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Ling, Shih Fu; Wong, Yoke-Rung

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Improved measurement of resistance and calculation of arc power in fusion welding

Yoke-Rung Wong¹ and Shih-Fu Ling

School of Mechanical & Aerospace Engineering, Nanyang Technological University, Block N3-B01C-03, 50 Nanyang Avenue, Singapore 639798.
Tel.: +65 6790 5577; fax: +65 6791 1975

¹E-mail: wong0663@e.ntu.edu.sg

Abstract

We reported a new method based on the input electrical impedance of a welding system to measure the resistance of the welding system for the arc power calculation in fusion welding. This impedance can be obtained by dividing the measured voltage to current in their analytic form. Two time recorded waveforms, namely, resistance and reactance of impedance are therefore calculated. Theoretically, the resistance used for arc power calculation is obtained by dividing measured voltage to current directly without considering the influence of inductance. Through experimental studies, we confirm that the error of arc power calculation incurred by the influence of inductance can range from 2 to 10% depending on the welding voltage and current setting. Since the proposed method can obtain the resistance of welding system without the influence of inductance, it is a better approach as compared with the current method to obtain the accurate resistance and then arc power.

Keywords

Fusion welding; Arc power; Resistance, Input electrical impedance

1. Background

Fusion welding is an important manufacturing process to join two pieces of material together by heating and melting the material. Theoretically, arc power is the primary factor to determine the total heat input which is important for modeling the dynamic welding mechanism, stress concentration, weld bead geometry and metallurgical change of weld.¹⁻³ Therefore, it is crucial to calculate the arc power accurately in order to have rational results of prediction.

In order to melt the material, electrical power is converted into heat in the welding system which is governed by Joule's Law:⁴

$$H = I^2 R \quad (1)$$

where H is known as heat generated by arc power in fusion welding. It is calculated based on the measured resistance (R) of welding system and the welding current (I). In order to calculate H , both welding current and resistance have to be measured. The welding current can be directly measured by employing a current probe. This current probe is usually a transducer in clamp type which is hooked on the welding power cable. However, the measurement of resistance is not as easy as current measurement because there is no direct measuring method to obtain the resistance. Therefore, indirect measuring method has to be used.

As shown in equation (2), Ohm's Law⁵ is commonly used to obtain the resistance due to the easy measurement of DC welding voltage (V).^{6,7} Similar to current measurement, the welding voltage can

be measured by a voltage probe being attached to the power terminals. After taking the quotient of welding voltage to current, the resistance is then calculated. Alternatively, Joseph *et al.*⁸ presented the arc power calculation (as shown in equation (3)) by substituting equation (2) into equation (1). Therefore, heat is equal to the arc power.

$$R = \frac{V}{I} \quad (2)$$

$$H = VI \quad (3)$$

Considering an electrical circuit, equation (2) is valid when the welding system consists of resistor only so that the resistance is measured without the influence of inductance. However, many papers reported that the welding system does not only consist of resistor but also inductor due to self-induced magnetic flux surrounding the welding arc (as shown in fig. 1).⁹⁻¹² Therefore, the application of equation (3) to calculate H is subjected to substantial error because the resistance obtained by equation (2) is inaccurate due to the influence of inductance.

Figure. 1 A typical welding system of fusion welding process.

According to Ling *et al.*¹³, the accurate resistance of a welding system without the influence of inductance can be obtained by measuring the input electrical impedance of the welding system such as Resistance Spot Welding. In system modeling, the welding system can be represented by an equivalent circuit consisting of a resistor (R), inductor (L) and capacitor (C) connected in series. They are naturally the system properties which reflect the welding mechanism of a welding system. By measuring the input electrical impedance of equivalent circuit, the accurate resistance of welding system can be obtained directly from the real part of input electrical impedance as shown in equation (7) and (8) which will be discussed later.

The objective of this research aims to propose a unique method for accurate resistance measurement and arc power calculation based on the input electrical impedance of a welding system. The method was presented in this paper by introducing the equivalent circuit of the welding system such as FCAW. After that, the error of resistance was revealed by comparing the real part of impedance with the conventional resistance obtained in equation (2). Furthermore, the effect of inaccurate resistance measurement on arc power calculation was then discussed.

2. Input Electrical Impedance of a Welding System

As shown in Fig. 2, a typical welding system such as Flux Cored Arc Welding (FCAW) is presented. It consists of a welding torch, welding wire, welding arc and base metal. Due to the complexity of welding process, the important parameters of welding system such as heat input is varying with respect to time. Such dynamic behavior is known as time varying system. To simplify the investigation of the time varying system, an equivalent circuit, which consists of a resistor (R), inductor (L) and capacitor (C) connected in series is employed to reflect the dynamic behavior of

Improved measurement of resistance and calculation of arc power in fusion welding welding system. Basically, they form the input electrical impedance which is capable to reveal the time-varying properties of the welding system.

Figure 2. Flux Cored Arc Welding (FCAW) and its equivalent circuit.

The input electrical impedance, $Z_{in}(t)$ of the equivalent circuit is obtained by probing the welding voltage and current simultaneously at the input port of welding system. Conventionally, the signal processing of $Z_{in}(t)$ is carried out by applying Fourier Transform to the signals and later calculating the result in frequency domain. However, the drawback is that the result does not reflect the $Z_{in}(t)$ in real-time. Therefore, the Hilbert Transform is employed to calculate the time varying $Z_{in}(t)$.

Hilbert Transform of a real valued time domain signal, $x(t)$, is denoted as $h[x(t)]$, or $\tilde{x}(t)$ which yields the original signal in its analytic form, $\hat{x}(t) = x(t) + jh[x(t)]$. Although the analytic signal is defined as a magnitude function of $A(t)$ and an instantaneous phase function of $\theta(t)$, it is different from the Fourier Transform of $x(t)$ in its complex-valued frequency domain signal $X(\omega)$. The main difference is that both magnitude and phase are functions of time, which means that they not only provide the information in frequency domain but also vary with time. This feature is especially important to obtain the $Z_{in}(t)$ because it is capable to provide the time-varying properties of welding system.

Theoretically, the Hilbert Transform of any raw signal can be defined as: ¹⁴

$$h[x(t)] = \tilde{x}(t) = \int_{-\infty}^{\infty} \frac{x(u)}{\pi(t-u)} du \quad (4)$$

The $Z_{in}(t)$ can be obtained by taking the quotient of welding voltage to welding current which are firstly converted into analytic form (see equation (5) and (6)):

$$\hat{V}(t) = V(t) + jh[V(t)] \quad (5)$$

$$\hat{I}(t) = I(t) + jh[I(t)] \quad (6)$$

$$Z_{in}(t) = \frac{\hat{V}(t)}{\hat{I}(t)} = Z_r(t) + j\omega Z_x(t) = |Z_{in}(t)|e^{j\omega\phi(t)} \quad (7)$$

$$Z_{in}(t) = R(t) + j\left(\omega L(t) - \frac{1}{\omega C(t)}\right) \quad (8)$$

Equation (7) and (8) show that the $Z_{in}(t)$ can be presented either in polar form ($|Z_{in}(t)|, \phi(t)$) or complex form ($Z_r(t), Z_x(t)$). The $|Z_{in}(t)|$ and $\phi(t)$ is the magnitude and phase of $Z_{in}(t)$ whereby the $Z_r(t)$ and $Z_x(t)$ is the real part and imaginary part, or the resistance and reactance of $Z_{in}(t)$. For the convenience of presenting the $R(t)$, $L(t)$ and $C(t)$, the complex form of $Z_{in}(t)$ is used to present the result in this paper. Basically, the $Z_r(t)$ is the reflected resistance of welding system which converts electrical power into heat. The $L(t)$ and $C(t)$, however, are related to the electrical power being conserved in the reactance without dissipated as heat energy. Based on equation (8), it clearly shows that the resistance of welding system can be obtained accurately without the influence of inductance because the signal of $Z_r(t)$ is naturally shielded from the influence of inductance which only appears in $Z_x(t)$.

3. Measurement of $Z_{in}(t)$

The detail of experimental set-up is shown in Fig. 3. The welding torch was attached to a 2-axis Cartesian Robot so that the leading angle, wire extension and welding speed can be controlled. This welding torch was also connected to a contact relay so that the welding process was initiated by automatic triggering. In order to hold the welding torch and prevent heat damage to the robot during welding process, a costumed made torch holder with heat isolator was designed and built.

Flux Cored Arc Welding (FCAW), Panasonic KR π 500, was used in this research as the welding process to carry out the bead-on-plate test¹⁵ for low carbon steel (AISI 1023) plates. The thickness of steel is 15mm. During the experiments, welding voltage and current were varied according to table 1 while the other important welding parameters were fixed as: wire diameter = 1.2mm; wire extension = 15mm; welding speed = 7.5 mm/s; leading angle = 15 °; flow rate of CO₂ shielding gas = 20 L/min; welding time = 20s.

Table 1 Setting of welding voltage and current

Voltage/V	Current/A
24	150
24	175
24	200
26	200
28	200

For the acquisition of welding voltage and current signal, voltage probe (Tektronix, P520) and current probe (Hioki, 3285) were used to acquire the signals. The voltage probe was attached to the output terminals of welding machine in order to measure the DC voltage. The current probe was hooked on the welding power cable as shown in fig. 3 to measure the DC current. These input signals were sampled simultaneously and digitized by the DAQ system (National Instrument, SCXI-1305, 1000 & DAQCard-6062E) at 3 kHz. On the other hand, a built-in analog filter with 100Hz cut-off frequency was used for individual channel to prevent signal aliasing.

As shown in Figs. 4 and 5, the experimental result of real valued $V(t)$ and $I(t)$ based on 24V, 150A welding parameters setting are plotted for 0.2s of welding time. In order to convert both real valued signals into analytic signals, the Hilbert transform was calculated. It shows that the Hilbert Transform of $V(t)$ and $I(t)$ oscillates at the same frequencies of $V(t)$ and $I(t)$ except the frequency at 0 Hz. This result agrees with the modulation property of Hilbert Transform which the Hilbert Transform of any real-valued $x(t)$ is equal to zero at 0 Hz.¹⁴ After combining the $V(t)$ and $I(t)$ with $h[V(t)]$ and $h[I(t)]$ according to equation (5) and (6), the $Z_{in}(t)$ was then calculated based on equation (7). All the calculations were done by using Matlab.

Figure 3. Schematic diagram of experimental setup.

Figure 4. Transient welding voltage and $h[V(t)]$.

Figure 5. Transient welding current and $h[I(t)]$.

The $Z_r(t)$ and $Z_x(t)$ of $Z_{in}(t)$ are then plotted in fig. 6. It is observed that the $Z_r(t)$ oscillates at positive value as the reflected resistance of welding system. On the other hand, the $Z_x(t)$ oscillates at zero value as a result of energy exchange between $L(t)$ and $C(t)$ which is commonly seen in an electrical $R-L-C$ circuit. With these observations of experimental results, the presence of inductor and capacitor in the welding system is confirmed. Furthermore, the $Z_r(t)$ has to reflect the resistance of welding system accurately since the influence of inductance and capacitance are naturally isolated and presented in $Z_x(t)$.

Figure 6. A typical time record result of $Z_{in}(t)$.

4. Discussions

In order to demonstrate the error of resistance caused by the influence of inductance, the $Z_r(t)$ is compared with the conventional resistance, $R(t)$ which is obtained by using equation (2) based on the measured welding voltage and current. Fig. 7 shows a typical comparison between the $Z_r(t)$ and $R(t)$ for 0.1s of welding time. It can be seen that the $Z_r(t)$ is always lower than $R(t)$. Obviously, the difference between $R(t)$ and $Z_r(t)$ is the measurement error caused by the influence of $Z_x(t)$ as presented in fig 6. On the other hand, this error can be critical because it will lead to a significant error of arc power calculation which will be discussed below.

Figure 7. Comparison between $Z_r(t)$ and $R(t)$ along welding time.

According to Table 1, five cases with variation of welding voltage and current were studied in order to evaluate the effect of inaccurate resistance measurement on arc power calculation. For each case, five experiments were carried out to confirm the repeatability of results. The results of measured $R(t)$ and $Z_r(t)$ were averaged out and listed in table 2. The arc power was then calculated according to equation (1) based on the averaged $R(t)$ and $Z_r(t)$. Subsequently, the difference of arc power for each case was therefore computed according to equation (9).

Table 2 Measurements of averaged $R(t)$ and $Z_r(t)$

Voltage/V	Current/A	$R(t)/\Omega$					$Z_r(t)/\Omega$				
		1	2	3	4	5	1	2	3	4	5
24	150	0.1712	0.1684	0.1749	0.1753	0.1756	0.1617	0.1589	0.1647	0.1634	0.1672
24	175	0.138	0.1364	0.1343	0.1378	0.1371	0.1281	0.127	0.1245	0.1282	0.1279
24	200	0.1345	0.1356	0.1335	0.1359	0.1342	0.1231	0.1228	0.1201	0.1229	0.1213
26	200	0.1353	0.136	0.1303	0.1363	0.1351	0.1281	0.1267	0.124	0.1287	0.1283
28	200	0.1418	0.146	0.1462	0.1444	0.1448	0.1401	0.1438	0.1436	0.1425	0.1418

Figure 8 shows the comparison of arc power based on variation of welding current and voltage. It is observed that the arc power based on $Z_r(t)$ is always lower than the arc power obtained by $R(t)$ because the $Z_r(t)$ is lower than $R(t)$ as shown in table 2. This result further proves that some portion of the electrical energy is not converted into heat but conserved in the $Z_x(t)$. In other words, the $Z_r(t)$ allows us to calculate the actual arc power. On the other hand, the comparison results also reveal that low welding voltage always cause larger difference because more energy is conserved in the $Z_x(t)$. Conversely, the energy being conserved in the $Z_x(t)$ is lesser for high welding voltage because the capacitance appearing in $Z_x(t)$ is possible to compensate for high inductance.

$$H_{diff} = \frac{H_{R(t)} - H_{Z_r(t)}}{H_{R(t)}} \times 100\% \quad (9)$$

Figure 8. Comparison of arc power based on variation of welding current and voltage.

5. Conclusions

A unique method was proposed in this paper to obtain the accurate resistance based on the input electrical impedance of a welding system. When the welding system is represented by an equivalent circuit, the input electrical impedance which consists of resistor, inductor and capacitor connected in series can be correlated with the dynamic welding mechanism of welding system. Therefore, the two major components of impedance, namely resistance and reactance, are important for obtaining the system parameters of welding system.

The results presented in this paper confirm that the proposed method using the resistance of impedance for arc power calculation is more accurate as compared to the conventional approach. The error of arc power calculation incurred by the influence of inductance can range from 2 – 10% depending on the welding voltage and current setting. Since the proposed method can obtain the resistance of welding system without the influence of inductance, it is a better approach as compared to the current method of obtaining the arc power.

Since the $R(t)$, $L(t)$ and $C(t)$ of $Z_{in}(t)$ can be correlated with the dynamic welding mechanism, they become effective monitoring signatures to evaluate the weld quality or characterize the welding process. In theory, real-time weld quality monitoring and characterization of welding mechanism can be achieved because the proposed monitoring signatures are time varying. By selecting the features of $R(t)$, $L(t)$ and $C(t)$ carefully, they can be correlated with the physical result of weld quality inspection. Furthermore, the proposed monitoring signatures can be correlated with the physical change of welding mechanism so that online characterization of welding process can be achieved. More related work on real-time weld quality monitoring and characterization of welding process will be carried out and the results will be published in near future.

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28	200	0.1418	0.146	0.1462	0.1444	0.1448	0.1401	0.1438	0.1436	0.1425	0.1418