Sensing of GMAW Droplet Transfer Modes Using an ER100S-1 Electrode

Current and voltage signals from various transfer modes are studied as a means of defining parameters for automated welding

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ABSTRACT. We evaluated the capability of a 16-MHz microcomputer with a fast analog-to-digital conversion board to capture welding data and to develop through-the-arc sensing and control parameters for the gas metal arc welding process. After software was customized for this application, current and voltage data at sampling rates up to 50 kHz could be recorded for relatively long times, limited only by available disk space. The analysis software enabled us to extract numerical data and manipulate it using statistical analysis, Fourier transforms, amplitude frequency histograms, peak-searching algorithms and smoothing procedures. To determine the capabilities of this system, it was applied to the study of welding with an ER100S-1 electrode. The current and voltage were recorded for 197 welds, which formed a matrix of welding conditions encompassing short-circuiting, globular and spray transfer modes, as well as the transition regions between these modes.

From the processed data, we identified several parameters that could be used to characterize the metal transfer modes. These parameters have application in real-time control of welding. We describe the hardware configuration, the acquisition and analysis software, the data characteristics at the various transfer modes and the behavior of the different control parameters in these modes.

Introduction

Through-the-arc sensing of the current and voltage during gas metal arc welding (GMAW) is a well-known method of studying the behavior of a welding arc. The instantaneous values of the current and the voltage are recorded during a welding experiment, and analysis of the fluctuations in these values as a function of various welding parameters (power supply voltage setting, wire feed speed, etc.) provides an insight to the arc’s behavior and can be correlated to the various metal transfer modes known to exist in GMAW.

In early studies (Ref. 1), the analog signals were recorded on a strip chart. Manual analysis of these data was time-intensive, and therefore could not include a large number of data. In later studies, the data were acquired by using a digital oscilloscope and were recorded in a digital form (Refs. 2–6). Some basic data analysis could be carried out using the functions (such as Fourier transform) in the oscilloscope, or after transferring the recorded data to a computer, additional analysis could be carried out. One major limitation found for such a data recording method was that of insufficient data record length. The oscilloscope memory size limited the amount of data which could be recorded for each experiment to 8 kbytes. This limitation forced a choice between either high resolution (high acquisition rate) or a good statistical sample of the repetitive signals associated with droplet transfer (long acquisition time). Other restrictions were the limited data processing capability of the digital oscilloscope and the slow process of transferring the data to a mainframe computer for further analysis.

In recent studies (Refs. 7–10), a computer equipped with an analog-to-digital conversion board was used for data acquisition. This arrangement overcomes the memory limitation problem found for digital oscilloscopes used in previous studies and facilitates the data analysis. Online data acquisition (and analysis) by a computer is essential if the data are to be used for real-time automatic control of welding.

The aim of this work was to develop automatic data capture and evaluation techniques, keeping in mind a longer term goal of using those techniques for automatic control of the welding process.

Computer control that can achieve the same weld integrity and consistency as an experienced welder permits substantial automation and the resultant benefits. For modern manufacturing, automation and quality control are critical components for success. Using the control parameters derived from the arc’s current-voltage signals as a means of welding process control and automation within the various metal transfer modes was the main motivation for conducting this research.

Experimental Procedure

The experimental setup is illustrated in Fig. 1. One hundred ninety-seven bead-on-plate welds were produced on ASTM Type A36 steel using Ar-2% O₂ as the shielding gas. A 1.2-mm (0.045-in.) diameter AWS Type ER100S-1 electrode was used. Welding parameters varied from 100 to 420 A and 6.5 to 32 V. A low-noise transistorized current regulator filtered the line ripple from a 750-A power source and was adjusted to simulate a constant potential power source.

The justification for using the current regulator was to supply very stable power (virtually direct current, with less than 0.1-V ripple when connected to a 500-A load grid) to the arc. This meant that fluctuations found in the voltage and current signals were those induced by the arc response. The regulator could be adjusted to simulate a wide variety of power sources by using the controller potentiometers to change the effective slope or inductance. For this study, the regulator -Negev, Beer-Sheva, Israel, and was on sabbatical leave when the research was conducted. T. A. SIEWERT is with the Materials Reliability Division, National Institute of Standards and Technology, Boulder, Colo.
was set to simulate the characteristics of the 750-A primary welding power source (minimum inductance and a slope of 0.66 V per 100 A). A larger slope would have been more appropriate for the lower current levels, but a single slope was chosen to simplify the experiment matrix. Because the reproducibility of the slope was determined, the wire feed knob was set to the desired level, and the voltage was varied upward and downward by means of precision ten-turn potentiometers on the controller to cover the desired range. Thus, the matrix consisted of five ranges of wire feed rates (72, 97, 122, 152 and 182 mm/s) (168, 229, 288, 359 and 430 ipm), chosen to bracket common welding practice. The voltage range for each wire feed rate varied with transfer from periods of total arc outages at the low end to arc lengths almost as long as the 16-mm (0.63-in.) contact tube-to-work distance used in the study. This range, extending a distance both above and below the usable welding range, was evaluated in 1-V increments, the 0.5-V increments were used in regions of transition in the transfer mode. While the wire feed rate was held constant, the current varied as the resistance across the arc changed. When current is plotted, the instantaneous or root-mean-square values are reported.

At each combination of wire feed speed and voltage, an 8-s weld was produced. The resultant current and voltage signals were digitized by a 100-kHz high-speed analog-to-digital board that had 16 bit resolution, which was found to be sufficient for our purpose, and stored on a 16-MHz microcomputer's hard disk. The microcomputer was an 80386-based personal computer with a clock rate of 16 MHz. A less powerful computer would have been quite suitable for the data capture phase, but the power of this unit proved quite useful for the data analysis phases. The computer, analog-to-digital boards, and software were all commercially available units.

The data were transferred using a direct memory access (DMA) method in which the data are transferred from the board directly to a buffer in the computer's memory, without processor intervention. Once the buffer was filled, the data stream was switched to a second buffer, and the contents of the first buffer were transferred to the hard disk. This process was repeated until a prespecified number of buffers was filled. Using this method, sampling rates of up to 50 kHz could be achieved, and the amount of recorded data was limited only by the available disk space.

In this study, the optimum sampling rate was determined to be 1 kHz. This rate was found to be high enough to avoid aliasing problems and, for 8-s welds, produced data files that were convenient (32 kbytes) for manipulation. The data were analyzed offline on the same computer because the aim of this study was to develop control parameters that could be used to define and monitor the metal transfer mode. Once the control parameters are defined and chosen, the analysis can be carried out in real time and its results used to monitor and control the welding process. The necessary acquisition and analysis software were written using a high-level, scientifically oriented programming language and are described in detail elsewhere (Ref. 11). The acquisition software enables the operator to use the computer as an oscilloscope for monitoring the voltage (or current) signals in real time, and after deciding that the arc has stabilized, to start the acquisition process. The operator controls the amount of acquired data and the sampling rate. The analysis software is menu-driven and contains routines for frequency domain analysis (Fourier transforms and auto-correlation), data smoothing, histogram analysis, peak searching and counting, statistical analysis, and plotting. The data, as well as the results, can be viewed either as graphs on the computer's screen and on an attached printer, or in a numerical format as ASCII files, which can be printed or transferred to other analyzing or plotting programs.

Results and Discussion

Current and Voltage Data

When looking at the captured voltage or current data, we note marked changes in appearance as the welding parameters are changed. These changes in appearance can be correlated with the different metal transfer modes, as well as with the arc's general appearance and behavior in terms of stability, spatter, noise and length. Keeping the wire feed speed constant and gradually increasing the voltage setting of the power source allows us to identify five distinct patterns. At the lowest voltage setting for the current data records, we find a pattern similar to the one reproduced in Fig. 2. These current signals represent the short-circuiting mode. Note that the current reaches a maximal value, then drops to 0 (or to a very small value) as the arc extinguishes. Welds within this mode are associated with spatter, and the best welding conditions in this mode are the conditions that produce a signal that has the highest frequency (Ref. 6). When the voltage setting is increased further, a very sharp transition between short-circuiting and globular transfer occurs. A typical current signal representing this transition is reproduced in Fig. 3. In this case, the arc is no longer extinguished. Consequently, the current does not reach zero; instead, there are long periods of high current (short-circuiting) mixed with globular droplet transfer. This condition is associated with a less stable arc, a crackling sound and more spatter, and is generally not a good welding condition. As the voltage is increased further a globular transfer mode appears—Fig. 4. The signal is very similar to the short-circuiting signal presented in Fig. 2, but in this case, the current never reaches 0, since the arc is not extinguished between the droplets. This mode is associated with low spatter,
stable arc and a buzzing sound, and is a desirable mode of operation for some welding situations. Again, the best welds and most stable conditions are found when the frequency of the signals (corresponding to the droplet rate) is the highest. Increasing the voltage further moves the arc into a transition zone between the globular and spray transfer modes. The current signals are represented in Fig. 5 and are associated with higher spatter and less-stable arc length. The next zone, which is reached by further increasing the voltage setting, is the spray transfer mode zone—Fig. 6. The signal in this mode shows a sinusoidal pattern, but the frequency of the waves is too low to be associated with droplet transfer. This mode is associated with a very stable arc, hissing noise, a large quantity of ultraviolet radiation and minimal spatter, and is the mode of choice for many welding situations. In summary, we see that each zone is associated with a specific shape of the current data. (This information is contained in the voltage data as well, but the differences are smaller and more difficult to detect.) So, by examining the shape of the acquired data, we can determine which mode was present during welding. This information can be used as feedback in a control loop governing the welding process. In the following, we will describe various modes of data analysis that can quantify the transfer mode.

**Fourier Transform**

The smoothed Fourier transforms of the current signals for short-circuiting, globular and spray transfer modes are presented in Figs. 7–9. Figure 7 shows the transform for a short-circuiting mode where we see a main peak at the droplet transfer frequency (about 90 Hz), as well as additional sharp peaks between 0 and 20 Hz, which decay with increasing frequency. These low-frequency peaks are characteristic of the transform of a square wave (box transform) and represent the occasional square current wave encountered in this welding mode. Figure 8 represents the Fourier transform of the current signal for a globular transfer mode. It is characterized by a well defined and relatively sharp main peak. The width of the
peak is a measure of the variation of the repetitive signal over time in the sense that a uniform droplet rate will result in a narrow peak, while the location of the peak represents the main droplet frequency. The droplet frequency data should be particularly useful in control since it has been shown that the highest droplet rate corresponds to the best welding conditions in this mode (Ref. 6). This specific shape of the Fourier transform could be used as an indication of the globular transfer mode. Controlling the welding parameters so that the main peak will be kept as narrow as possible and its frequency as high as possible will serve as an automatic control for good welding conditions in the globular transfer mode. Figure 9 represents the Fourier transform of the current signals during spray transfer mode. A small peak representing the waveform frequency is evident, but it cannot be associated with the droplet transfer rate, which is known to be higher in this mode.

Signal’s Standard Deviation

For each of the welds, the standard deviations of the current and signal data were calculated. A plot of the current’s standard deviation at a constant wire feed speed versus the power source’s voltage is presented in Fig. 10. We can distinguish three distinct areas in this plot. At a low voltage setting, high values of the standard deviation are obtained, which correspond to a short-circuiting mode. Between 12 and 12.5 V there is a sharp transition from pure short-circuiting to a mixture of short-circuiting and globular modes. The standard deviation then decreases continuously until a pure spray transfer mode is reached at 25 V, above which, the standard deviation remains constant. Standard deviation can be used for spray mode or short-circuiting mode detection and control. It cannot, however, be used to isolate the pure globular transfer mode from its adjacent transition zones.

Amplitude Histograms

These histograms show the time-weighted distribution of the current (or voltage) amplitude values over the duration of the test. In other words, peaks in the histogram indicate that the current (or voltage) was often recorded at that value. A voltage histogram for the short-circuiting transfer mode is presented in Fig. 11. For this mode, there are two main peaks in the histogram, because the voltage remains in two discrete ranges (short and open circuit) most of the time. The globular mode histogram shown in Fig. 12 presents one main peak at the average voltage and two smaller ones representing the voltage spikes (above and below the average value) associated with the droplet transfer. In spray transfer, where the voltage variations are very small (about 0.5 V), the histogram is characterized by a single sharp peak centered around the average voltage, as seen in Fig. 13. Those distinct shapes of the histograms can be used to determine the metal transfer mode, and to interactively keep the system in a preselected mode. However, as we move from one mode to another through a transition zone, the shape of the amplitude histogram changes gradually and continuously, so it is difficult to establish the exact point at which we leave a pure transfer mode and enter a transition zone. In order to overcome this difficulty, and because shape monitoring is difficult to automate, two more sensitive parameters were developed from the amplitude histogram.
Peak Ratios in the Voltage Amplitude Histogram

Looking again at Figs. 11-13, we notice that the ratio of the two highest peaks in the short-circuiting mode is about 1, as the voltage spends approximately equal amounts of time in short-circuit and open-circuit positions. This ratio is small (about 0.1) but not 0 in the globular transfer mode, because the voltage is kept at the base value for most of the time and changes from that value only when a drop is transferred. In spray transfer mode, where there is only one peak, this ratio is zero. The value of this ratio for a constant wire feed speed versus the power supply’s voltage is represented in Fig. 14. The three areas on the plot correspond to the three metal transfer modes, and we can define the transition zone between pure short circuiting and pure globular transfer modes. Transition between globular and spray transfers is not as well defined, but this ratio could be used to monitor and control the welding process.

Integral of Current Amplitude Histogram

Another parameter that was investigated is the integral of the current amplitude histogram over a current range of 0 to 60 A. The value of this integral is proportional to the time of arc outage and thus is large for the short-circuiting mode, very small or zero for pure globular and spray transfer modes, and of intermediate size in the transition zone between the latter two modes — Fig. 15. The shape of this curve is relatively insensitive to the integration limits, and we have obtained a similar shape for integral limits ranging from 0–30 A to 0–100 A. The welding conditions that produce a zero value for this integral (no arc outages) in the globular and spray transfer modes, coincide with the welding conditions that produce pure metal transfer modes and hence, good welds. The value of this parameter is particularly useful for control and feedback purposes during an automatic welding process because it is very sensitive to the transition between globular and spray modes.

Frequency Determination

Each drop of metal transferred during the welding process is associated with a peak in the current or voltage signals. This was previously shown (Ref. 3) by comparing the number of peaks in the electrical signals to the number of droplets counted by use of a laser backlighting and a fast video camera. In trying to develop routines for automatic peak counting, we ran into some problems in the spray transfer zone because the signals are the same order of magnitude as the noise in the system.

Three different approaches were tried for peak counting: 1) Smoothing the signal, calculating the first derivative of the signal, and then counting the number of times the derivative changes its sign in a given time period. 2) Smoothing the signal, finding the voltage (or current) level corresponding to 20% of the highest peak (reasoning that peaks having a half-height smaller than 20% of the maximum do not represent droplet transfer), and then subtracting this value from the whole signal. This operation caused each peak to have both a negative and a positive component. Counting the number of times the transformed signal changed sign allowed us to calculate the number of peaks. 3) A modification of the procedure described in 2) but in which the value to be subtracted from the signal is determined manually.

All three schemes gave essentially the
Comparison of the Control Parameters

The Fourier transform, standard deviation, amplitude histogram, amplitude peak ratio, and integral of the amplitude histogram were identified as control parameters. Those control parameters show different sensitivity (and hence applicability) to the different metal transfer modes, so that there is no one parameter which is suitable for monitoring and controlling the welding process across the whole spectrum of the metal transfer modes. Table 1 summarizes the relative sensitivity of the control parameter to different transfer modes.

Conclusions

1. A microcomputer is an efficient tool to acquire and process welding data on-line at high sampling rates for long periods of time.

2. Control parameters that characterize the metal transfer mode include Fourier transforms, frequency histograms and further subsets of these.

3. Monitoring these parameters can make sure that the welding process will be carried out in a pure metal transfer mode, thus ensuring the best welding conditions for this mode.

4. Identification of individual transfer events in spray transfer by through-the-arc sensing will require a power supply with extremely low noise.

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References


