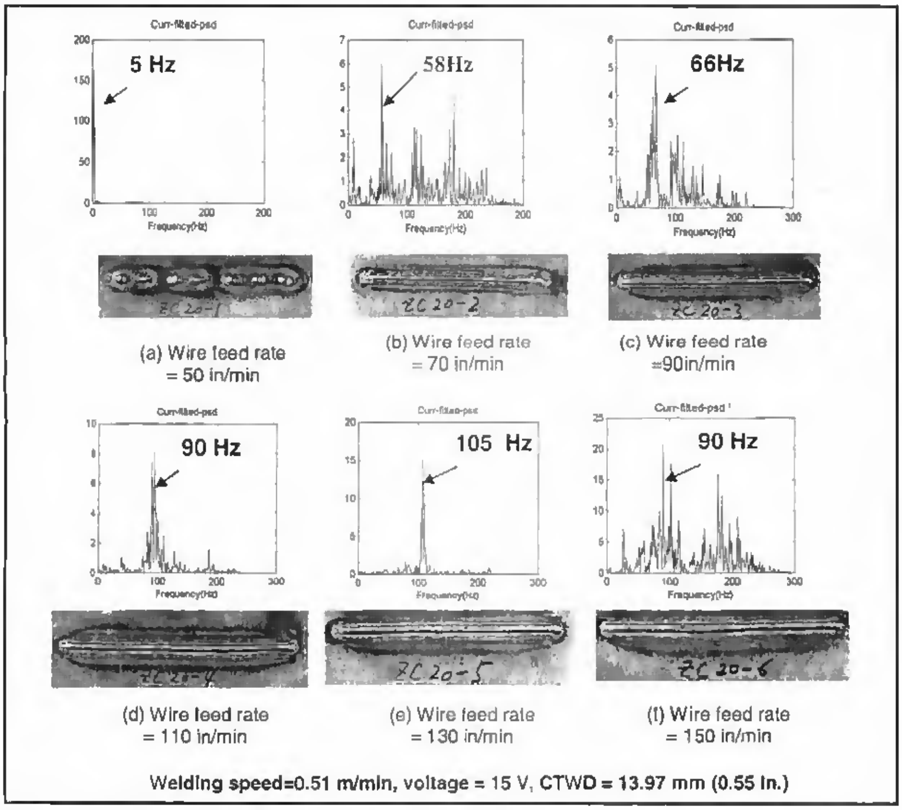


Fig. 3 — Power spectral density analysis for different wire feed rates (bare steel): A — 50 in./min; B — 70 in./min; C — 90 in./min; D — 110 in./min; E — 130 in./min; and F — 150 in./min. Welding speed = 0.51 m/min, voltage = 15 V, and CTWD = 13.97 mm (0.55 in.).

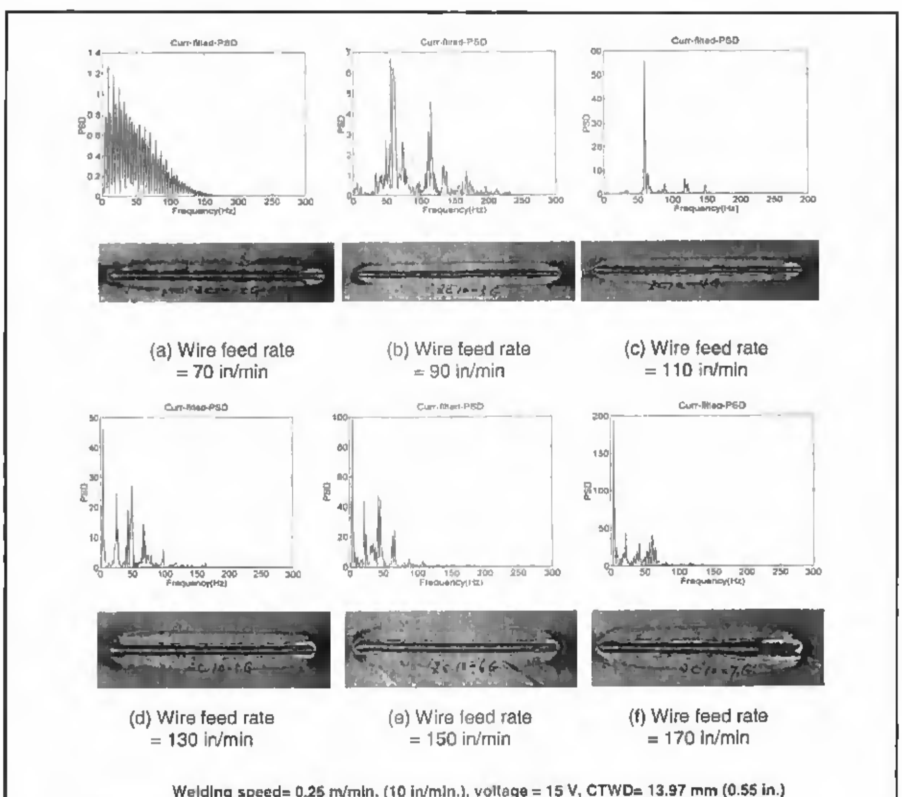


Fig. 4 — Power spectral density analyses for different wire feed rates (galvanized steel): A — 70 in./min; B — 90 in./min; C — 110 in./min; D — 130 in./min; E — 150 in./min; and F — 170 in./min. Welding speed=0.25 m/min (10 in./min), voltage=15 V, and CTWD=13.97 mm (0.55 in.).

how the frequency content of a signal is changed in time. There are several ways to theoretically describe the spectra of time varying signals, including the short-time Fourier transformation, the generalized spectrum, the evolutionary spectrum, the instantaneous autospectrum, and physical spectrum. The wavelet waveform can also be used to analyze nonstationary signals. The short-time Fourier transformation method is one of the simplest and most commonly used time-frequency representations and is employed in this study to analyze the time-frequency properties of the welding signals. A brief description of this method follows.

The basic idea is to first select, by means of a "window" function, a small piece of the signal about a time of interest. A standard Fourier analysis of this windowed signal is then used to infer frequency content at the selected time. We illustrate as follows: Consider $x(t)$ a time-varying signal, $h(t)$ a window function. Let t be the time of interest and τ the running time, then the window function $h(\tau)$ can be designed to emphasize the times around the time of interest $t-\tau$. Multiplying the signal $x(\tau)$ by the window function $h(t-\tau)$, centered on the time of interest $t-\tau$ obtains the weighted signal

$$x_h(\tau - t) = x(\tau)h(\tau - t). \tag{4}$$

Considering this signal as a function of τ and taking the spectrum of it yields the short-time Fourier transform (Ref. 11)

$$\begin{aligned} S(f,t) &= \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} x_h(\tau)e^{-j2\pi f\tau}d\tau \\ &= \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} x(\tau)h(\tau - t)e^{-j2\pi f\tau}d\tau \end{aligned} \tag{5}$$

where f is the frequency.

Then the power spectrum (also called the spectrogram) of the modified signal becomes

$$\begin{aligned} G(f,t) &= \left|S(f,t)\right|^2 \\ &= \left|\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty} x(\tau)h(\tau - t)e^{-j2\pi f\tau}d\tau\right|^2. \end{aligned} \tag{6}$$

The short-time Fourier transformation is the prototype of a time-frequency distribution and an extremely powerful tool in many areas. The advantage of the short-time Fourier transformation is that it has an easily understandable interpretation, as described above, and gives a good time-frequency representation for many signals.

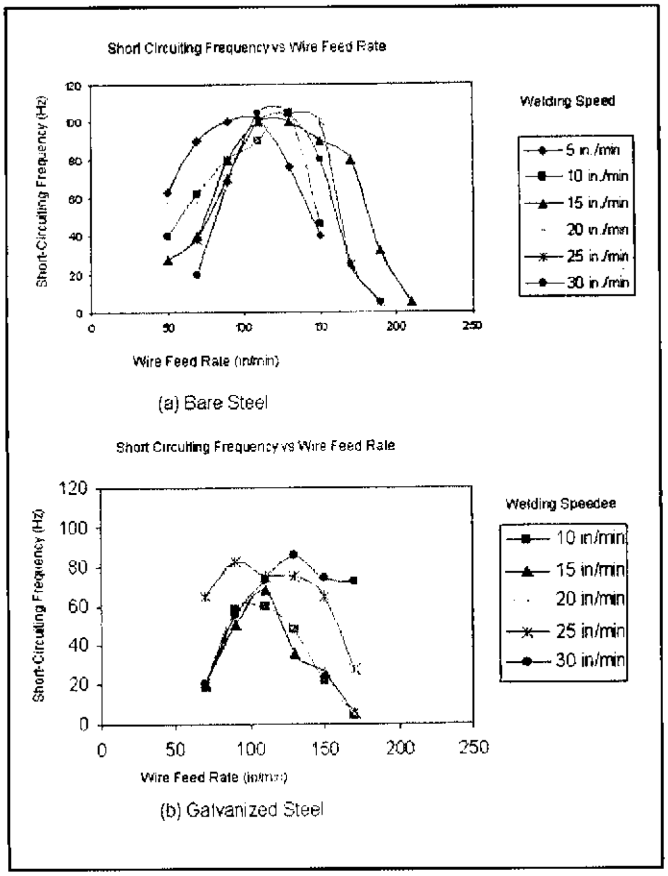


Fig. 5 — Relationship between the short-circuiting frequency and wire feed rates: A — bare steel; and B — galvanized steel.

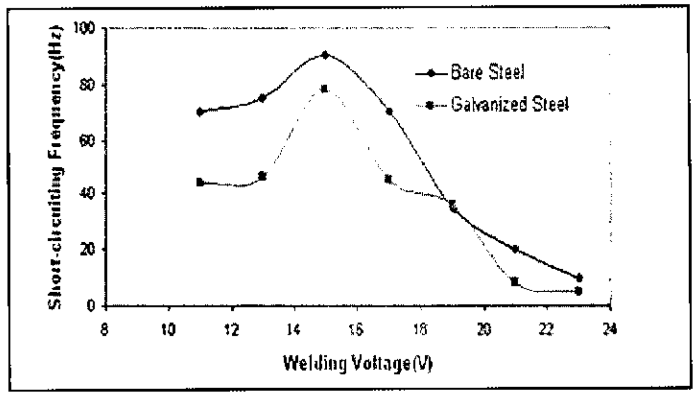


Fig. 6 — Relationship between short-circuiting frequency and welding voltage.

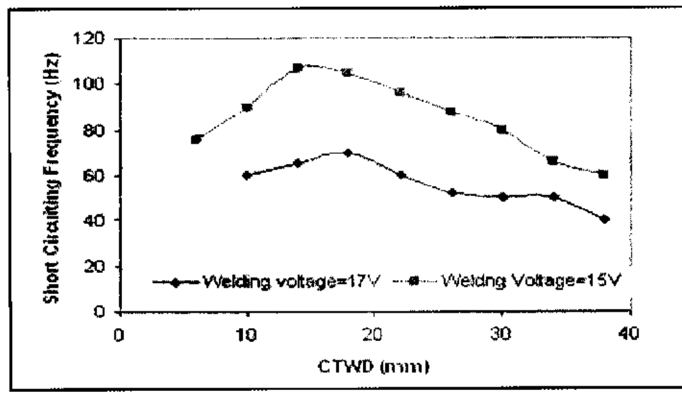


Fig. 7 — Relationship between short-circuiting frequency and CTWD.

The commonly used windows include rectangular, triangular, Hanning, Hamming, and Blackman windows. In this study, a Hanning window was chosen and it worked well for the welding signal analysis. The mathematical formula defining the Hanning window (Ref. 11) is as follows:

$$h(t) = \begin{cases} \left(1 - \cos(2\pi t)\right)/2, \ 0 \le t \le 1, \\ 0, \ otherwise \end{cases} \quad (7)$$

For the sequence of a sampled signal, the discrete form of the short-time Fourier transformation is used. The signal processing and algorithm implementation were done with the signal processing toolbox of Matlab.

Results and Discussion

Several sets of experiments with different welding parameters were conducted. Welding signals were collected and analyzed as described previously. A Powerwave 455 welding machine made by Lincoln Electric Co. was used as the welding power source, and an automatic traveling cart was employed to move the welding torch according to a preset welding speed. ER70S-6 was chosen as the welding filler metal. The contact tip-to-workpiece distance (CTWD) was 13.97 mm (0.55 in). Bare and galvanized steels with gauges of 0.063 in. (1.6 mm) were used in the welding trials. Bead-on-plate welds were made with GMAW using various welding parameters. Table 1 lists the welding parameters and welding consumables used in this study.

Table 1 — Welding Parameters and Consumables Used in the Study

Wire Type	Wire Diameter in. (mm)	Feed Rate in./min (m/min)	Voltage (volt)	Welding Speed in./min (m/min)	Electrode CTWD in. (mm)	Gun Angle	Shielding Gas	Flow Rate (ft^3/h)
ER70S-6	0.035 (0.9)	50–190 (1.27–4.83)	15	5~30 (0.127~0.765)	0.55 (13.97)	90 deg	75%Ar +25%CO_2	30

The welding voltage and current signals were collected by the data acquisition system during the experiments. Photographs of the weld surfaces were taken and weld specimens were cut to measure the weld bead geometry, and to check internal weld quality, porosity, and weld penetration. The weld surface quality was evaluated based on three criteria: uniformity of the weld bead width, smoothness of the weld surface, and amount of the spatter. Based on the evaluation result of the weld surface and the examination outcome of the weld cross section, a weld quality judgment was given to each weld. With the welding voltages and current signals, a low-pass filter is designed and applied to filter measurement noise and induced noise.

In the discussion that follows, we describe the analysis of various welding signals using the methods described above.

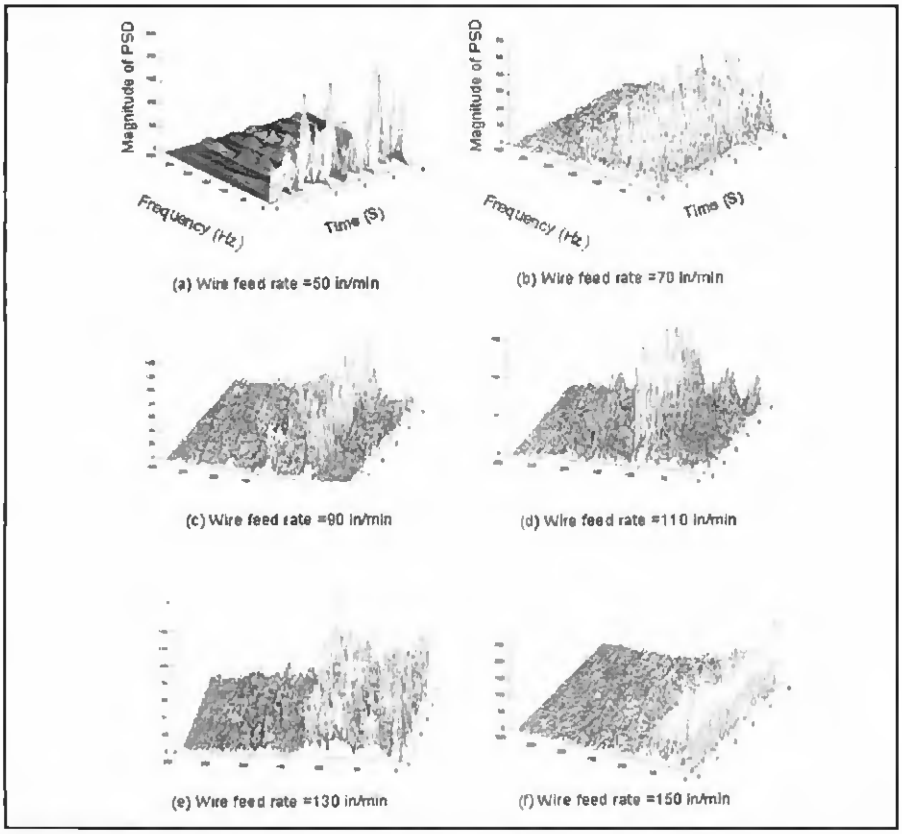


Fig. 8 — Time-frequency spectrum analyses for various wire feed rates under a welding speed of 30 in./min (for bare steel): A — 50 in./min; B — 70 in./min; C — 90 in./min; D — 110 in./min; E — 130 in./min; and F — 150 in./min.

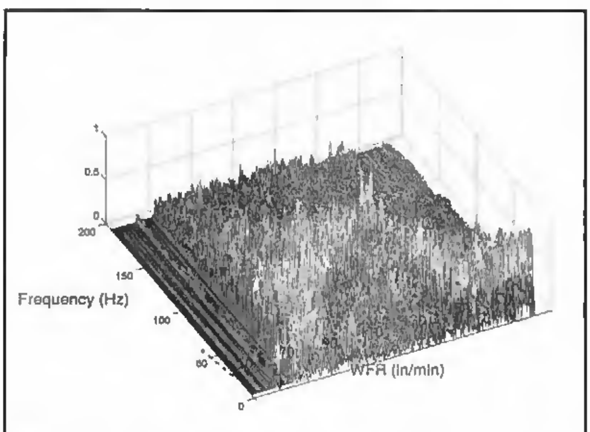


Fig. 9 — Frequency-wire feed rate spectral graph of the welding process for a welding speed of 20 in./min (for bare steel).

Power Spectral Density Analysis

By computing the power spectral density of welding currents (Equations 1 or 3), an analysis of welding experiments was carried out. Figures 3 and 4 show the power spectral density analysis results of the welding current at different wire feed rates for bare steel and galvanized steel, respectively. In the figures, the x-axis is the short-circuiting frequency (Hz); the y-axis is the power (or energy) density magnitude. As can be seen in Fig. 3, the maximal spectral peak varies when the wire feed rate changes from 50 to 150 in./min (1.27 to 4.83 m/min). The corresponding dominant frequency increases when the wire feed rate increases from 50 to 130 in./min (1.27 to 3.30 m/min). However, while the wire feed rate continues to increase, the dominant frequency decreases. This implies that there exists a wire feed rate at which the short-circuiting frequency reaches the maximum. At 130 in./min (3.30 m/min) wire feed rate in this set of experiments, the weld bead is observed to be the most uniform and exhibits the best surface quality. The different magnitudes in the power spectral density mean that the signals consist of different frequency components with comparable energy. The multifrequencies, as shown in Figs. 3A, 3B, 3C, and 3F, correspond to nonuniform welds and significant spatter. The welding process with a unique frequency (Figs. 3D and 3E) corresponds to uniform welds and good weld surface quality. A systematic analysis based on experimental data shows that the short-circuiting frequency is a determining factor on the stability of welding processes.

A series of experiments for galvanized steel was also conducted. The analysis results show that when the wire feed rate is 110 in./min (2.79 m/min), the dominant short-circuiting frequency of the process stays constant during the whole welding process and reaches the maximum, as shown in Fig. 4C. Similarly, as the wire feed rate increases from 70 to 170 in./min (1.78 to 4.32 m/min), the weld quality changes from poor to good, then to poor again. The best weld quality is obtained at a wire feed rate of around 110 in./min (2.79 m/min). A very interesting phenomenon is that there is a low-frequency component with very high energy when the wire feed rate is larger than 130 in./min (3.3 m/min) for galvanized steel. This can be explained by the fact that there is always a periodic long arc period after several normal short-circuiting periods. Once this phenomenon had occurred, there was much spatter during welding, which can be observed from the welds pictured in Fig. 4. A further study will be conducted for detailed explanation and analysis.

Figures 5A and B illustrate the relationship between the dominant short-circuiting frequency and the wire feed rate at different welding speeds for bare and galvanized steel, respectively. As can be seen, there is the maximal frequency around 105 Hz corresponding to different welding speeds for the bare steel. The maximal frequency has a slight right shift, but not much change when the welding speed increases. There is no significant change of the short-circuiting frequency for the galvanized steel and bare steel welding. The above analysis results show that most uniform welds can be obtained under a unique short-circuiting frequency reaching maximum value. Furthermore, keeping a constant short-circuiting frequency is a necessary condition to obtain a stable welding process and good weld quality. With this method, it is easy to test the various welding conditions and identify whether a welding process is stable or not. Based on the stability analysis, an operational range resulting in stable welding processes can be suggested.

Figure 6 shows the relationship between the short-circuiting frequencies and the welding voltages while other welding parameters are kept constant at a wire feed rate of 110 in./min (2.79 m/min), welding speed of 20 in./min (0.51 m/min), and CTWD of 0.55 in. (13.97 mm). From the figures, it can be seen that the short-circuiting frequency varies as the welding voltage changes. Especially when the voltage increases to 15 V, the frequency starts decreasing. As the welding voltage increases beyond this, the short-circuiting frequency decreases and weld surface quality becomes poor. In other words, under these experimental conditions, the short-circuiting frequency reaches a maximum around a welding voltage of 15 V, where the welding process is most stable, and the best weld quality is obtained.

Figure 7 illustrates the relationship between the short-circuiting frequency and CTWD when other welding parameters keep constant at a wire feed rate of 110 in./min (2.79 m/min), welding speed of 20 in./min (0.51 m/min), and welding voltage of 15 and 17 V, respectively. As shown in Figure 7, the short-circuiting frequency does not have much change; it becomes slightly smaller as CTWD increases. But the weld surface quality becomes poor. Similarly, there is a maximum short-circuiting frequency at which the welding process is most stable. With the same CTWD, the short-circuiting frequency under a welding voltage of 15 V is higher than under a welding voltage of 17 V. Compared with the CTWD and the welding voltage, the CTWD has less influence on the short-circuiting frequency and weld surface quality. However, it does affect the weld bead geometry and ignition of welding arc. The higher the CTWDs are, the shallower the penetrations.

Time-Frequency Analysis

If a welding process is stable and with constant metal transfer frequency, then the power spectral density can be used for analysis by taking any piece of the signal from the long welding process. But if a welding process is not stable or there are surface disturbances, then the welding voltage or current may fluctuate and the short-circuiting frequencies of the signals cannot be kept constant. For these nonstationary signals we use the time-varying spectrogram analysis method described above to perform a time-frequency analysis for the welding current. In this section we apply time-frequency analysis to again study the effect of wire feed rate on process stability. In the following subsection, we apply the method to explore the effect of several types of surface disturbances on process stability.

The experimental parameters were the same as used in the previous subsection. Figure 8 shows the time-frequency spectral graphs of the welding currents at six different wire feed rates at a constant welding voltage of 15 V, a constant CTWD of 0.55 in. (13.97 mm), and a welding speed of 30 in./min (0.76 m/min). In Fig. 8,

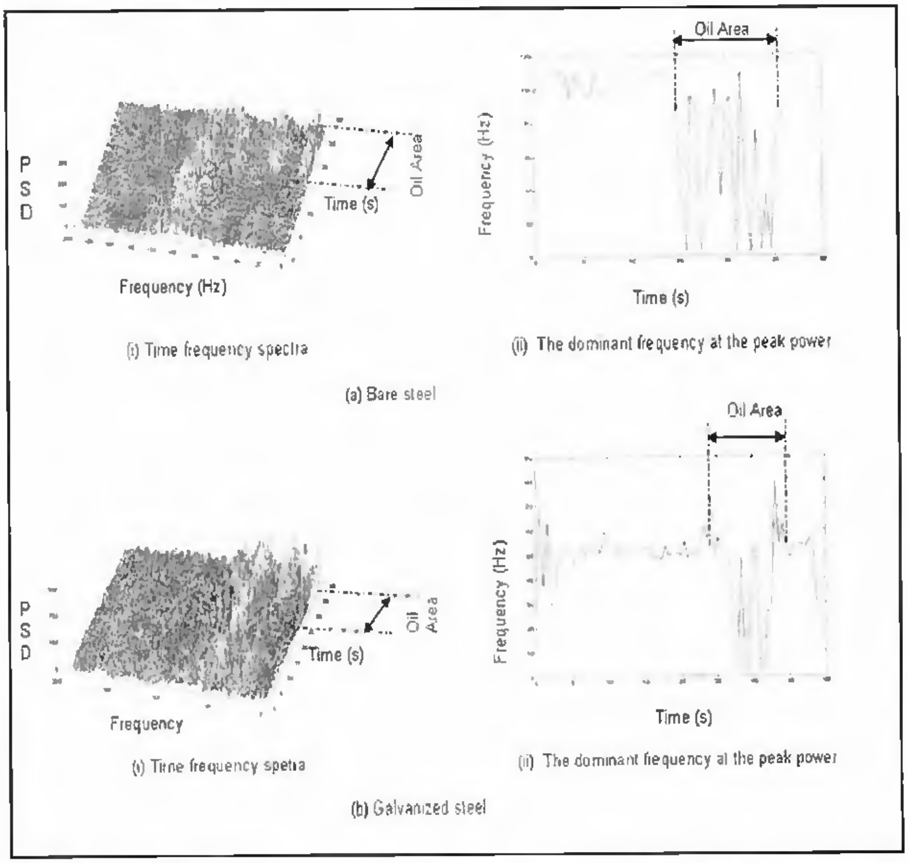


Fig. 10 — Time-frequency analyses of welding currents with oils on part of weld surfaces: A — bare steel; B — galvanized steel.

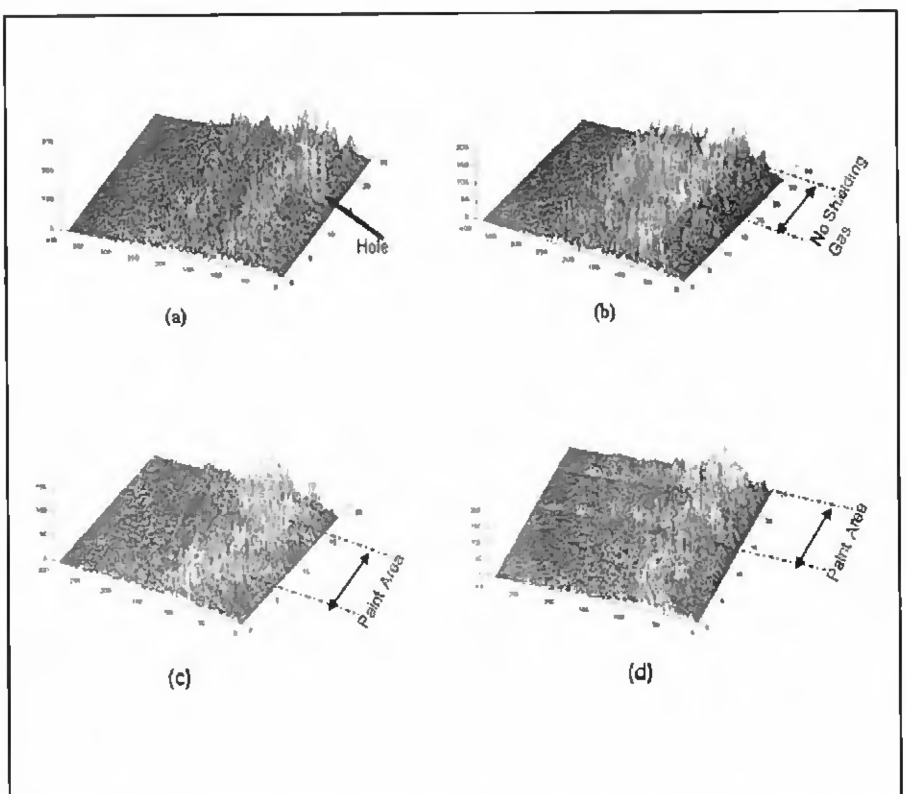
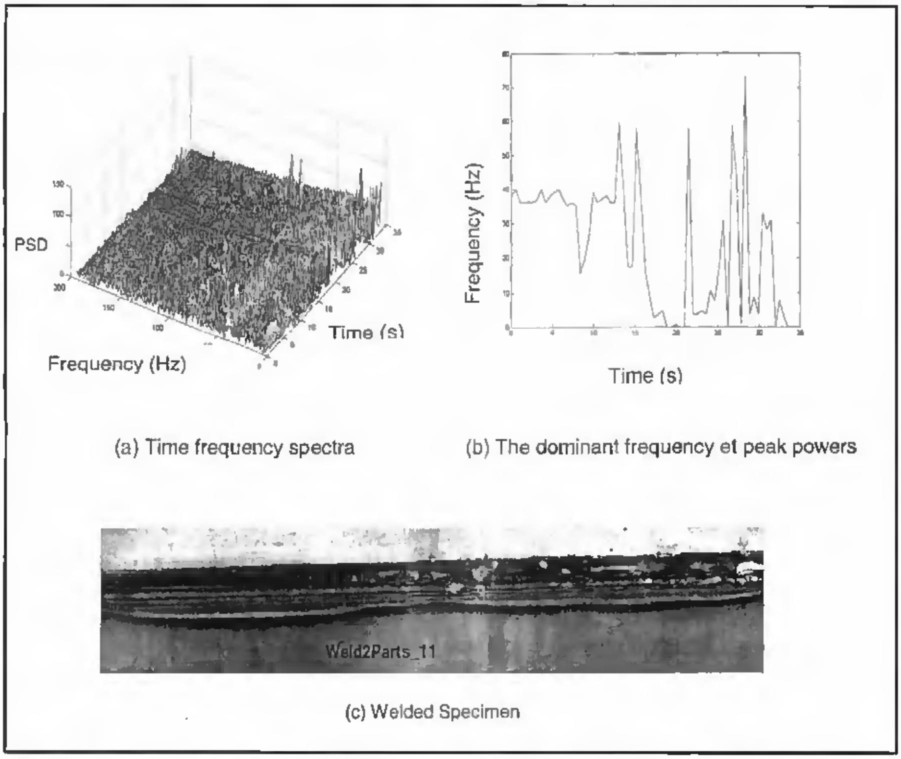


Fig. 11 — Time-frequency analyses with various disturbances: A — hole; B — no shielding gas; C — paint (bare steel); and D — paint (galvanized steel).



(a) Time frequency spectra

(b) The dominant frequency et peak powers

(c) Welded Specimen

Fig. 12 — Time-frequency analysis of welding current with the butt joint for two materials of bare and galvanized steels with different thicknesses: A — time-frequency spectra; B — dominant frequency at peak powers; and C — welded specimen.

the x-axis is time; y-axis is the short-circuiting frequency (Hz); and z-axis is the magnitude of the time-varying power spectrum function. From these graphs, it can be seen how the short-circuiting frequencies vary during a welding process and under different welding parameters.

As shown in Fig. 8, when the wire feed rate is 50 in./min (1.27 m/min), no periodic components and frequency components can be identified during certain time periods due to the irregular short-circuiting processes. No continuous weld was formed, only some weld spots. When the wire feed rate increases to 70 in./min (1.78 m/min), the frequency components distribution along the time axis is clearly shown in Fig. 8B. This figure shows that the spectrum of welding current contains a wide range of short-circuiting frequency components with comparable energy of signals. This means that the spectrum of welding current consists of different short-circuiting frequencies and the welding process was not stable. Based on the observation from Figs. 3, 8, and 9, the nonuniform weld surface is consistent with the signal analysis results. When the wire feed rate increases to 110 in./min (2.79 m/min) (Fig. 8D), the short-circuiting frequency stays almost constant during the whole welding process. This is a stable welding process and thus results in a very uniform weld surface. The analysis results show that the wire feed rate from 100 to 120 in./min (2.54 to 3.05 m/min) is a good range for obtaining stable welding processes for bare steel with a thickness of 0.06 in. (1.52 mm) under the welding voltage of 15 V, the CTWD of 0.55 in. (13.97 mm), and welding speeds from 5 to 30 in./min (0.127 to 0.762 m/min). Therefore, with the time-frequency analysis, it is easy to identify which welding process is stable, whether a process remains stable during a long welding process, and the variation of the short-circuiting frequency.

In Fig. 9, seven normalized time-frequency spectral results are combined together to intuitively compare the frequency components of signals under different wire feed rates (WFR), in the x-axis corresponding to 50, 70, 90, 110, 130, 150, and 170 in./min (1.27, 1.78, 2.29, 2.79, 3.30, 3.81, and 4.31 m/min), respectively. As can be seen in the figure, while the wire feed rate varies from 50 to 150 in./min (1.27 to 3.81 m/min), the obvious change of the dominant frequency can be observed. The figure demonstrates the stable regions [110–130 in./min (2.79~3.30 m/min)] of the welding processes at the designed welding conditions.

Time-Frequency Analysis for Welding with Disturbances

Various welding conditions were created for bead-on-plate welds by setting some disturbances on the plate surfaces. We examined the effect of oily surfaces, small holes, lack of shielding gas, and paint on the weld plate surface. With these disturbance conditions, two sets of experiments were conducted; one set for bare steel, the other for galvanized steel. The welding parameters kept constant were wire feed rate [110 in./min (2.79 m/min)], welding voltage (15 V), CTWD [0.55 in. (13.97 mm)], and arc welding speed [20 in./min (0.51 m/min)]. Also, a butt joint weld was carried out with two different materials, joining a bare steel sheet to a galvanized steel sheet.

Figures 10A and B show the time-frequency analysis results of the welding current with dirty oil on the plate surfaces for bare steel and galvanized steel, respectively. As observed from the appearance of the weld bead, this influenced the weld surface quality. The bead width and reinforcement become smaller than normal on the oily parts. As shown in Fig. 10A, at the first part, the welding process was operated under the normal condition; the dominant frequency is at mean 106.4 Hz, standard deviation (STD) 5.87 Hz. When going to the part with oil, the short-circuiting process was abnormal and the dominant frequencies at the peak powers vary dramatically with mean 60.2 Hz and STD 38.1 Hz. Thus, this results in the nonuniform weld. Figure 10B shows similar analysis results for galvanized steel, except that the mean value of the short-circuiting frequency was 60 Hz for galvanized steel, instead of 105 Hz for bare steel.

Figures 11A–D show the time-frequency analysis results for four kinds of disturbances: a small hole on the weld plate, lack of shielding gas, and some paints on plate surfaces, respectively. As shown in Fig. 11A, when the welding path passes a small hole, the welding current drops sharply and the short-circuiting frequency at that time decreases signifiantly.

Shielding gas is used to prevent oxidation and contamination of weld joints. The weld surface quality is sensitive to the lack of shielding gas. The weld surfaces of both the bare steel and the galvanized steel exhibit significant porosity when the shielding gas was insufficient or lost. The reinforcement and bead width are smaller than normal welds. The short-circuiting process during that period is not dominated by one frequency, but multifrequency components, as seen in Fig. 11B. This implies an unstable process. When some paint was put on the surfaces of both bare and galvanized sheet steels, the experimental results show that the weld bead geometries and surface quality changed at the painted area, which reflects the change of the welding voltage and current.

The bead width and weld penetration

at the painted area are narrower and shallower than those made at nominal conditions. As shown in the time-frequency analysis result of Fig. 11C, the mean of the short-circuiting frequency has changed, decreasing to 57.8 Hz on the painted surface from 97.5 Hz under the normal condition. For the galvanized steel, the welding current suddenly jumps from its normal value at the first boundary between the painted area and the unpainted area, and then returns to normal on the painted surface. But at the secondary boundary end edge between the painted area and the unpainted area, the welding current has a second jump. At these two boundaries, the weld beads have serious defects, very nonuniform, almost no reinforcement. The time-frequency analysis also shows the frequency change at the two boundaries in Figs. 11C and D.

Finally, we examined the joining of two sheets with different coatings. Bare steel and galvanized steel were welded together using a butt joint method. Figure 12C shows the picture of the weld. The first part of the weld is uniform and of good quality, but the second part of the weld shows defects due to the deviation of the root opening between the two parts caused by heat deformation after welding of the first part. The short-circuiting frequency at the first part is about 40 Hz, but at the second part, the short-circuiting frequency dropped and varied dramatically. The change of the frequency represents the weld surface quality change.

Summary

This paper focuses on the signature analysis of the short-circuiting frequency of GMAW processes for weld surface quality by using power spectral density and time-frequency analysis methods. The relationship between the short-circuiting frequency, welding stability, weld quality, and other welding parameters, such as the travel speed, the wire feed rate, and the welding voltage, was investigated based on experimental data analysis. A systematic analysis shows that the short-circuiting frequency is a determining factor on the stability of welding processes. A series of experiments was carried out for validation of the analysis results. The characteristic difference between welding processes for bare steel and galvanized steel were studied and compared. Based on the frequency signature analysis, a stable welding process and uniform weld beads can be obtained when the short-circuiting frequency remains stable and reaches its maximum. The analyses show that the time-frequency analysis method for welding signals is an effective approach for identifying the stability of processes and weld surface quality. This method is also very useful in tuning or refining a welding procedure to obtain the greatest level of stability. The study on the short-circuiting frequency of the metal transfer process is important in understanding the effect of welding parameters on short-circuiting processes and weld stability in GMAW.

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