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Detection of Metal-Transfer Mode in GMAW

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ABSTRACT

One of the requirements of a sensing system for feedback control of gas metal arc welding (GMAW) is the capability to detect information about the metal-transfer mode. Because the operating boundary for the desired transfer mode, expressed as a function of mass input and heat input, may vary due to conditions beyond the control of the system, a means of determining the transfer mode during welding is necessary. A series of sensing experiments is performed during which the ultrasonic emissions, audio emissions, welding current fluctuations, and welding voltage fluctuations are recorded as a function of the transfer mode. In addition, high speed movies (5000 frames/s) of the droplet formation and detachment are taken synchronously with the sensing data. An LED mounted in the camera is used to mark the film at the beginning and end of the data acquisition period. A second LED is pulsed at a 1 kHz rate and the pulses are recorded on film and with the sensor data. Thus events observed on the film can be correlated with the sensor data. Data acquired during globular transfer, spray transfer, and stiff spray or streaming transfer are observed to correlate with droplet detachment and arc shorting. The audio, current, and voltage data can be used to discriminate among these different transfer modes. However, the current and voltage data are also dependent on the characteristics of the welding power supply.

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] Various types of sensors that can be used to measure properties of the GMAW process provide input to the system. From the raw 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 is performed using multiple sensors to sense the metal-transfer mode dynamically. Acoustic emissions, audio emissions, and welding current and voltage fluctuations are recorded as a function of the transfer mode. To correlate sensor data with the actual transfer mode, high speed movies of the droplet transfer are acquired synchronously with the sensing data.

Each of the sensing devices could be applied in a nonintrusive manner into an automated welder. These experiments using all the sensors allow 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 [3] based on a MicroVax II computer and a Computer Automated Measurement And Control (CAMAC) crate (IEEE-583 Standard) is used for data acquisition. Four channels of sensor data are acquired along with a fifth channel, which records signals used to synchronize the

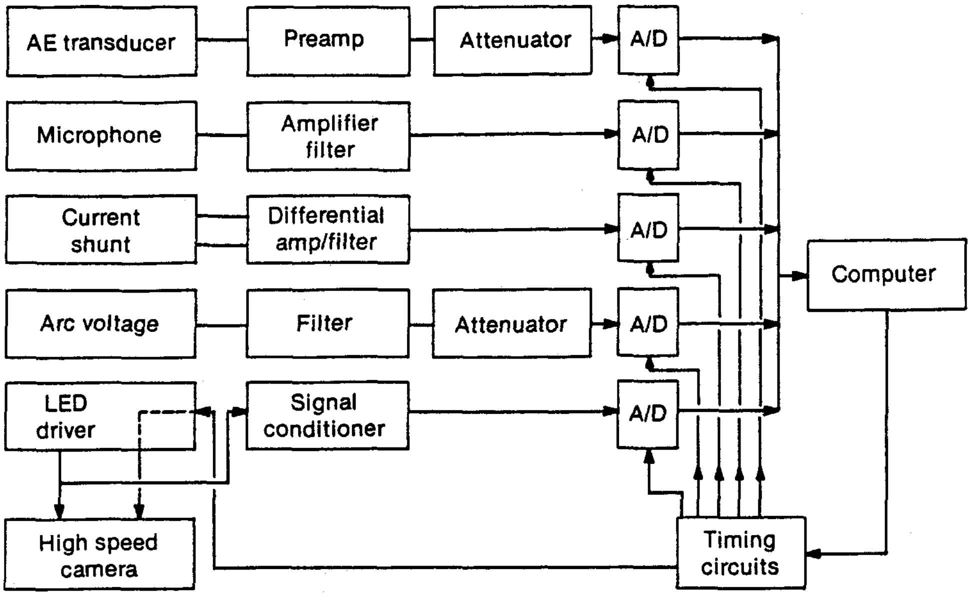

Fig. 1 - Schematic for multiple sensor data acquisition

sensor data with individual frames on the film taken with a high-speed camera.

The sensors are a piezoelectric sensor mounted in a fixture which is clamped to the weld sample, a Shure 5775 microphone mounted 320 mm 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 passes the entire bandwidth of the sensor amplifies vibrations in the sample for digitization. The signal from the microphone is amplified over a bandwidth from 10 Hz to 30 kHz. The bandwidth of the microphone is not measured. A shunt in the ground cable from the weld sample to the power supply is used to measure the welding current. The voltage across the shunt is amplified by a differential amplifier with a bandwidth from 10 Hz to 30 kHz. Thus the DC portion of the welding current is not measured, only the fluctuations about the average DC value. The voltage signal is obtained from leads connected to the contact tip and the ground on the work piece. The voltage is also filtered to a bandwidth from 10 Hz to 30 kHz so that only the AC component of the signal is digitized.

The acoustic emission signals are acquired at a 500 kHz sampling rate and the other channels are 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 is initiated when a signal is sent to a buffer that triggers all five digitizers.

The fifth channel acquires the analog pulses from a multichannel light-emitting diode (LED) driver for the high-speed camera so that the sensor data can be correlated with the film data. These pulses are sent to the camera at a set repetition rate where they trigger an LED, which then places a mark on the margin of the film. The control box is designed so that a double mark is 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 is pulse stretched to assure 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 is 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 is also sent to the camera LED to mark the termination of acoustic emission data acquisition.

EXPERIMENTS WITH A TRANSISTORIZED POWER SUPPLY

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

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

Data are acquired for three different transfer modes - globular, spray, and streaming. A portion of the data taken during globular transfer is shown in Figure 2. (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 cover only 1/10 of the time covered by the other four plots.) The 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 includes a triple mark.

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

The voltage and current data have 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 obvious are two features in the audio signal which occur about 1 ms after the current and voltage features. This 1 ms delay is the time required for the 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 [4].

The entire data set for the audio, current, and voltage sensors for this experiment in globular-transfer mode is shown in Figure 3. A total of nine features is seen in the entire data set and each corresponds to a droplet detachment observed on the expected frame of the film. Note that at the beginning of the data set is a tenth drop that 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,

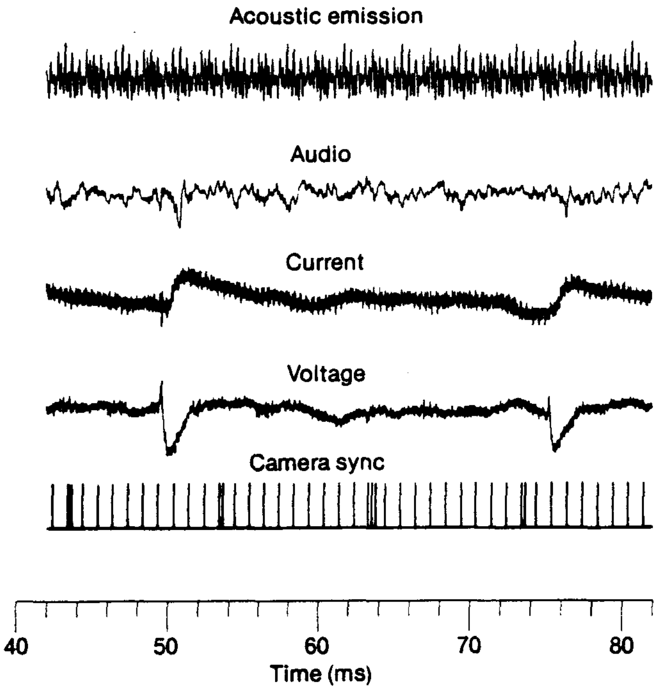

Fig. 2. - Acoustic emission, audio, current, and voltage data from globular transfer shown with the camera synchronization pulses

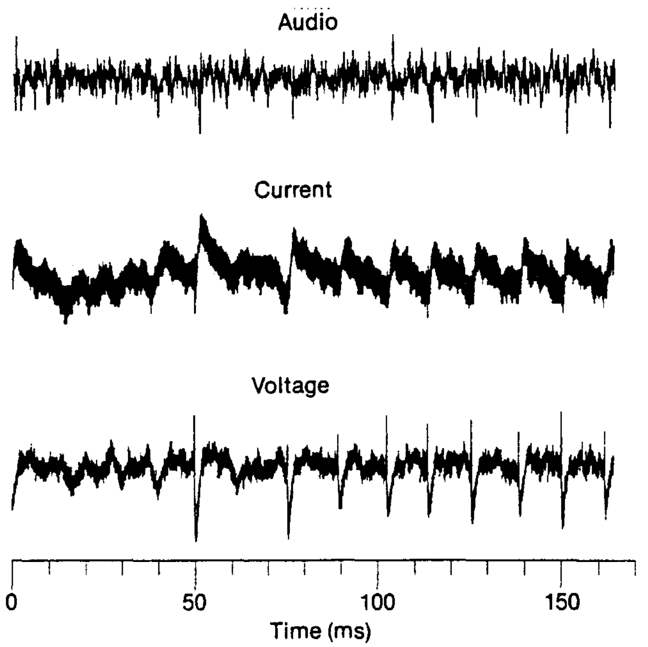

Fig. 3 - Audio, current, and voltage data for globular transfer

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 2 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 - are acquired. Figures 4 and 5 show results analogous to Figure 3 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 4). 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 a nearly continuous stream of liquid melts off the wire, breaking up only after traveling downward some distance. Little fluctuation is observed in the digitized data for this mode (Figure 5), which correlates with the lack of a well defined detachment. 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 comparing the voltage data for the three modes of transfer, the amplitudes of the features are seen to decrease and the frequency increase as the size of the droplets decreases going from globular to spray. 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 is 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 are 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. 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

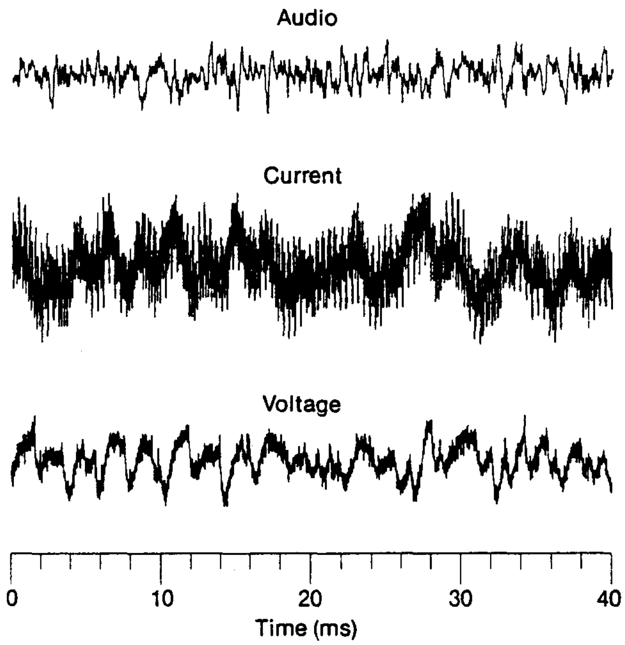

Fig. 4 - Audio, current, and voltage data for spray transfer

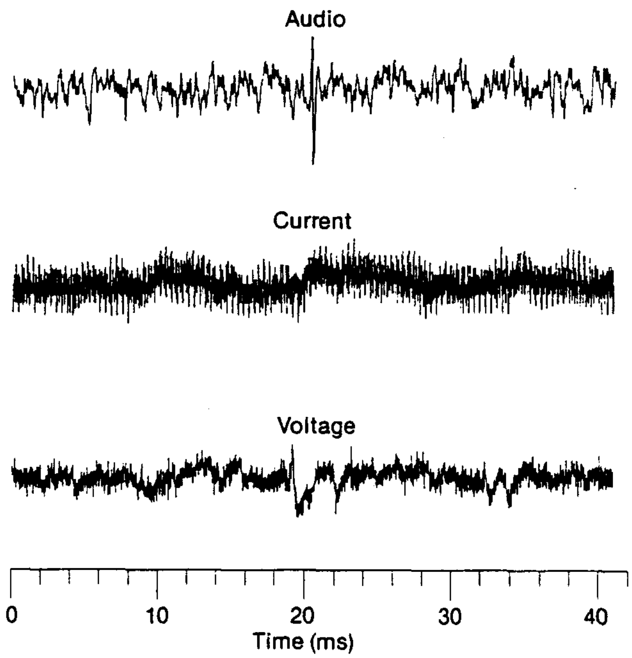

Fig. 5 - Audio, current, and voltage data for streaming transfer

and the amplitude of the fluctuations decreases when 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 of streaming transfer mode, few fluctuations in the voltage and current data are 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, the 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. The 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, the 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 demonstrates the potential to determine the droplet transfer mode by monitoring current and voltage of the power supply. 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 potential problems in any welding application. Because the approach is capable of monitoring droplet detachment dynamically, the desired transfer mode can be maintained throughout the entire welding pass.

These tests have demonstrated the ability to detect the detachment of individual droplets and to distinguish among three transfer modes. The same approach should be capable of detecting the detachment in a pulsed welding application. The detection of the detachment would ensure that a droplet is detached at each pulse of the welder. This would aid greatly in closed-loop control of the heat and mass input during pulsed welding.

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