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REVIEW OF ELECTRON-BEAM WELDING STUDIES UTILIZING
X-RAY SPECTROSCOPY

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SUBJECT DESCRIPTORS

Welding
Electron Beam Welding
Welding Machines
Weld Properties
X-Radiation
Energy Dispersive X-Ray Analysis
X-Ray Spectroscopy
X-Ray Detection
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Statistics
Analysis

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REVIEW OF ELECTRON-BEAM WELDING STUDIES UTILIZING X-RAY SPECTROSCOPY

Raymond D. Dixon

Abstract. A review is presented of results obtained using an X-ray spectroscopy technique to study the electron-beam welding process. Results show that the technique is well suited for this kind of study. In particular, accurate voltage control is possible, and such control reduces weld-penetration variations significantly. Analytical techniques developed for studying noise on electron beams have general applicability for signal analysis. The work also shows that no voltage or current pulses were seen, and that the noise on the beam is probably not significant with respect to weld variations.

INTRODUCTION

The use of X-ray spectroscopy to study the electron-beam welding process has resulted in significant progress towards understanding electron beam welding. The results obtained have limited application toward solving production problems; however, these results are beneficial in characterizing machine parameters used for electron beam welding. Additional benefits are the confirmation of existing ideas and the establishment of techniques that can be used to investigate new ideas. Of greatest importance is the guidance that these results provide for additional work. Efforts to date have resulted in a thorough knowledge of beam voltage variations¹ and the effect of beam voltage upon weld penetration.² The origin and characterization of alternating current (AC) signals on the electron beam also have been obtained.³

Even though the experimental techniques described in this report were used only on electron beam welders, the concept of voltage measurement has been used on electron microscopes,⁴ and the techniques described for measuring noise on an electron beam should be applicable to other electron beam devices.⁵ In addition, the data analysis procedures that were developed provide an excellent means of quickly and reliably extracting signals from noise.⁶

The emphasis of past work, as reported here, has been on studying machine parameters. Future work is expected to focus on welding mechanisms.

MATHEMATICAL BACKGROUND

The X-ray spectrum generated by electrons striking a metal target has been the subject of much work over many years. Past work has been theoretical and experimental with emphasis on understanding, modeling, and predicting characteristic X-ray radiation and Bremsstrahlung radiation. The variables required to accomplish such predictions encompass electron-beam parameters and detector parameters in addition to parameters relating to the target and its environment. A particularly useful result, although it is not considered extremely accurate, was obtained by Kramers⁷ and is used to describe the Bremsstrahlung spectrum.

From Kramers work, the spectral intensity of the Bremsstrahlung spectrum, as a function of X-ray energy (I_E), is given by the following:

$$I_E = JZK^1(E_0 - E) \quad (1)$$

where J = beam current

Z = target atomic number

K^1 = proportionality constant

E_0 = beam voltage

E = X-ray energy

Equation 1 provides the foundation for the welding studies. From this equation, it can be seen that as the X-ray energy approaches E_0 , the spectral intensity approaches zero. Thus, by inspecting the X-ray spectrum for the high-energy zero point (high-energy cutoff), the electron-beam accelerating voltage, can be determined.

Integrating Equation 1 between Energies E_1 and E_2 with $0 \leq E_1 \leq E_2 \leq E_0$ yields the following X-ray intensity (I):

$$I = KJ(E_0 - D) \quad (2)$$

where $K = K'Z(E_1 - E_2)$

$$D = \frac{E_2 + E_1}{2}$$

If either or both the beam voltage and beam current are time dependent (t) a time-dependent X-ray intensity (I) is obtained. This intensity is determined as follows:

$$I(t) = K(t) [E_0(t) - D] \quad (3)$$

Signal analysis of data taken under conditions applicable for Equation 3 will show the presence of AC signals on the beam. The analysis will also show signal changes corresponding to beam parameters.

Equation 1 has been known for a number of years, and Equation 3 readily follows from Equation 1. It was not until the late 1960's, however, that experimental equipment and techniques were available for their application to studies such as this.

Equation 1 predicts that the electron-beam current should be obtained readily from the X-ray intensity; however, this would require measuring the absolute X-ray intensity, which is extremely difficult to do and which is not suited for routine application. The difficulty in doing absolute spectral-intensity measurements results from the need to accurately account for such things as absorption, spot size, electron distribution, beam angle of incidence, detector take-off angle, target surface condition, detector efficiency, and characteristic X-ray emission at all X-ray energies.

To determine noise on the electron beam, Equation 3 is presented as a Fourier series that, for $2N$ even and equally spaced points, is as follows:

$$I(t) = \frac{A_0}{2} + \sum_{K=1}^{N-1} (A_K \cos 2\pi f_K t + (B_K \sin 2\pi f_K t) + \frac{A_N}{2} \cos 2\pi f_N t) \quad (4)$$

The harmonic frequencies f_k , $k = 1, 2, \dots, N-1$ are as follows:

$$f_k = \frac{K}{2N\Delta} \quad (5)$$

where $2N$ = the number of data points

Δ = the time interval

The time is given by $t = r\Delta$:

where $r = 0, 1, 2, \dots, 2N-1$

After substituting discrete representations for f_k and t into Equation 3, and after applying Parseval's theorem, the mean squared power is obtained as follows:

$$\sum_{r=0}^{2N-1} \frac{I(r\Delta)^2}{N} = \frac{A_0^2}{2} + \sum_{K=1}^{N-1} (A_K^2 + B_K^2) + \frac{A_N^2}{2} \quad (6)$$

Decomposition of Equation 6 into the average AC power at the harmonic frequencies is known as the Fourier line spectrum. In general, the convergence of the Fourier line spectrum to the power spectrum is smooth in the limit of long periods; thus, the line spectrum is a reasonable estimator of the power spectrum. Hypothesis tests,⁶ applicable to the power spectrum from a time series, were applied to the line spectrum to determine if the line spectrum originates from a white noise source or if power is indicated at the harmonic frequencies.³ The Fourier series coefficients (coefficients in Equation 4) were found using a fast Fourier transform algorithm, which was then squared and summed at the harmonic frequencies to produce the line spectrum (Equation 6).

RESULTS AND DISCUSSIONS

The experimental work was done using electron-beam welding machines from two different manufacturers. The voltage study¹ and penetration study² were done using a Hamilton Standard (7.5 kW) machine. Details of the experimental setup are described in the reports of that work.^{1, 2} The experimental setup for the noise study³ was done using a Sciaky Brothers low voltage (30 kW) machine and is described in detail in the report of that work.³

The time series for the noise study was X-ray intensity as a function of time. The energy band width ($E_2 - E_1$, see Equation 2) of the X-ray intensity was 10 keV, and E_2 was E_0 (the high energy cutoff) minus 1 keV. This band width was sufficient to permit acquisition of an adequate number of X-rays during a sampling time of 10^{-3} seconds. There were 2^{11} data points in the time series; thus, there were $2^{10} + 1$ terms in the line spectrum. Visually inspecting a plot of the line spectrum is one means of determining if power is indicated; however, plotting was time consuming. In most cases, there were a number of peaks in the spectrum. In some cases, for the entire spectrum, a decision concerning the existence of power could not be made. It was because of this inability to make a decision that the statistical tests were used.

The statistical tests included (1) a test to determine if the spectrum was from a white noise source, (2) a test to determine at what significance level acceptance could be given to the hypothesis that a given peak contained power, and (3) a Student's *t* test of the direct current (DC) and high frequency terms. The second test began by testing the largest term and proceeding toward the smallest until three consecutive terms were rejected at the 5-percent significance level. These tests were successful in that if the source was shown to be white noise, the test for power at the harmonic frequencies showed that the peaks did not contain power. A detailed discussion of the statistical tests is given in Reference 6.

Examples of the time series and resulting line spectra are shown in Figures 1(a), (b), and 2(a), (b).

The statistical tests, when applied to Figure 1, show that the time series originates from a white noise source. For Figure 2, the significant peaks are indicated by the magnitude of the line spectrum amplitude and the corresponding harmonic frequency. From these figures, it is obvious that analytical techniques are required to completely inspect line spectra for the existence of power.

The data shown in Figure 1 were taken with the filament current well below the knee of the electron emission versus filament current curve. As previously mentioned, analysis of the line spectrum showed that the time series originated from a white noise source. This is expected since the electron gun is not yet space charge limited; also because the beam current would then be composed of random, thermal electron emission in addition to field-emitted electrons, which also will be random. This confirms the need for operating the gun in the space-charge-limited mode, i. e., operating with the filament current above the knee of the electron emission versus filament current curve.

A number of time series similar to Figure 2 were taken with different combinations of electron beam parameters. The varied parameters involved voltage, beam current, filament current, and focus voltage.

Figures 3 and 4 are reproduced from Reference 5. Figures 5, 6, and 7 are reproduced from Reference 3. These figures are included here for ease of discussion.

Figure 3 shows the DC X-ray power ($A_0^2/2$ from Equation 6) versus the electron beam power. Figure 4 shows the X-ray power (from Equation 6)

$$\sum_{r=0}^{2N-1} \frac{I(r\Delta)^2}{N}$$

versus the electron beam power. The electron beam power is calculated from the product of the beam current and high voltage. For this calculation, the beam current and high voltage are measured by a Faraday cup and X-ray, high-energy cutoff respectively. Figure 3 shows that the DC power is directly proportional to the beam power.

FIGURE 1(a) and (b). Time Series (a) and Resulting Line Spectrum (b). The line spectrum is a result of the time series originating from a white noise source. None of the peaks in the line spectrum are statistically significant.

The average total power also is directly proportional to the beam power, as is shown in Figure 4. A comparison of Figures 3 and 4 shows that the average total power is greater than the DC power. For constant beam parameters, the two curves would be coincident. The difference is caused by the amount of random and periodic noise on the beam.

The amount of periodic noise (AC) in the spectrum is shown in Figure 5 where the AC power terms are plotted against the beam current. In all cases, the AC power is directly proportional to the beam current and is a small fraction of the DC power.

In most cases, the AC power is less than 10 percent of the DC power.³

It is important to note that there was no power found at frequencies other than 120, 180, 240, and 360 Hz. This indicates that no voltage or current spikes occurred on the beam since their occurrence would produce a large amount of low frequency power.

Figure 6 shows the DC and AC power versus filament current at constant beam voltage and current. Note that the curve showing DC power versus filament current is similar in shape to the curve representing

FIGURE 2(a) and (b). Time Series (a) and Resulting Line Spectrum (b). The frequency and corresponding amplitudes of the significant peaks are shown in the line spectrum.

electron emission versus filament current. The similarity of these curves is in agreement with the DC power being proportional to the beam current.³ Note also that the AC power peaks at a filament current near the middle of the knee of the DC power versus filament current curve. This is significant in that it implies that as the gun becomes space-charge limited, the space charge acts as a filter and diminishes the amplitude of the noise on the beam. This is another reason for operating the gun in the space-charge-limited mode since it is assumed that a nearly DC (or low noise) beam is most advantageous to the welding process.

Figure 7 shows the effect of focus on the DC and AC powers. The sharp focus positions that are indicated were determined by visual monitoring. Those positions are the focus currents for maximum brightness. As shown in Figure 7, the peaks of the DC and AC powers versus focus current do not coincide with the visually determined, sharp focus current. The reason the peak does not coincide with the visual sharp-focus current is because of self absorption of the X rays. This self absorption is the result of non-uniform electron distribution in the electron beam and of the beam's position on the target.³

FIGURE 3. Direct Current Power
versus Electron Beam Power

FIGURE 4. Total X-Ray Power
versus Electron Beam Power

FIGURE 5(a) and (b). Alternating Current
Power versus Electron Beam Current

FIGURE 6(a), (b), and (c). Direct Current and Alternating Current Power versus Filament Current. The filament is peaked at 52 amps. The DC power in Figure (a) is similar to the electron emission versus filament temperature. Figures (b) and (c) show smaller AC powers when the filament is peaked.

Prior to studies of the noise on the electron beam, a study was done to determine how accurately the voltage meter on the welder reproduces the accelerating voltage. This was accomplished by using the meter on the welder to set the welder accelerating voltage. The accomplishment also

involved measuring the actual accelerating voltage by observing the high energy cutoff of the Bremsstrahlung X-ray spectrum.¹ Results of this work showed that reproducing the volt meter value only reproduces the accelerating voltage to within ± 5 percent. This is outside the calibration of the

FIGURE 7(a), (b), (c), and (d). Direct Current and Alternating Current Power versus Focus Coil Current. Visual sharp focus is shown by the vertical lines.

volt meter on the welder (± 2 kV) and is a significant variation. The source of variations is unknown at this time.

The effect of voltage variation on weld penetration is significant. A study to determine this effect showed that penetration variations could be reduced from ± 25 percent to ± 10 percent in 1100 aluminum and from ± 18 percent to ± 5 percent in 6061 aluminum by using the X-ray technique to establish the beam acceleration voltage.² The study also showed that weld penetration is material dependent and thus indicates that more fundamental work is required to characterize electron beam welding.

SUMMARY

The results described in this report show that the techniques of X-ray spectroscopy are useful for studying the electron-beam welding process. This is due to X-ray techniques providing a means of observing phenomena directly associated with beam parameters; i.e., the observed results can be correlated directly to the electron beam, which is the mechanism for electron beam welding.

The results show that the beam voltage, as measured by the meter on the welder, is not accurate,¹ and that accurate control of the voltage reduces penetration variations.² The results also show that there is not a significant amount of noise on the beam and that there are no voltage or current pulses occurring.

The data analysis technique⁶ will be useful for other signal analysis work. In addition, the techniques used to observe the noise on the electron beam would find application in other electron beam devices.

Even though significant results have been obtained, there is a large amount of work that still must be

done to better understand electron beam welding. Two areas of work are obvious as a result of this and other work. These areas are (1) the origin of the beam voltage variations and (2) the degree to which penetration variations depend on specific material.

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