Separately Excited Resonance Phenomenon of the Weld Pool and its Application

Resonance phenomenon of the weld pool is used for measurement and real-time control of full joint penetration

BY Q. L. WANG, C. L. YANG AND Z. GENG

ABSTRACT. On the basis of a study of weld pool resonance phenomenon in stationary gas tungsten arc (GTA) welding of a thin steel plate with a straight polarity pulsating current of a certain frequency, a new method of real-time full joint penetration detection from the top side of the weld using an arc sensor was developed. The correlation between weld pool resonance frequency and top bead width, as well as under bead width, has been studied. An experimental system of full joint penetration control for a thin steel plate was developed. It is shown that by using this system, the real-time control of top and under bead widths can be successfully realized in thin steel plate welding. Stable and regular weld formation, even under severe external interference, has satisfactorily verified its promised controlling capability.

Introduction

Along with the development of welding technology, many researchers have been engaged in the study of full penetration control of welds. The aim is to find a reliable real-time automatic control system to get the expected topside and underside bead formation without lack of penetration or burn through, even under severe interferences such as different heat sinking conditions or joint misalignment. The key problem of this project is how to detect reliable penetration information, especially from the topside of the weld pool, conveniently and in real-time. Miscellaneous influences on the weld penetration of welding conditions, and the impossibility of direct measurement of penetration, make the problem more difficult to solve. Though various efforts have been made to sense the weld pool size in real-time from the topside such as ultrasonic detection, infrared sensing, pool image processing, and radiographic sensing, and considerable success has been made (Refs. 1–5), the problem is still far from being solved, and much work still has to be done, especially in practical applications.

In recent years an approach of weld pool size detection by weld pool oscillation signals was developed. D. J. Kotecki, *et al.*, first discovered the phenomenon of weld pool oscillation in the study of weld formation (Refs. 6, 7). R. J. Renwick and R. W. Richardson, *et al.*, have studied weld pool control on the basis of weld pool oscillation in GTAW by superimposing a current impulse on the DC welding current (Refs. 8–10). They implemented a method to detect pool oscillation from the arc voltage signal and obtained a close correlation between weld pool size and weld pool oscillation frequency. Later studies (Refs. 11 through 14) focused on the philosophy of pool oscillation, weld pool size control by pool oscillation, and implementing the new approach in practice. But the results have met with limited success due to unsatisfactory reproducibility of the signal, and inability to avoid interference from the joint misalignment and the arc traveling. Thus, this method is difficult to use in practice for weld pool size detection and control. This paper presents a new way to detect real-time information of weld pool size directly from the arc voltage signal on the topside of the weld pool, using separately excited resonance phenomenon of the weld pool. It may offer a very promising prospect for full penetration control of welds and may be easier to introduce in production.

KEY WORDS

Resonance Phenomenon
Weld Pool
Real-Time Control
Full Penetration
GTAW
Thin Steel Plate
Arc Sensor
Butt Joint Welds
Arc Voltage
Computer Monitor

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Principle and Experimental Method

Any volume of liquid with definite mass, shape, size and restraint conditions will be excited to oscillate with a definite natural frequency if a separate instantaneous force is imposed on it. If a periodic force, other than an instantaneous one, is applied on a liquid surface, and if the frequency of the periodic force is equal to the natural oscillation frequency of the liquid, a resonance will happen. At that moment the maximum oscillating amplitude of the liquid surface will be produced. At any periodic force frequency other than the natural oscillation frequency of the liquid, the resonance will not happen, though the liquid will oscillate with the periodic force frequency at an amplitude much less than that of resonance.

When a stationary GTA welding arc ignites on the work, a weld pool will form and gradually grow with the arc heating until it reaches thermal equilibrium. Meanwhile, the natural oscillation frequency of the weld pool will vary accordingly and its value will always correspond with the weld pool size. If a straight polarity pulsating current (consisting of a DC base current component

and a sine wave ripple current component) with a certain frequency is applied to the arc, the arc force imposed on the weld pool surface will also be pulsating. According to the above mentioned principle, the weld pool will oscillate, and the oscillation frequency will be equal to that of a pulsating current. As soon as the growing weld pool size reaches a value where the weld pool natural oscillation frequency is equal to the frequency of the pulsating current, the weld pool will be in resonance, with the pulsating current and the pool oscillation amplitude reaching their maximum.

Since all actions of weld pool oscillation are involved in arc voltage signals through arc length variations, the arc itself can be used as a sensor to signal the moment of weld pool resonance by measuring the maximum weld pool oscillation amplitude. Corresponding with the given frequency of the pulsating current, the definite resonance weld pool size can be detected at the moment when the maximum oscillation amplitude occurs. By changing the pulsating current frequency, different weld pool resonance sizes can be obtained and controlled. On the basis of this principle, a new method of real-time full joint penetration control in GTA welding is presented in this paper.

In order to detect weld pool resonance, an experimental resonance monitoring system was built. It consisted mainly of a transistor current supply for the welding arc, a filter, a computer data acquisition unit, and an oscilloscope (a digital memory scope type MS-1650B, TRIO) — Fig. 1. The transistor current supply for the welding arc outputs a straight polarity pulsating current i(t) of various frequencies and different levels — Fig. 2. Essentially, this output current is a combination of a direct base current component I_b and a sine wave ripple current component $i_r(t)$. Because the current supply features an infinite internal impedance and its output current is independent from the external load, the weld pool oscillation information is reflected in the arc voltage variation signal and can be derived from it without significant deviation.

It is obvious that the voltage signal picked up from the arc also exhibits straight polarity pulsating behavior, but the amplitude of the alternating voltage component is changed vs. time due to the arc length variation produced by the oscillation of the growing weld pool. Maximum amplitude implies that the weld pool is in resonance with the pulsating arc current. We are interested only in the alternating voltage component of the signal, since the weld pool oscillation is related only to this. In fact, the alternating voltage component itself consists of two parts.

The first one is the arc load voltage drop, equal to the product of the applied pulsating current and the arc resistance. This voltage drop is similar to that of the pulsating current. Generally, the given pulsating current is set up and the arc shielding gas is unchanged, so this part of the alternating voltage component is definite and independent from the weld pool oscillation.

The second part is the arc length variation due to the weld pool oscillation, which is excited by the pulsating current. Since the weld pool is gradually growing, its natural oscillation frequency is varying, while the frequency of the pulsating current is fixed. As the weld pool natural oscillation frequency approaches the frequency of the pulsating current, the amplitude of the weld pool oscillation gradually increases. As soon as the weld pool reaches a size where the weld pool natural oscillation frequency is equal to that of the given pulsating current; *i.e.*, resonance occurs, and the amplitude of the alternating voltage component of the signal reaches maximum value. Thus, only the amplitude variation of the alternating voltage component of the signal can provide the information for weld pool resonance. The moment when the maximum amplitude appears can serve as the moment when the weld pool size reaches the value determined by the preset frequency of the pulsating current. So the filter (Fig. 1), with a central frequency equal to that of the pulsating current, permits picking up the alternating arc voltage component. This signal is then put into the computer for sampling and discriminating after analog-digital (A/D) conversion to provide the resonance moment of a certain weld pool size, and simultaneously to give a control pulse to the power source for turning off the arc current.

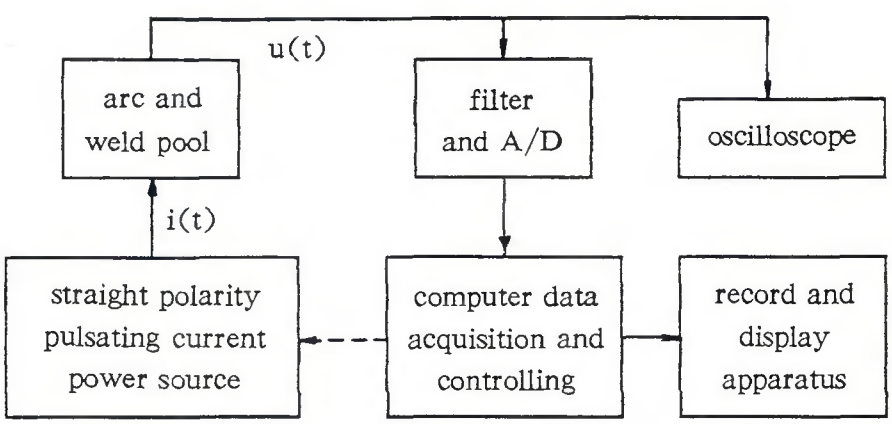
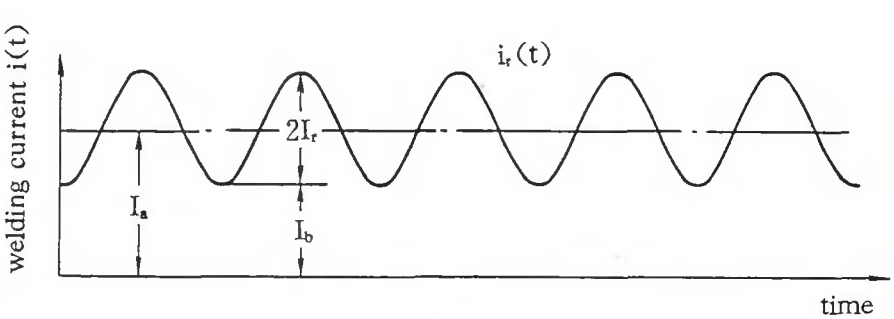


Fig. 1 — Schematic diagram of the monitoring system of weld pool resonance signal. Solid line = monitoring circuit of weld pool resonance signal; dotted line = controlling circuit of power source by a pulse signal.



$i(t)$ = instantaneous value of the straight polarity pulsating current
$i(t) = I_b + I_r + i_r(t) = I_b + I_r(1 + \sin\omega t)$
ω = frequency of pulsating current
I_b = direct base current component
I_r = amplitude of the sine wave ripple current component
I_a = average value of the straight polarity pulsating current. $I_a + I_b + I_r$
$i_r(t)$ = instantaneous value of the sine wave ripple current component. $i_r(t) = I_r \sin\omega t$

Fig. 2 — Straight polarity pulsating current.

Weld Pool Size Monitoring and Its Analysis

Specimens for the test were made from low carbon steel (type 1015) and stainless steel (type 304) 1–3 mm thick. The specimen dimension was 300 × 40 mm. The GTA welding was conducted without backing or filler metal. The tungsten electrode diameter was 3 mm. The flow rate of argon was 5 L/min.

In this paper, we shall only deal with thin steel plates 1–3 mm thick. For such thin plates, a full penetration weld will be a generally accepted requirement. In this case, in order to simplify the concept of weld pool size, we define it as the average of topside and underside diameter of the weld pool (for a series of overlapping spot welds, with average topside and underside bead width).

Welding Pool Resonance Phenomenon

Using the electrode negative (straight polarity) pulsating current with a definite frequency as shown in Fig. 2, a stationary GTAW arc is started on a 2-mm low-carbon steel plate. The arc voltage trace is displayed by an oscilloscope, and at the same time, the arc voltage amplitude variation is recorded and processed by a computer. The following two phenomena were discovered:

1. During the process of weld pool growth, the maximum amplitude of the arc voltage alternating component can clearly be observed at the instant when the weld pool resonance apears — Fig. 3A. The weld pool oscillation amplitude corresponds well with the amplitude of the alternating arc voltage component. When the alternating arc voltage amplitude reaches its maximum, the weld pool size is at its resonance size.

2. With the arc heating, the weld pool grows, and the amplitude of the alternating arc voltage gradually increases. As soon as the weld pool size exceeds that of resonance, the amplitude of the alternating arc voltage component decreases sharply, then reaches its minimum value and gradually returns to the level before resonance — Fig. 3A. This phenomenon will be discussed in detail later.

Figure 3B is a computer monitored record of this phenomenon. Experiments have proven its good reproducibility and reliability with pulsating current frequencies in the range of 30–120 Hz. When the pulsating current frequency is varied, the moment of weld pool resonance appearance changes accordingly. The higher the pulsating current frequency, the earlier the resonance appears and the smaller the weld pool resonance size. Experiments indicated that the variation of the average value of the straight polarity pulsating current I_a and the amplitude of the sine wave ripple current component I_r within certain limits, does not affect the weld pool resonance features very much. Figure 3B is obtained by I_a = 70 A, I_r = 30 A, f (frequency of pulsating current) = 60 Hz, δ = 2 mm, material: low-carbon steel.

Detection of the Weld Pool Size and its Relationship with the Resonance Frequency

To detect weld pool size with the weld pool resonance method, stationary arc welding is carried out on thin steel plate with a straight polarity pulsating current at different frequencies. The amplitude variation of the alternating arc voltage component is acquired using a computer. Meanwhile, the acquired values are compared with the given data in real-time. As soon as growing pool size exceeds resonance size, the amplitude reaches the maximum and suddenly decreases steeply. In experiments, we take a 100 mV decrease in arc voltage as a threshold for the computer to offer a control pulse to turn off the welding power source (through the dotted line in Fig. 1). At this moment the weld pool possesses the resonance size, which can be measured after the weld pool solidifies. As a result, the measured weld pool resonance sizes correspond with the preset frequencies of the pulsating current. This process is explained schematically in Fig. 4. Changing the frequency of the pulsating current, various distinctive points of the weld pool natural oscillation frequency and the

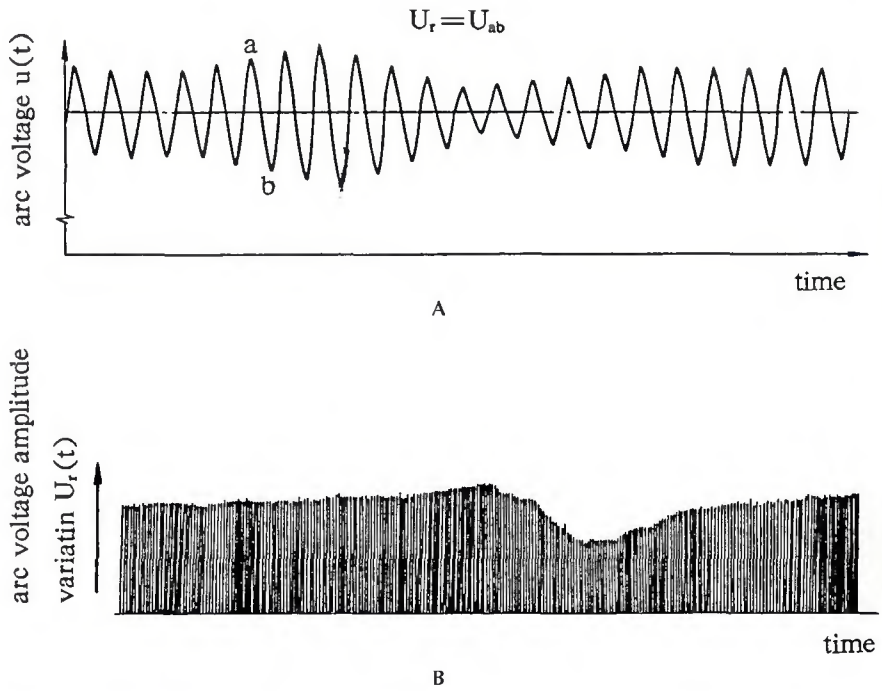


Fig. 3 — The voltage amplitude variation in the weld pool oscillation process. A — Oscillation observation of the arc voltage from oscilloscope; B — the computer monitored result of the arc voltage amplitude variation.

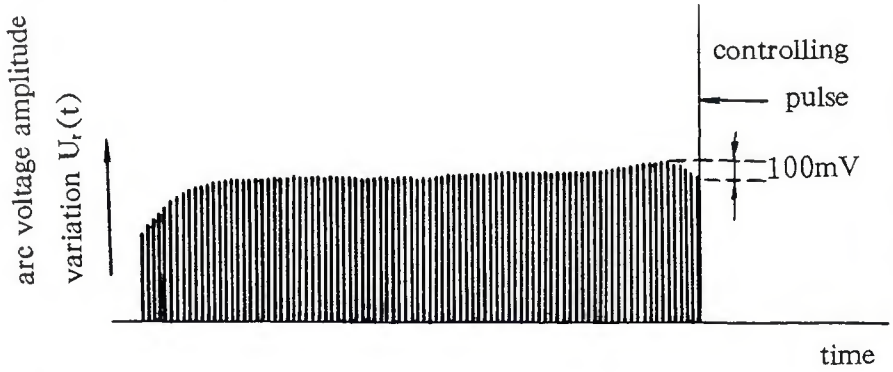


Fig. 4 — Computer monitored amplitude variation of the arc voltage and the controlling pulse provided by computer.

corresponding weld pool resonance sizes can be obtained. This is demonstrated schematically in Fig. 5. It shows that different weld pool sizes can be obtained by changing the superimposed pulsating ripple current frequency. Plots of weld pool resonance frequencies vs. weld pool resonance sizes are shown in Fig. 6. These results indicate good linearity between the weld pool resonance frequency and resonance sizes. The larger resonance size, the lower the resonance frequency. We have also found that for a constant pulsating current frequency, the maximum deviation of the weld pool resonance sizes is 0.3 mm.

Analysis of the Weld Pool Resonance Phenomenon

For weld pool oscillation monitoring through arc voltage, the input of the system is the welding current, and the output is the arc voltage. The output arc voltage is essentially determined by the welding current and the arc length. Generally, in GTA welding, the torch-work distance is fixed and the arc length variation is only caused by the weld pool oscillation excited by the welding current. Thus, the arc voltage can be considered as a monotropic function of the welding current.

In order to study the arc voltage variation $\Delta U(s)$ response to the welding current $I(s)$, the input welding current and the output arc voltage can be related by the transfer functions indicated in Fig. 7 whereby $G_1(s)$ is a transfer function determined by the arc dynamic characteristic $v_a(t)$, $G_2(s)$ is a transfer function between the arc current $I(s)$ and the arc force $P(s)$, $G_3(s)$ is a transfer function between the arc force $P(s)$ and the weld pool oscillation amplitude $Y(s)$. $G_4(s)$ is a transfer function between the weld pool oscillation amplitude $Y(s)$ and the arc voltage variation $\Delta U_2(s)$.

In GTA welding with pulsating current, due to arc heat inertia, the arc dynamic characteristic features in a hysteresis loop. To simplify the problem, $G_1(s)$ can be approximated to a first order ratio differential system with inertia. Then $G_1(s)$ can be approximated as

$$G_1(s)=\frac{\Delta U_1(s)}{I(s)}=\frac{K_1T_1S}{T_1S+1} \qquad (1)$$

where K_1 is a coefficient, T_1 is a time constant of the arc dynamic characteristic, and $\Delta U_1(s)$ is the arc voltage variation caused by the welding current variation.

It has been proven that arc force is proportional to the square of the current in GTAW. Within the low current range, the relation of arc force and arc current can be aproximated to a proportional relation, as:

$$G_2(s)=\frac{P(s)}{I(s)}=K_2 \qquad (2)$$

where K_2 is a factor of proportionality.

It is well known that the weld pool is a second order oscillation system. Thus, $G_3(s)$ can be shown as

$$G_3(s)=\frac{Y(s)}{I(s)}=\frac{K_3}{T_2^2S^2+2\xi T_2S+1} \qquad (3)$$

where T_2 is a time constant of oscillation, $T_2 = 1/\omega_n$, ω_n is the weld pool natural oscillation frequency, ξ is a damping coefficient of weld pool oscillation, and K_3 is a coefficient.

It is clear that arc voltage is proportional to arc length, so

$$G_4(s)=\frac{\Delta U_2(s)}{Y(s)}=K_4 \qquad (4)$$

where $\Delta U_2(s)$ is an arc voltage variation caused by the arc length variation and K_4 is a factor of proportionality.

From Equations 2 through 4, a transfer function of $I(s)$ and $\Delta U_2(s)$ caused by weld pool oscillation is derived as

$$\frac{\Delta U_2(s)}{I(s)}=G_2(s)G_3(s)G_4(s)=\frac{K_2K_3G_4}{T_2^2S^2+2\xi T_2S+1} \qquad (5)$$

From Fig. 7,

$$\Delta U(s)=\Delta U_1(s)+\Delta U_2(s) \qquad (6)$$

In Equation 3, the weld pool natural oscillation frequency ω_n is closely related to the weld pool size. We can study the weld pool oscillation law through frequency-response analysis of the transfer function. The typical method of frequency-response analysis is to input a sine wave to study the output variation vs. the sine wave frequency.

In order to make a frequency-response analysis for the arc weld pool system, we assume $i_r(t) = I_r\sin\omega t$ as the

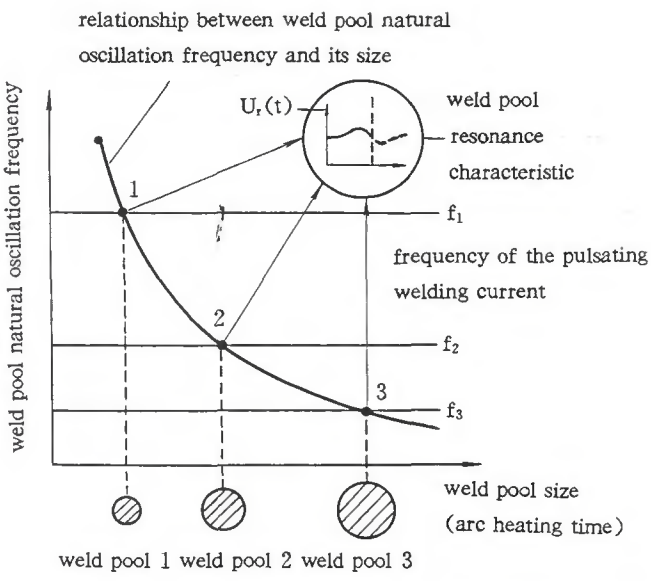


Fig. 5 — Principle of weld pool resonance size detection by using different pulsating current frequencies.

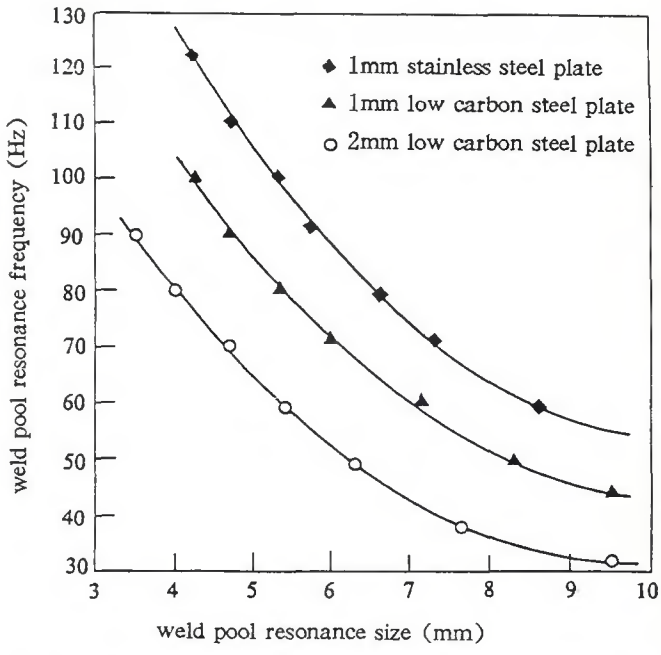


Fig. 6 — Relationships of the weld pool resonance frequency and the resonance size (the average of topside and underside diameters of the weld pool).

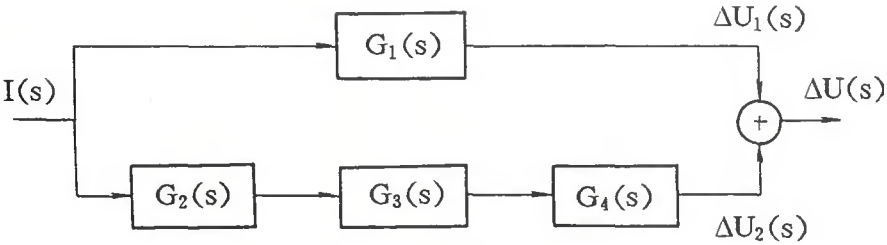


Fig. 7 — Block diagram of transfer function of the monitoring system.

input sine wave welding current, where ω is the frequency of the sine wave current — Fig. 2. It differs from the real welding current by a direct current component I_a. Because this direct current component has no effect on the dynamic response of the system, it can be ignored in the frequency-response analysis.

The frequency response of the system can be obtained from its transfer function by substituting $s = j\omega$. By the action of a sine wave signal, when the system reaches stabilization after the transient process, the ratio of output amplitude to input amplitude can be expressed by the amplitude-frequency response of the system, and the phase difference between them can be expressed by the phase-frequency response. Thus, the frequency response of the system indicated in Fig. 7 can be achieved.

The frequency response equation of the arc voltage variation $\Delta U_1(s)$ caused by the welding current variation can be written as follows:

amplitude-frequency response

$$\Delta U_1(\omega) = \frac{K_1 T_1 \omega}{\sqrt{1+T_1^2\omega^2}} \tag{7}$$

phase-frequency response

$$\Phi_1(\omega) = arctg\frac{1}{T_1\omega} \tag{8}$$

The frequency response equation of the arc voltage variation $\Delta U_2(s)$ caused by the arc length variation produced by the weld pool oscillation, which is in turn excited by the pulsating arc current, can be written as follows:

amplitude-frequency response

$$\Delta U_2(\omega) = \frac{K_2 K_3 K_4 I_r}{\sqrt{\left(1-T_2^2\omega^2\right)^2 + \left(2\xi T_2\omega\right)^2}} \tag{9}$$

phase-frequency response

$$\Phi_2(\omega) = -arctg\frac{2\xi T_2\omega}{1-T_2^2\omega^2} \tag{10}$$

As mentioned above, K_1 through K_4 are constant and can be determined experimentally $T_2 = 1/\omega_n$. The damping coefficient ξ has been proven by the impulse response test to be $\xi < 0.05$, and the weld pool can be regarded as a low damping system.

In our study, a sine wave current component with a definite frequency is used to excite the weld pool oscillation. Along with the arc heating time, the weld pool grows and its natural oscillation frequency varies correspondingly. The weld pool can be considered as an oscillation system at every moment of its growth. Thus, we can investigate the law of arc voltage variation using the weld pool natural oscillation frequency ω_n as a variable parameter.

When the frequency ω of the alternating welding current is definite, from Equations 7 through 10, we can achieve the frequency responses ($\Delta U_1(\omega)$, $\Phi_1(\omega)$) of arc voltage variation $\Delta U_1(s)$ caused by current variation, and the frequency responses ($\Delta U_2(\omega_n)$, $\Phi_2(\omega_n)$) of arc voltage variation $\Delta U_2(s)$ caused by weld pool oscillation. These frequency responses are shown in Fig. 8. It is clear that when the welding current frequency ω is definite, $\Delta U_1(\omega)$ and $\Phi_1(\omega)$ are constant and independent from the weld pool oscillation. However, $\Delta U_2(\omega_n)$ and $\Phi_2(\omega_n)$ are closely related to the weld pool oscillation.

When $\omega_n > \omega$ (weld pool size is small), $\Delta U_2(\omega_n)$ increases gradually with the ω_n decreasing (weld pool growing). When $\omega_n = \omega$, $\Delta U_2(\omega_n)$ reaches its maximum, which implies that the weld pool has grown into a certain size whose natural oscillation frequency ω_n is equal to the frequency ω of the pulsating welding current. The amplitude of the weld pool oscillation reaches its maximum, as does the arc voltage variation. When $\omega_n < \omega$ (the weld pool size exceeds the weld pool resonance size), $\Delta U_2(\omega_n)$ decreases with ω_n decreasing (weld pool grows further).

The combination of arc voltage variations results from the vector sum of two parts $\Delta U_1(\omega)$ and $\Delta U_2(\omega_n)$. Its amplitude-frequency response can be written as follows:

$$\Delta U(\omega_n) = \sqrt{\begin{array}{l}\Delta U_1^2(\omega) + \Delta U_2^2(\omega_n) \\ +2\Delta U_1(\omega)\Delta U_2(\omega_n) \\ \cos(\Phi_1 - \Phi_2)\end{array}} \tag{11}$$

The amplitude-frequency response curve of $\Delta U(\omega_n)$ is shown in Fig. 8. It shows that $\Delta U(\omega_n)$ varies abruptly near the point of the resonant peak of $\Delta U_2(\omega_n)$; *i. e.*, the point where $\omega_n = \omega$. As the weld pool grows, the amplitude of the arc voltage variation increases with ω_n decreasing. When ω_n is near ω, $\Delta U(\omega_n)$ reaches its maximum, then abruptly falls to its valley point when ω_n is slightly less than ω, and then gradually increases to its original level. The existence of a valley point can be explained with the phase-frequency response of $\Delta U_1(s)$ and $\Delta U_2(s)$. In fact, when ω is fixed, $\Delta U_1(s)$ possesses a constant phase-shift independent from the weld pool oscillation (from Equation 8). However, the phase-shift $\Phi_2(\omega_n)$ of $\Delta U_2(\omega_n)$ will vary from 0 to –180 deg with ω decreasing (Equation 10). At the point where $\omega_n = \omega$, the phase-shift is –90 deg, $\Delta U_1(s)$ and $\Delta U_2(s)$ are in homophase and subtracted from each other. At the point where $\Phi_1 - \Phi_2 = 90$ deg, $\Delta U(\omega_n)$ reaches its maximum. Because of Φ_1, from Equation 8, the maximum value of $\Delta U(\omega_n)$ appears not just at but near and before the reso- nance point. After that, the $\Delta U(\omega_n)$ abruptly decreases and falls to the valley point. As ω_n further decreases, $\Delta U(\omega_n)$ will gradually return to the level of $\Delta U_1(\omega)$. A similar result can be achieved if either ω_1 or ω_2 is substituted for ω. Based on the above analysis, the phenomena indicated in Fig. 3B can be explained satisfactorily. It is also verified that the newly developed approach of weld pool resonance for detection and control of weld pool size is reasonable and feasible.

Real-Time Full Penetration Control System for GTA Welding of Thin Steel Plate

The Principle Components Of The Control System and Its Working Procedure

Our experiments have proven that in stationary GTA welding of a thin steel plate, the weld pool size can be monitored and controlled by using the weld pool resonance principle. But for a continuously traveling arc, some problems still exist in detecting the weld pool oscillation signal. In the case of a continuously traveling arc, the weld pool shape is other than a circle and is asymmetrical about its transverse axis. The action point of the arc force mostly deviates from the center of gravity of the weld pool (Ref. 16). As a result, the weld pool oscillation will be weak and irregular, and its signal will no longer represent the weld pool size as it would in stationary GTA welding. Therefore, a satisfactory weld pool oscillation signal can be obtained only at very low traveling

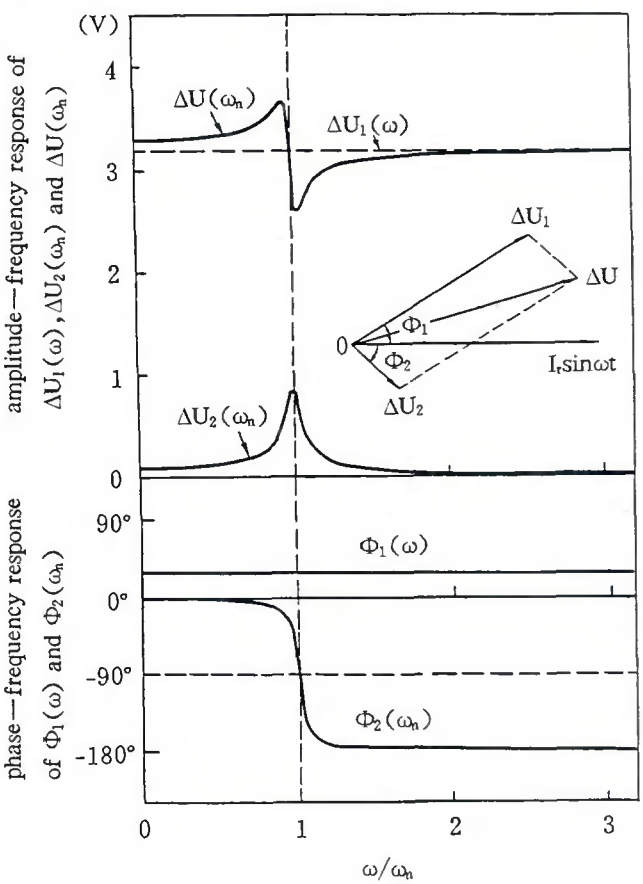
speeds. For our study, we used a step arc traveling method to overcome all the difficulties in the continuous welding process. For this purpose, a control system consisting of a straight polarity pulsating current power source, a step arc traveling mechanism, and a computer data acquisition and controlling installation was developed — Fig. 9. Before welding, the pulsating current frequency was preset according to calculation and experiment. The current value (both the direct base component and the amplitude of the sine wave ripple current component) was selected according to plate thickness. For a steel plate 1–3 mm thick, I_b = 40–80 A, and I_r =30–50 A. The frequency of the pulsating current was selected according to the expected weld pool size and the welded plate thickness. It ranged from 50–130 Hz for 1–3 mm steel plates.

The direct base current component mainly contributes to maintaining the arc when it moves step-by-step. The aim of the sine wave ripple current component is to heat the new welding point, to establish a new weld pool and to excite the weld pool oscillation.

The welding starts with the stationary arc. After the arc strikes, the computer acquires the amplitude of the alternating arc voltage component and makes data comparisons. As soon as the weld pool resonance appears and the amplitude of the arc voltage decreases to the threshold value 100 mV, the computer outputs a control pulse, first to remove the sine wave ripple current component and to have the arc burning only with the direct base current component, and second to put the traveling mechanism into operation. The arc moves to the next spot with the spot pitch of about half or less than half of the pool diameter, and repeats the welding procedure for the next spot — Fig. 10. Thus we can get a series of spot welds overlapping each other. The overlapping pitch can be preset and adjusted freely by the step traveling mechanism.

Relationship Between Weld Pool Resonance Frequency and Weld Bead Width

With the above mentioned control system, a GTA butt joint welding process without filler metal was carried out for a low-carbon steel plate of 1–2 mm and a stainless steel plate of 2 mm. Changing the pulsating current frequency, the controlling system will result in different topside and backside weld widths. Figure 11 shows the relationships between the weld width and the pool resonance frequency equal to



$\Delta U_1(\omega)$ = amplitude-frequency response of the arc voltage variation caused by welding current variation.
$\Phi_1(\omega)$ = phase-frequency response of the arc voltage variation caused by weldingcurrent variation.
$\Delta U_2(\omega_n)$ = amplitude-frequency response of the arc voltage variation caused by weld pool oscillation.
$\Phi_2(\omega_n)$ = phase-frequency response of the arc voltage variation caused by weld pool oscillation.
$\Delta U(\omega_n)$ = amplitude-frequency response of composition of the arc voltage variations.

Fig. 8 — Frequency response of the arc voltage variation.

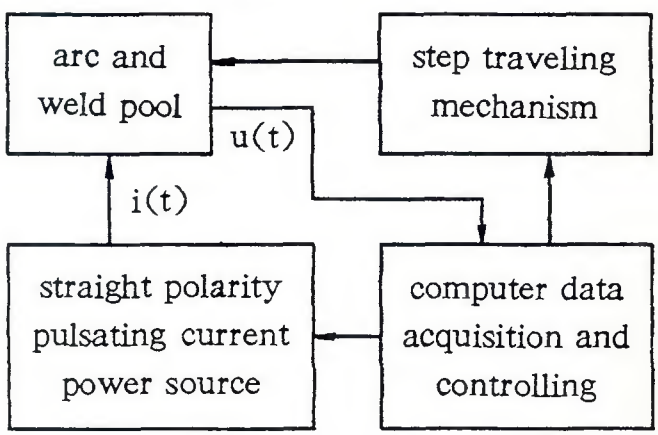


Fig. 9 — Block diagram of the experimental system of weld full penetration control.

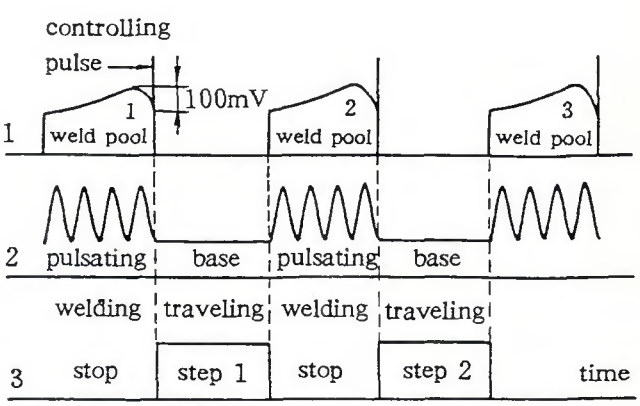


Fig. 10 — Schematic diagram of the weld full penetration monitoring and controlling process. 1 — Computer acquisition of the arc voltage variation amplitude and the controlling pulse; 2 — pulsating ripple and base current; 3 — step-by-step traveling.

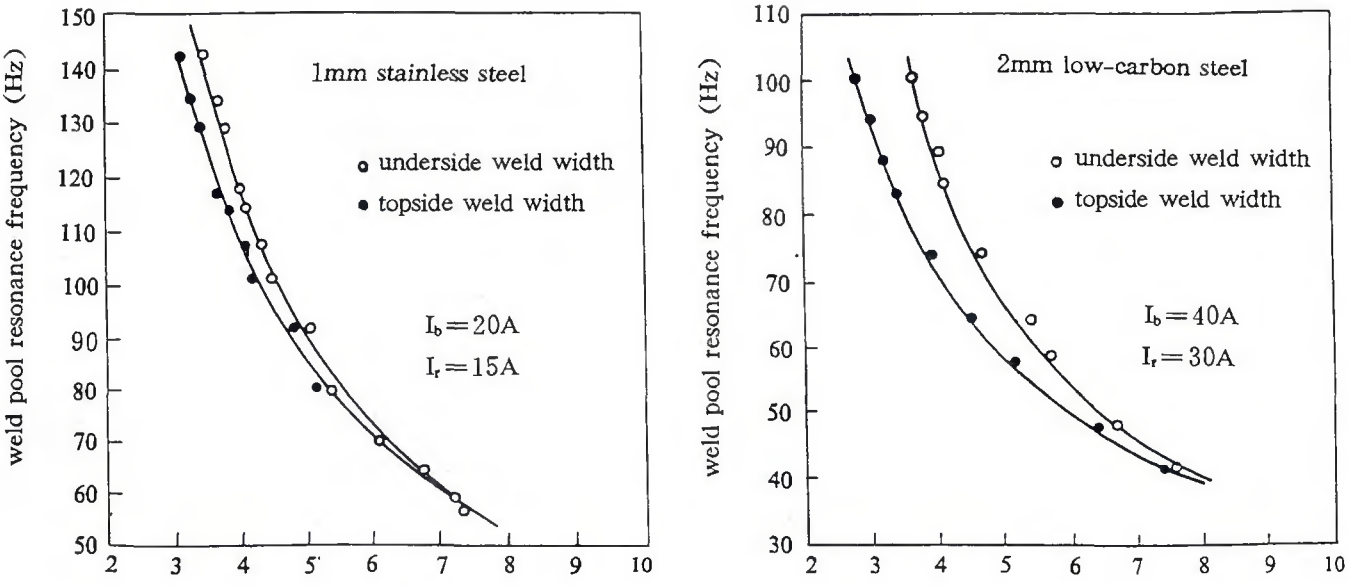


Fig. 11 — Relationships between weld pool resonance frequency and weld bead width. A — Stainless steel; B — low-carbon steel.

that of the preset pulsating current frequency. Figure 12 is a photograph of the welded sample of a 2-mm low-carbon steel plate welded with a pulsating current of 64 Hz. Figure 13 shows a sample of the computer data acquisition and monitoring, as well as the controlling process. It verifies that the control system is in effect and indicates that the new method realizes an actual real-time full penetration control process, since it monitors the weld pool oscillation at every moment during weld pool growth. As soon as the expected weld pool size is detected, the computer immediately sends the control order. Most control systems make data acquisition with some time interruption, and the monitoring process cannot be disconnected; in fact, they cannot implement the actual real-time full penetration control.

Results of Full Joint Penetration Control Under Severe, Uneven Heat Sinking Conditions

In order to test and verify the applicability of the control system in practice, we intentionally carried out the welding of a specimen with a particular configuration that creates severe, uneven heat sinking conditions. Figure 14 shows the satisfactory welding result of the designed feedback control system. Figure 15 shows the welding result of the same specimen and the same welding parameters without control.

Conclusions

In a stationary GTA welding process with straight polarity (electrode negative) pulsating current, the weld pool resonance information can be reliably used for weld pool size monitoring.

A fixed relationship between weld pool resonance size and frequency of the pulsating current has been proven for stationary GTA welding.

With the designed full joint penetration feedback control system, a satisfactory result for groove welding has been verified, even under severe, uneven heat sinking conditions.

The main advantages of the weld pool resonance method can be summarized as:

1) Use of the arc itself as a sensor and simplification of the detection of weld pool size.

2) Good reproducibility of the monitoring information.

3) High accuracy in controlling the weld pool size.

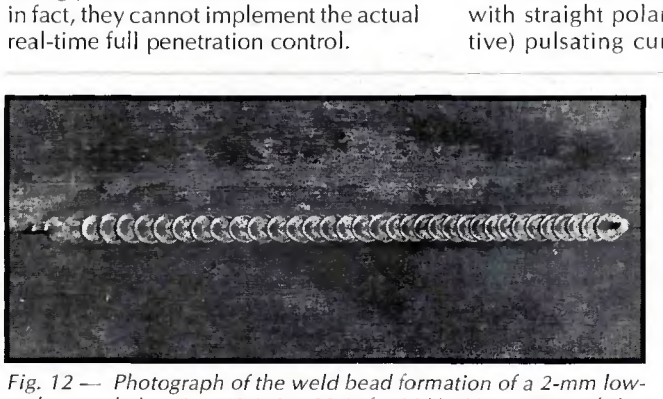


Fig. 12 — Photograph of the weld bead formation of a 2-mm low-carbon steel plate (I_b = 40 A, I_r = 30 A, f = 64 Hz, V_w = 140 mm/min).

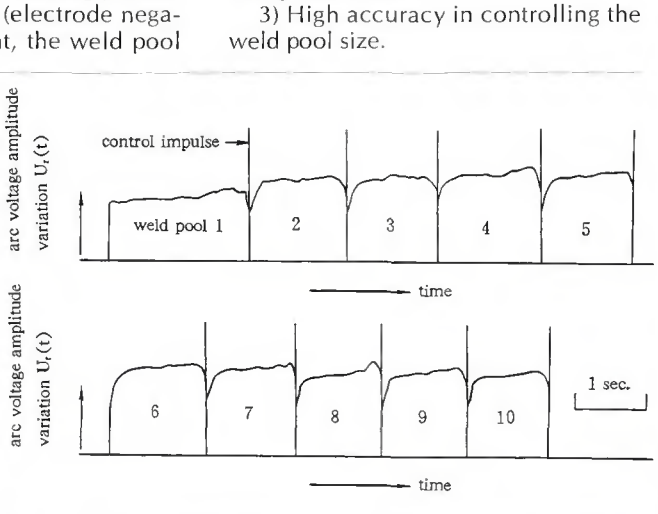
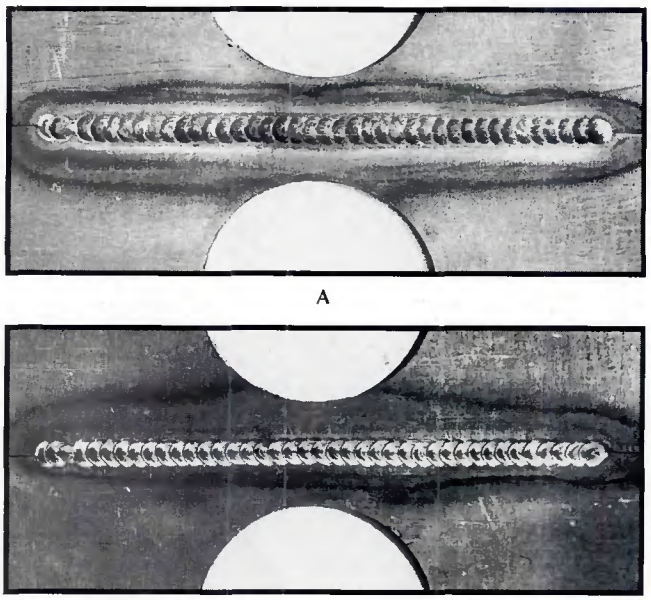


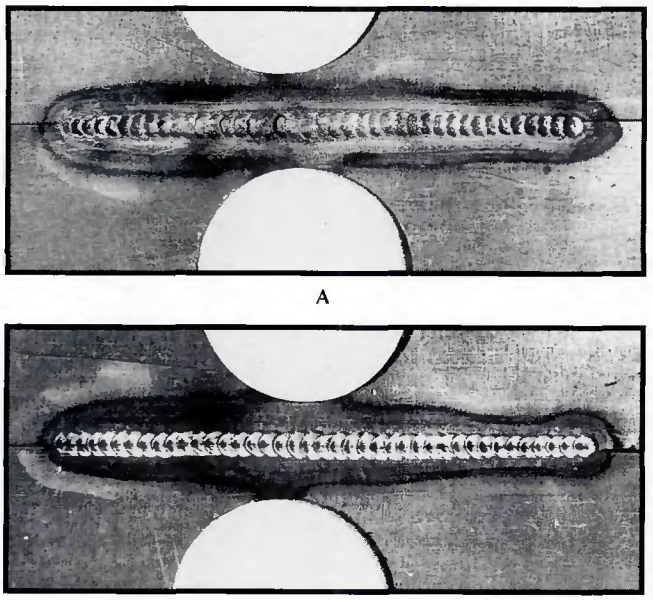
Fig. 13 — Computer monitoring process in step-by-step traveling arc welding.



A

B

Fig. 14 — Welding result with control under severe uneven heat sinking conditions (1 mm low-carbon steel plate) (I_b = 20 A, I_r = 15 A, f = 8 Hz, V_w = 180 mm/min). Arc time of every spot is feed-back controlled. A — Topside; B — underside.



A

B

Fig. 15 — Welding result with control under severe uneven heat sinking conditions (1 mm low-carbon steel plate) (I_b = 20 A, I_r = 15 A, f = 8 Hz, V_w = 180 mm/min). Arc time of every spot is fixed. A — Topside; B — underside.

4) Simplicity of parameter selection in the weld pool size control.

5) Higher welding speed.

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