An Accurate Method for Determining Electron Beam Welding Voltages

X-ray technique provides the absolute measure of operating voltage needed for reproducibility

BY R. D. DIXON

ABSTRACT. A simple and accurate method of measuring the operating voltage of an electron beam welding machine is described. The method involves using an energy dispersive spectrometer to measure the x-ray spectrum generated by an electron beam and determining the voltage from the high energy cutoff (short wave-length cutoff). A series of measurements was made to compare the voltages determined by this method with the beam voltage meter on a Hamilton Standard W2 electron beam welding machine. The result of this study shows that reproducing the beam voltage meter values does not reproduce the beam voltage. The actual voltage can be as much as 5% different from that indicated on the voltage meter.

Introduction

A great deal of research effort on electron beam welding has resulted in phenomenological theories which are reasonably successful in predicting the beam voltage and current dependence of penetration (Refs. 1, 2), power density (Ref. 3) and minimum beam diameter (Refs. 3, 4). Penetration theories predict that the penetration is directly proportional to the power density (Refs. 1, 2):

$$X \propto D \tag{1}$$

where, X = depth of penetration
D = power density.

The power density is in turn inversely proportional to the beam diameter squared and directly proportional to the beam voltage and current:

$$D \propto VI/d^2 \tag{2}$$

where, V = beam voltage,
I = beam current,
d = beam diameter.

If a weld development program establishes that all welds should be made at a fixed beam diameter or at the minimum beam diameter (measured for example by a flying wire) (Ref. 4) the power density and thus the penetration can still vary from weld to weld due to changes in beam voltage and/or current. In particular, Schwarz's (Ref. 3) equation for the maximum power density attainable for given voltage, current, cathode emission density, cathode temperature, and lens system is:

$$D \propto I^{1/4}V^{7/4}. \tag{3}$$

Equation 3 describes the power density dependence on beam voltage, current, and minimum beam diameter where the minimum beam diameter has been written in terms of voltage and current. Combining equation 3 with equation 1 gives the penetration:

$$X = KI^{1/4}V^{7/4} \tag{4}$$

where K is a proportionality constant which depends on the material parameters and the welding speed (Refs. 1, 2).

Using equation 4, the standard deviation of the penetration due to errors in beam voltage and current is given by:

$$S_X = [(7KI^{1/4}V^{3/4}/4)S_V^2 + (KI^{-3/4}V^{7/4}/4)^2S_I^2]^{1/2} \tag{5}$$

where, S_X = standard deviation of the penetration,
S_V = standard deviation of the voltage,
S_I = standard deviation of the current.

If one assumes that the standard deviation of the current is zero, the standard deviation of the penetration is:

$$S_X = 7KI^{1/4}V^{3/4}S_V/4. \tag{6}$$

Thus, the penetration error can still be significant and is in fact an increasing function of the voltage. This can only be minimized by minimizing the error on the voltage ($S_V \simeq 0$). As will be shown, there is a significant error in reproducing the beam voltage using the voltage meter on the machine. In particular, the results of a recent study (Ref. 5) show that reproducing the electron beam welding machine settings will not reproduce the weld geometry better than ±40%. It is for this reason and the fact that voltage errors could produce large penetration errors that the present work was done.

Measurement of the beam voltage by a calibrated voltmeter is an accurate means of determining voltage. However, this is an indirect measure of the beam voltage since it does not measure the energy of the electrons in the beam. The method described here is to measure the x-ray spectrum generated when the beam interacts with the target and to determine the beam voltage from the x-ray spectrum. Thus, we have a first principle means of measuring the beam voltage.

The x-ray spectrum generated by an electron beam machine is composed of the characteristic x-rays of the target material as well as a large

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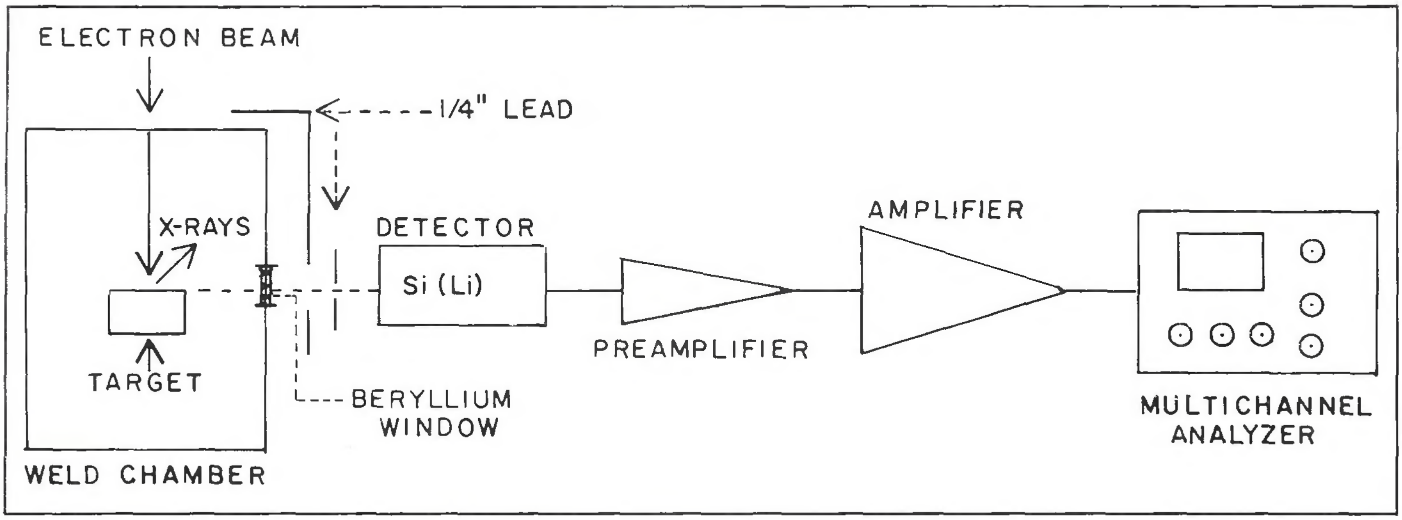

Fig. 1 — Block diagram of the experimental set-up

amount of background radiation (bremstralung). The bremstralung spectrum is continuous with the discrete charactersistic spectrum superimposed upon it. For this work, the primary interest was in the bremstralung spectrum. However, the characteristic x-ray lines do provide an additional means of calibration.

The bremstralung spectrum is generated when the electrons of the beam are scattered by the target atoms. The electron energy loss per scattering event appears as x-ray photons. Since there are scattering events occurring until there is electron capture, the resulting spectrum is continuous.

The electrons in the beams are considered to be monoenergetic because the spread in energy is essentially due to the thermal energy distribution at the filament. This is usually less than 1 eV. This implies that the energy of the beam electrons is equal to the accelerating voltage (i.e., the voltage one desires to measure).

Now, an electron energy of E cannot generate an x-ray photon having an energy greater than E. Also, there is a finite probability that an electron will be stopped in one scattering event. All the electrons in the beam have nearly the same energy and hence they will produce a significant number of x-ray photons having energies equal to the accelerating voltage. The energy of these x-rays is given by:

$$E_m = h\nu = \frac{hc}{\lambda} \qquad (7)$$

where, E_m = maximum photon energy
= maximum electron energy,
h = Planck's constant,
c = speed of light,
ν = photon frequency,
λ = photon wavelength.

The electron energy is related to the accelerating voltage through:

$$E_m = eV \qquad (8)$$

where, e = electron charge
where, V = accelerating voltage.

Combining equations 7 and 8 yields:

$$eV = \frac{hc}{\lambda} \qquad (9)$$

From equation 9 we see that the accelerating voltage in volts is numerically equal to the x-ray photon energy in electron volts. The technique used to measure the accelerating voltage was to acquire an x-ray spectrum (number of photons vs. energy) and to determine the maximum energy. This method has been successfully used to determine the operating voltage of an electron microprobe (Ref. 6). In the microprobe application the increased precision permits eliminating the operating voltage as a source of error in quantitative microanalysis.

Experimental

An energy dispersive spectrometer (EDS) was used to obtain the x-ray spectra. The EDS consists of a Li drifted Si (Si(Li)) x-ray detector, detector bias power supply, preamplifier, amplifier, multichannel analyzer (MCA), and read-out facilities. The MCA separates voltage pulses, from the amplifier, into energies according to pulse heights.

The voltage pulses originate in the detector and the pulse heights are proportional to the energy of the x-rays which created the pulse. The pulses are stored in the MCA memory channels with each channel corresponding to a particular energy increment. The EDS system was calibrated with an Am(241) gamma ray source. The calibration yielded the energy increment per channel and the energy of channel zero. The calibration permitted x-ray energy determinations to within ±0.1 kV. The EDS could be adjusted to obtain the entire x-ray spectrum from 0 to 150 kV. For this work, all spectra were taken using a 1 μs time constant and high level baseline restoration. After acquiring a spectrum, the spectrum could be displayed immediately on a cathode ray tube (CRT) or outputted to a plotter, printer, or paper tape.

The electron beam welding machine used for this work was a Hamilton Standard W2. A 7 cm diam by 0.2 cm thick beryllium window was fixed 61 cm above the chamber floor and in the center of one of the viewing ports. The view port window was replaced by an aluminum sheet 2.5 cm thick in order to mount the beryllium window. The beryllium window was necessary in order to eliminate absorption of low energy x-rays.

The entire view port, with the exception of a 1.3 cm hole at the center of the beryllium window, was covered with 0.64 cm of lead to reduce radiation levels in the laboratory and to serve as partial collimation. Additional collimation and shielding were obtained with another 0.64 cm thick lead sheet placed 12 cm away. The aperature in this sheet was also 1.3 cm. The x-ray take-off angle was 90 degrees and the source to detector distance was approximately 92 cm.

In all cases absorber material had to be placed in the x-ray path in order to decrease the dead time of the MCA. The absorber material was placed between the two lead sheets. All spectra were taken with the electron beam impact point approximately 0.3 cm from the edge of the target. This was done to eliminate the

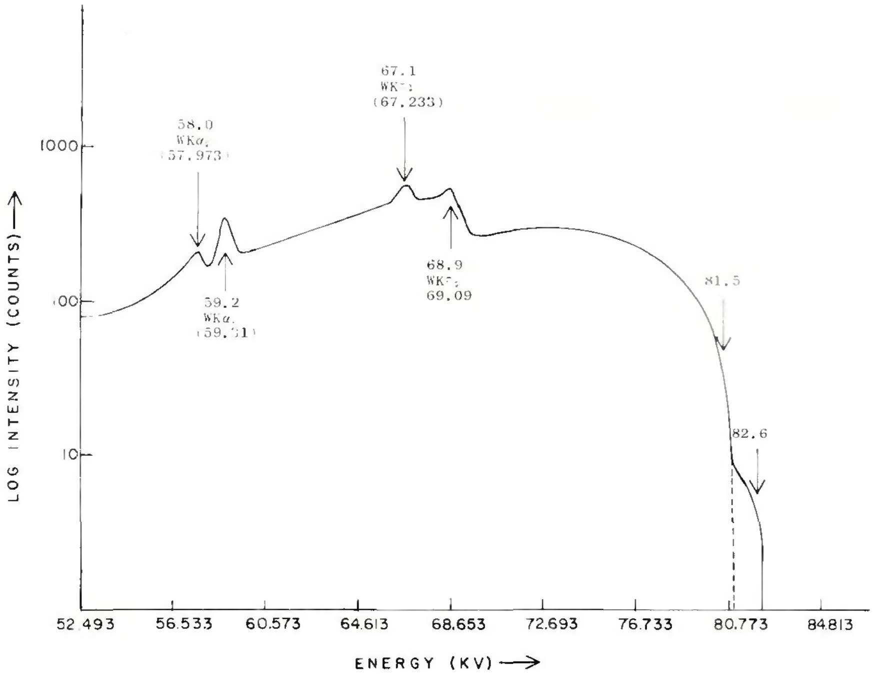

Fig. 2 — X-ray spectrum taken using tungsten target, beam voltage meter setting of 74 kV, beam current meter setting of 1 ma, and 0.13 cm of molybdenum absorber. The peaks shown on this spectrum are the tungsten $K\alpha_1$, $K\alpha_2$, $K\beta_1$, and $K\beta_2$. The measured energy is given above each peak along with the identification of the peak and its known energy (in parentheses). The high energy cutoff is 81.5 kV

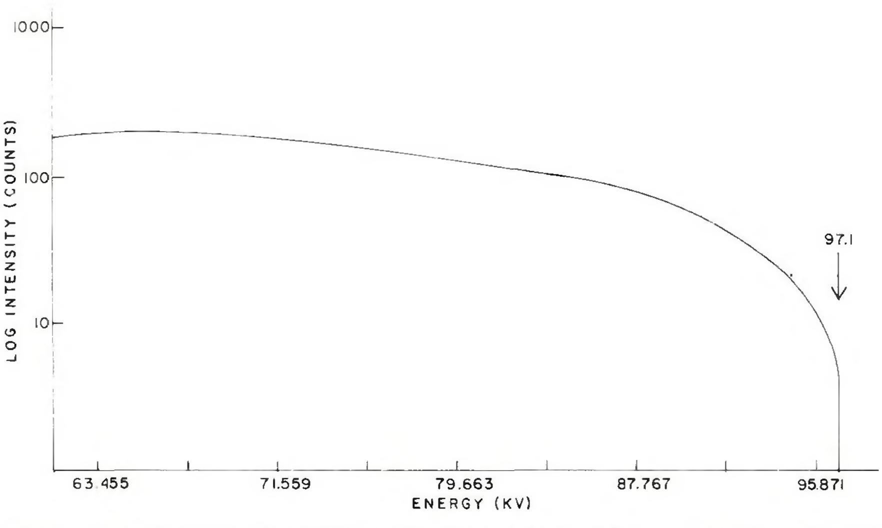

Fig. 3 — X-ray spectrum taken using a copper target, beam voltage meter setting of 90 kV, beam current meter setting of 1 ma, and 8.6 cm of aluminum absorber. High energy cutoff is 97.1 kV

large amount of self-absorption which occurs for the take-off angle used. The target material was copper or tungsten. A block diagram of the experimental system is shown in Fig. 1.

The experimental procedure used was to set the beam voltage using the voltage meter on the welder, obtain an x-ray spectrum, and compare the voltage determined from the x-ray spectrum (V_o) to that set on the welding machine (V_m).

The operating voltage was determined from the x-ray spectrum by noting that the x-ray intensity decreases linearly to zero on the high energy side of the spectrum. Since the point at which the spectrum goes to zero was needed, a log display of the spectrum was used because the small number of counts is amplified. In this display mode a zero count appeared as a one so the voltage was determined by the channel number for which the count was zero or one.

In all the spectra taken to date, there were a significant number of counts beyond the point at which the spectrum went to zero. The possible causes for this are: there was a high frequency voltage fluctuation which would generate high energy x-rays; two or more voltage pulses from the x-ray detector occurred in such a short time that they add together and the MCA interpreted them as one pulse of increased amplitude (and thus energy) (this is known as pulse pile-up); or, a combination of both. No attempt has been made to determine which of these explains the observed counts beyond the high energy cutoff. It suffices to say that they are both likely; the voltage fluctuations because the shape of the spectrum beyond V_o is similar to that below V_o and the pulse pile-up because of the high count rate and low efficiency of the detector beyond 60 kV.

Results

Figures 2-4 are actual spectra obtained for different beam voltages. These spectra show the rapid decrease in x-ray intensity on the high energy side of the spectra and thus the ease with which the beam voltage can be determined. Also shown in Figure 2 are the tungsten K_{α_1}, K_{α_2}, $K\beta_1$, and $K\beta_2$ lines, their measured energies, and their known energies. From this it is seen that the energies of these lines is within ±0.1 kV of their known energies and thus the high energy cutoff can be determined to within ±0.1 kV. The dotted line is the extrapolation of the bremstralung to zero for the voltage determination. The portion of the high energy bremstralung excluded by the dotted line indicates that counts were obtained beyond 81.5 kV. As mentioned before, this can be due to pulse pile-up and/or voltage fluctuations.

A series of 55 measurements was made comparing the voltage meter (V_m) to the voltage determined using the x-ray technique (V_o). The voltage range was from 70 kV to 140 kV and currents of 1, 2, and 4 ma were used. The maximum and minimum values of these measurements are plotted in Fig. 5. The remaining values, for a fixed V_m, appear to be uniformly distributed between those shown. The voltage did not appear to depend upon the current. The straight line shown in Fig. 5 is that expected if there is an exact correspondence between V_m and V_o (i.e., $V_m = V_o$).

It is obvious from the figure that there can be a significant error (as much as 5%) in the operating voltage when the meter is used. Since the calibration of the EDS permits determination of the voltage, using the x-ray technique, to within ±0.1 kV, the deviations seen are indeed real. The x-ray technique offers a much better means of determining the operating beam voltage and therefore should improve weld reproducibility.

Discussion

There are several precautions which are necessary in making this kind of measurement. The intensity of the spectrum is directly proportional to the beam current and the square of the beam voltage. For a weld development program the beam current and voltage used should be those which are to be used for the weld. However, this may produce excessive count rates and cause degradation of the linearity and resolution of the EDS. This can be overcome to some extent by using absorber material in the x-ray path. A large high energy x-ray intensity is essential and thus the absorber should be chosen so as to pass these x-rays.

In general, the absorber should be a material of higher atomic number than the target material. This allows the low energy characteristic lines of the target to be absorbed and passes the higher energy bremstralung. The high count rate can be accommodated somewhat by using a short time constant in the amplifier (1μs) and using baseline restoration. This will permit operation at a high count rate but will cause some degradation of the system resolution. The resolution probably will not exceed 400 eV, depending upon the detector amplifier system, and thus will still allow the voltage determination to within < ±0.2 kV. It is also essential that the EDS be carefully calibrated. This is easily accomplished using gamma ray sources.

The method described is simple, rapid, and accurate. Measuring the beam voltage using the x-ray technique provides an absolute measure of the operating voltage which is independent of the measuring circuit within the instrument. This work has shown that there is a significant error in setting the operation voltage by the present meter method.

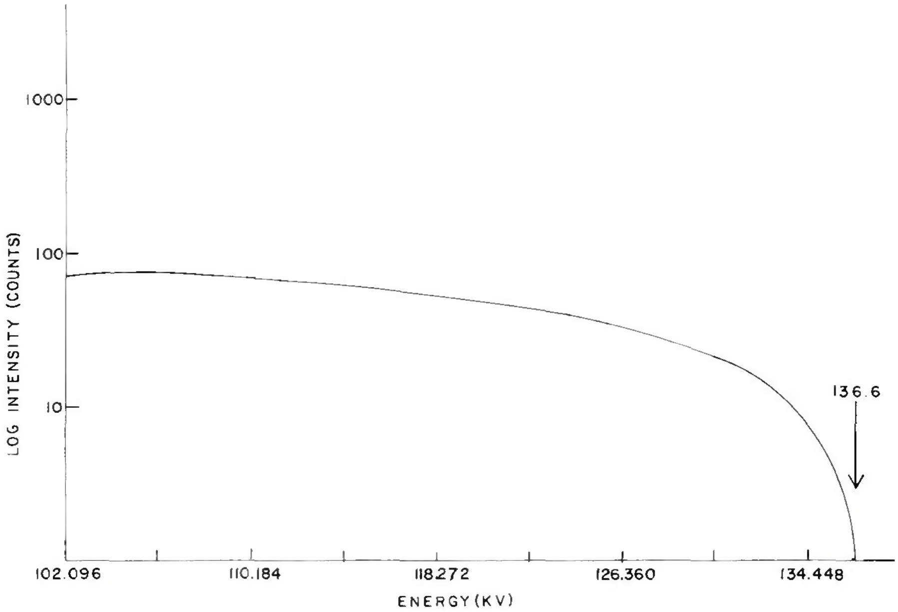

Fig. 4 — X-ray spectrum using a copper target, beam voltage meter setting of 130 kV, beam current meter setting of 2 ma, and 1 cm of copper absorber. High energy cutoff is 136.6 kV

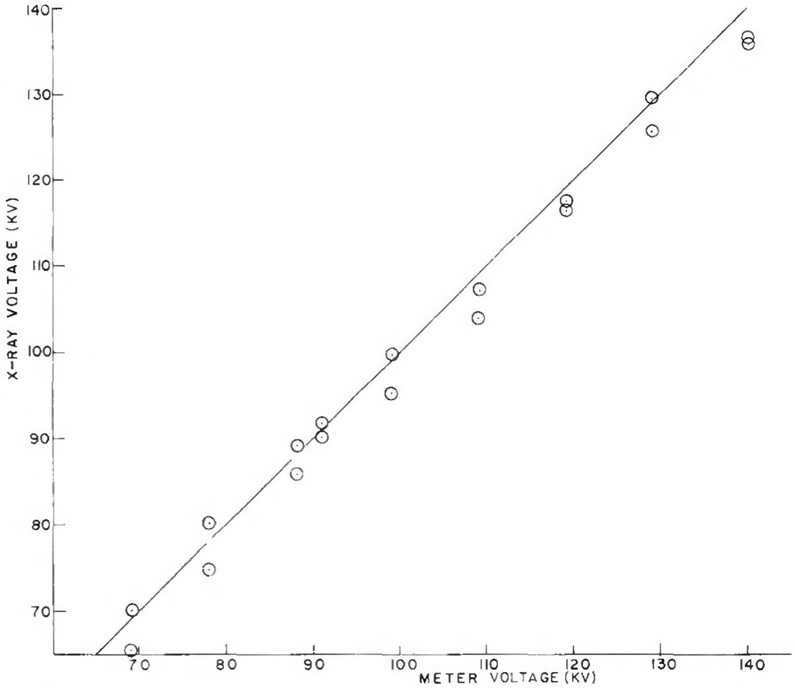

Fig. 5 — X-ray voltage vs meter voltage. The data shown indicate the extreme values obtained. The solid line is that which would be expected if there were a 1-1 correspondence between the voltage meter and the voltage determined by the x-ray technique

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