SENSING OF METAL-TRANSFER MODE FOR PROCESS CONTROL OF GMAW

Nancy M. Carlson, John A. Johnson, and Herschel B. Smartt
Idaho National Engineering Laboratory, EG&G Idaho, Inc.
P.O. Box 1625
Idaho Falls, ID 83415-2209

INTRODUCTION

Research in welding at the Idaho National Engineering Laboratory (INEL) is currently concentrating on the development of sensing, modeling, and control schemes for GMAW [1,2]. In the GMAW process, a welding arc is struck between the workpiece and the tip of a consumable wire electrode. The electrode carries the welding current, sustaining the arc. The electrode melts, resulting in the detachment of metal droplets which supply filler metal to the joint [3]. The standard practice for achieving a desired rate and size of metal droplet is to set welding parameters based on past experience.

For process control of GMAW, various types of sensors can be used to measure properties of the GMAW process and to provide input to the system. From the sensor data, the state of the system is determined and compared to the desired state. From this information, heat input and fill strategies are determined and sent to a model of the process which calculates appropriate values of standard GMAW parameters including current, wire feed speed, and weld travel speed.

The droplet transfer mode in the GMAW process has a large effect on weld pool metallurgy, influencing penetration, solidification, heat flow, and mass input. Although initial welding parameters are set for a desired droplet transfer mode, the operating boundaries of globular, spray, streaming, and stub-in transfer can vary during the welding pass, altering the transfer mode and the welding process. A series of experiments was performed using multiple sensors to sense the metal-transfer mode dynamically. Acoustic emissions, audio emissions, and welding current and voltage fluctuations were recorded as a function of the transfer mode. To correlate sensor data with the actual transfer mode, high speed movies of the droplet transfer were acquired synchronously with the sensing data.

Each of the sensing devices could be applied in a nonintrusive manner in an automated welder. These experiments using all the sensors allowed them to be compared and their relative potential for sensing the mode of metal transfer evaluated.
EXPERIMENTAL SETUP

A simplified schematic of the data acquisition system is shown in Figure 1. A portable workstation [4] based on a MicroVax II computer and a Computer Automated Measurement And Control crate (CAMAC, IEEE-583 Standard) was used for data acquisition. Four channels of sensor data were acquired along with a fifth channel, which records signals used to synchronize the sensor data with individual frames on the film taken with a high-speed camera.

The sensors were a piezoelectric sensor mounted in a fixture that was clamped to the weld sample, a Shure 5775 microphone mounted 320 mm (13 in.) from the weld pool, a current sensor, and a voltage sensor. The piezoelectric sensor is sensitive to acoustic emissions from about 1 kHz to 2 MHz. A preamplifier that passed the entire bandwidth of the sensor amplifies plate borne vibrations in the sample for digitization. The signal from the microphone was amplified over a bandwidth from 10 Hz to 30 kHz. The bandwidth of the microphone was not measured. A shunt in the ground cable from the weld sample to the power supply was used to measure the welding current. The voltage across the shunt was amplified by a differential amplifier with a bandwidth from 10 Hz to 30 kHz. Thus the DC portion of the welding current was not measured, only fluctuations about the average DC value. The voltage signal was obtained from leads connected to the contact tip and the ground on the workpiece. The voltage was also filtered to a bandwidth from 10 Hz to 30 kHz so that only the AC component of the signal was digitized.

The acoustic emission signals were acquired at a 500-kHz sampling rate, and the other channels were digitized at a synchronous 50-kHz rate. A maximum of 8192 points can be stored in each digitizer. At these sampling rates, approximately 16.4 ms of acoustic emission data and 163.8 ms of data on the other channels can be acquired. Data acquisition began when a signal was sent to a buffer that triggered all five digitizers.

The fifth channel acquired the analog pulses from a multichannel light-emitting diode (LED) driver for the high-speed camera so that the

Fig. 1. Schematic for multiple sensor data acquisition.
sensor data can be correlated with the film data. These pulses were sent to the camera at a set repetition rate where they trigger an LED, which then places a mark that can be seen in the margin of the film. The control box was designed so that a double mark was placed on the film every 10 cycles and a triple mark every 100 cycles. These double and triple pulses are also recorded by the digitizing system to allow correlation between the film and the digitized data. The LED film marker pulse sent from the control box to the fifth channel was pulse stretched to ensure that the pulse width is sufficient to be digitized. Knowing that the film LED marks occur five frames prior to that frame passing the shutter of the camera, the digitized data can be correlated to the film data within a frame of the actual occurrence of an event. In addition, a pulse was sent to the film control box from the workstation to trigger a second LED which marks the film at the beginning of the data acquisition cycle. A second signal was also sent to the camera LED to mark the termination of acoustic emission data acquisition.

EXPERIMENTS WITH A TRANSISTORIZED POWER SUPPLY

A Philips transistorized power supply (Model PZ 2351/60) was used in the experiments described in this section. This supply employs a filtered 40-kHz signal to provide power. For these experiments, the supply was used in the constant voltage mode. The voltage setting, the wire feed speed, and the torch-to-workpiece distance determined the current and the droplet transfer mode.

Data were acquired in the following manner. The welding operator established a steady arc in the desired transfer mode. At the operator’s signal, the high speed camera was turned on and the data acquisition system armed. After a programmed delay of up to 3 s to allow the film to get up to the final speed of 5000 frames per second, the acquisition system acquired a set of data on all five channels simultaneously and also sent pulses to the second LED to mark the film as described above. After data acquisition, the information was written to a disk for later analysis and plotting.

Data were acquired for three different transfer modes - globular, spray, and streaming. The three modes of metal transfer are achieved by using welding parameters listed in Table 1. Figure 2 presents photos made from camera frames acquired synchronously with the digitized data for three transfer modes. In globular transfer (Figure 2a), large droplets of a diameter in excess of the diameter of the electrode detach as discrete drops at a rate of up to a hundred per second. In spray transfer (Figure 2b), small droplets of metal detach from the electrode at a rate of several hundred per second. In streaming transfer (Figure 2c), small droplets detach from a liquid column of metal attached to the electrode [3]. The necessity for sensing and process control is evident in Figure 2b. Although spray welding parameters were set for spray transfer, notice that a short liquid column extended beneath the electrode indicating that the process was changing from spray transfer, the desired transfer mode, to streaming transfer.

A portion of the digitized data taken during globular transfer is shown in Figure 3a. (Note the time scale for the acoustic emission data is a factor of ten faster than that shown on the plot so that the acoustic emission data shown covers only 1/10 of the time covered by the other four plots.) Pulses in the "Camera Sync" plot occur at 1-ms intervals and are the record of the times that the LED marks are placed on the film. Note that every tenth pulse is doubled and that this particular data set.
TABLE 1. WELDING PARAMETERS

<table>
<thead>
<tr>
<th>Transfer Mode</th>
<th>Volts</th>
<th>Amperes</th>
<th>Wire feed Speed (mm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Globular</td>
<td>25.6</td>
<td>173</td>
<td>130</td>
</tr>
<tr>
<td>Spray</td>
<td>27.0</td>
<td>234</td>
<td>190</td>
</tr>
<tr>
<td>Streaming</td>
<td>26.7</td>
<td>275</td>
<td>250</td>
</tr>
</tbody>
</table>

Contact-tip-to-workpiece distance 15.9 mm
Travel speed 4.2 mm/s
Cover gas 98% Ar, 2% O₂

Fig. 2. Three metal-transfer modes

includes a triple mark which occurs every 100 ms. Using these pulse marks allowed a correlation between droplet detachments on the film and signals in the four sensor channels to be made.

The acoustic emission data showed no correlation with the film data. In fact, the data seen in that channel were at multiples and submultiples of the 40 kHz switching frequency of the power supply. Much of the noise in the other three sensor channels was also due to this source. However, this seemed to be the only signal present in this channel in all the acoustic emission data taken. These sensor data are not discussed further in this paper.

The voltage and current data had two obvious features at 50 and 75 ms which correlate precisely (to within one frame at 5000 frames/s) to a large globular droplet detaching from the end of the wire. Not quite so
Fig. 3. Data from different transfer modes. a. Globular transfer data shown with the camera synchronization pulses, b. Globular transfer, c. Spray transfer, d. Streaming transfer, e. Comparison of voltage data for the three transfer modes.
obvious were two features in the audio signal that occur about 1 ms after the current and voltage features. This 1 ms was the time required for sound to travel the 320 mm from the tip of the wire to the microphone.

The current data do not show the sharp features observed in the voltage data. This is probably due to the inductance of the shunt which limits the bandwidth of this sensor. A tubular shunt being developed for pulsed welding may be useful in extending the bandwidth of the current sensor [5].

The entire 160-ms data set for the audio, current, and voltage for this experiment in globular-transfer mode is shown in Figure 3b. A total of nine features is seen in the entire data set, and each corresponds to a droplet detachment observed on the expected frame on the film. Note that at the start of the data set, the positive going portion of a fluctuation cycle is observed due to an additional drop which detached just a few frames before the acquisition system began to record data. The audio signal is more difficult to correlate on this compressed scale. However, for eight of the nine droplet detachments (and for the detachment at the beginning, which can be observed in the audio data because of the 1 ms delay), a feature similar to those seen in Figure 3a can be observed. The detachment at 138 ms does not seem to have a correlating signal in the audio channel.

Data for three modes of droplet transfer - globular, spray, and streaming transfer - were acquired. Figures 3c and d show results analogous to Figure 3b for spray transfer and streaming transfer, respectively. For spray transfer, features similar to those observed for globular transfer are observed unambiguously in the current and voltage data (Figure 3c). Each of these features again correlates with a droplet detachment. The features are smaller in amplitude relative to the 40 kHz noise of the power supply and occur more often, corresponding to the smaller droplet size and the greater rate of droplet detachment. Between about 18 and 26 ms, the transfer mode changed slightly and very many small droplets detached. Following this period the droplets again returned to the normal size for spray transfer.

In streaming transfer, little fluctuation is observed in the digitized data on these three channels (Figure 3d). This correlates with the lack of a well defined detachment in this transfer mode since a nearly continuous stream of liquid melts off the wire, only breaking up after traveling downward some distance. One feature of significance occurs at about 19 ms and may correlate with the stream bridging the gap between the end of the wire and the weld pool, causing a short. It is difficult to identify shorts on the film.

In Figure 3e the voltage data for the three modes of transfer are compared. The amplitudes of the features are seen to decrease and the frequency to increase as the size of the droplets decreases going from globular to spray mode. In streaming transfer, it is difficult or impossible to detect individual droplets. These data could easily be used by a simple expert system to detect and discriminate among the transfer modes in real time and thus provide input information to the feedback system for control of the welding process.

POWER SUPPLY VARIATIONS

Data acquisition with the multisensing system was also conducted using a Linde (Model SVI-300) power supply. In this supply the three-phase, 60-Hz power is transformed and rectified to produce the
desired DC voltage. This results in a rather large 360-Hz noise ripple in the audio, current, and voltage signals. Bandstop filters at 360 Hz were placed in the circuits connecting the sensors to the digitizers. Comparison of the transistorized and rectified power supply data reveals that the mode of droplet transfer can be detected for either supply. However, the detection does require knowledge of the baseline signature of each power supply. In the globular mode of transfer for both supplies, the droplet detachments produce a distinct, large amplitude, low frequency fluctuation in both the voltage and current. When spray droplets detach, the frequency of fluctuations in current and voltage increases, and the amplitude of the fluctuations decreases compared to globular transfer. Detection of spray transfer depends on the droplet size. As the size of the spray droplets decreases, so does the ability to detect detachment of the individual droplets. In the extreme case of the streaming transfer mode, few fluctuations in the voltage and current data were observed. The fact that each mode of droplet transfer has a unique voltage signature in the acquired digitized data for both supplies demonstrates the feasibility of using voltage sensing to determine droplet transfer modes.

However, signatures of the different modes are not the same for the two power supplies, thus presenting some difficulty in introducing a generic system for all power supplies. Interpretation of the acquired current and voltage signals is based on knowledge of the power supply baseline signature and the change in that signature during droplet transfer. Since weld operators are capable of using the audio information they hear to determine the transfer mode, independent of the power supply, the audio signal should be independent of the power supply also. However, information from that sensor must be improved by decreasing the extraneous noise in that channel and enhancing the data feature associated with the droplet transfer. This will require improved microphones, electronics, and filtering for the audio channel. Several possibilities for improving the audio signal include using correlated signals from two microphones at equal distances from the welding torch or using a parabolic reflector focused on the welding torch to improve the signal-to-noise ratio.

CONCLUSION

The multisensor approach for sensing the metal-transfer mode for process control of GMAW demonstrates the potential to detect the droplet transfer mode by monitoring current and voltage of the power supply. The ability to sense the metal-transfer mode is vital to ensure that the welder operates in the required transfer mode to achieve the desired heat and mass input for the weld. The audio and acoustic emission sensors need to be evaluated and replaced with sensors with a more appropriate bandwidth and sensitivity for the application. The voltage and current data appear to be power supply dependent, based on the work completed with two power supplies used for the feasibility tests. This dependence may present a potential problem in analysis of the incoming signals in the closed-loop control system because of the difference in signatures from each power supply. The use of improved audio data may be the best method of overcoming this problem.

If only current and voltage are monitored, the input to the computer can be designed to be invisible to the user and thus more acceptable in industry. The sensors are simply monitoring the analog output generated by the power supply and creating no additional potential problems in any welding application. Because the approach is capable of monitoring droplet detachment dynamically, the desired transfer mode can be sensed and controlled throughout the entire welding pass by a closed-loop control system.
These tests have demonstrated the ability to detect the detachment of individual droplets and to distinguish among three metal-transfer modes in GMAW. The same approach should be capable of sensing droplet detachment in a pulsed welding application. The detection of the transfer would ensure that a droplet is detached at each pulse of the welder and that no more than one droplet detached. This would aid greatly in controlling the heat and mass input for pulsed welding with the closed-loop welding process control system with feedback control.

ACKNOWLEDGMENTS

This work is supported by the U.S. Department of Energy, Office of Energy Research, Office of Basic Energy Sciences under DOE Contract No. DE-AC07-76ID01570. Technical assistance was provided by U. S. Wallace, C. L. Shull, and A. L. Jones.

REFERENCES