DIGITAL SIGNAL PROCESSING AS A DIAGNOSTIC TOOL FOR GAS TUNGSTEN ARC WELDING

Carl D. Sorensen, Thomas W. Eagar
Materials Processing Center
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

ABSTRACT
One of the major difficulties involved with closed-loop control of welding processes is a lack of a suitable sensors of the welding process. A proposed welding sensor is the welding arc itself. The sensory information is obtained through digital signal processing of the arc voltage and current. Experiments performed to test the suitability of digital signal processing as an arc monitor indicated that the technique had promise as a laboratory sensor, but that it had neither the sensitivity nor the selectivity to act as a production monitor of the welding process.

IN RECENT YEARS there has been a great deal of interest in automating the arc welding process as a means of improving productivity, lowering costs, and improving reliability of welding processes[1]. One of the major difficulties with automation of arc welding is the lack of a suitable weld quality sensor. Typical automatic welding systems may be capable of controlling torch position, travel speed, arc voltage, and/or arc current[2]; however, these variables are generally controlled only according to some predetermined optimum schedule, rather than according to the actual weld condition. It order to use a feedback control system with arc welding, it is necessary to develop better weld quality sensors. If such sensors were available, the welding process could be monitored; and the torch position, travel speed, arc voltage, or arc current could be modified to improve the weld quality.

Several investigators have examined possible weld quality monitors[3-9, e.g.]. Most of these techniques are not yet useful for production systems, in many cases because the sensing systems add bulk to the welding torch or are adversely affected by the intense heat and light of the welding arc. To avoid these problems it is desirable to use the welding arc itself as the weld quality sensor.

The arc is a dynamic electrical element, and thus has electrical properties that vary with frequency. One method of examining the electrical properties of the arc is digital signal processing. This paper is a brief description of an analysis made at M.I.T. of the use of digital signal processing of the arc voltage and current as a diagnostic tool for GTA welding. It describes the analysis techniques and equipment used to measure the electrical properties of the arc. Experiments to test the ability of this analysis technique to measure voltage oscillations are discussed, correlation of the experimental results and theoretical predictions is examined, and the limitations of this technique as a practical weld quality monitor are discussed.

ANALYSIS TECHNIQUE
In order to study the electrical characteristics of the arc/puddle system, an impedance based measurement technique is used. The arc is treated as an electrical "black box" with the weld current as an input and the weld voltage as an output. The electrical characteristics of the arc were measured by means of the frequency response function[10], which is obtained by Fast Fourier Transform (FFT) analysis of the input (current) and output (voltage) of the system. The frequency response function is comprised of the gain, phase, and coherence functions, which measure the amplification, phase lag, and noise as a function of frequency. Of particular interest is the behavior of the system frequency response function near a resonant frequency, where gain will increase sharply and the phase will shift by 180 degrees. In addition, the coherence is expected to rise, since the magnitude of the output signal will increase due to the increased gain. In practice, the peak in the gain function is easiest to detect and will therefore be used most often to indicate a resonant frequency in the welding arc such as that of the puddle oscillations.
EXPERIMENTAL EQUIPMENT

The equipment used to perform this study consists of a gas-tungsten arc (GTA) welding apparatus combined with a computer-driven measurement system, shown schematically in Figure 1. Welding power is supplied by a 24V, 600 A-h battery. The current is controlled by a solid state linear D.C. current regulator designed by Alexander Kusko, Inc.[11]. This regulator is capable of providing 600 A RMS or 1000 A peak current regulated to within 1% of full scale at frequencies of up to 25 kHz. The desired current waveform is selected by means of an external reference supplied by a Wavetek model 166 signal generator.

![Schematic Diagram of Experimental Equipment](image)

Figure 1. Schematic Diagram of Experimental Equipment

The arc voltage and current are measured with a computer based data collection system. Current is measured by means of a shunt placed in the lead connecting the work to the current regulator. The voltage across the shunt, which is proportional to the weld current, and the arc voltage are fed to a compensated optical isolator to protect the computer. Each of these isolated signals is passed through a Frequency Devices model 901 variable frequency low-pass filter, which serves to prevent aliasing effects due to high frequency components in the signal. The output signals from the filters are connected to a Digital Equipment Corporation MINC/DECLAR-23 computer equipped with ADAC model 1601 timer, 1023 A/D and 1620 DMA modules. This system is capable of sampling both voltage and current waveforms at user-selected frequencies of up to 45 kHz each. These signals are then analyzed off-line to determine the frequency response of the arc-puddle system.

EXPERIMENTAL PROCEDURE AND RESULTS

Three different experiments were performed to evaluate the effectiveness of this new method for sensing the welding process. The first tested the sensitivity of the analytic technique to arc length when measuring weld pool oscillations, the second compared the oscillation frequencies of stationary weld pools with those predicted by a model, and the third investigated the ability of this analysis technique to detect changes in the welding process.

SENSITIVITY ANALYSIS - As part of the sensitivity analysis, the minimum detectable amplitude of weld pool oscillations was estimated and the input current waveform was optimized. These experiments are discussed in reference 12. An important part of the sensitivity analysis tested the effect of arc length on the ability to measure oscillations in stationary weld pools. Previous experiments with control of puddle size through examining puddle diameter had shown success only for very short arcs, a major concern with this analysis technique was how it would work at moderate or large arc lengths. A test was performed to measure the effect of arc length on the sensitivity of the measurement technique. The experiments were performed on a 9 mm (3/8") thick plate of A36 steel. The welding current was a 100 A background with a 300 A pulse of 5 ms duration occurring every 145 ms. A 2.4 mm (33") 2% thoriated tungsten electrode with a 60° tip angle was used. Helium was used as a shielding gas. Various arc voltages ranging from 9 to 15 volts were used, corresponding to arc lengths of up to 13 mm (1/2`).

Results - Figures 2 and 3 show the system gain function for welds made at 9V and 15V, respectively. The peak in each graph is at the natural frequency of the puddle. The natural frequency is different in each case because the puddle size is different. Figure 4 shows the observed correlation of puddle frequency with weld pool diameter.

![Gain function for 9.5 V arc](image)

Figure 2. Gain function for 9.5 V arc. Note resonance peak at 280 Hz.
Figure 3. Gain function for 15 V arc. Barely visible resonance peak is at 90 Hz.

Figure 4. Variation in resonant frequency as a function of weld pool diameter for stationary welds in steel.

Oscillation frequencies of stationary weld pools - Two different models of a partially penetrated weld pool were developed, a lumped parameter model and a distributed parameter model. These models are explained in more detail in reference 13. In order to verify these models of weld pool oscillation, a series of stationary gas-tungsten arc (GTA) welds were made on steel and copper. These welds were made at varying currents and voltages in order to achieve a variety of weld pool sizes and shapes in each material. As each weld was made, the arc voltage and current were recorded and analyzed as described above. The system transfer functions were evaluated in order to reveal the resonant frequency of the weld pool.

In order to obtain a predicted natural frequency, each weld was sectioned, polished, and etched and the weld width and depth were measured. The surface tension of liquid steel was assumed to be 1800 dyne/cm and that of copper 1300 dyne/cm[14]. The densities of steel and copper were assumed to be 7.0 g/cm³ and 7.8 g/cm³ respectively[15]. These data were then substituted into the weld pool models to give predicted frequencies for the lumped and distributed parameter models.

Results - Curves showing the behavior of the weld pool models as the weld pool width changes are plotted in Figure 5. The measured frequencies of each of the welds were plotted against the predicted frequencies for each of these welds in order to determine the agreement between theory and experiment. Figure 6 compares the observed frequencies with the predicted frequencies for steel and copper using both the lumped and the distributed parameter models.

Detection of weld defects - A suitable weld quality sensor must reveal certain information about the welding process. In order to be used in a closed-loop control system, it must be able to provide signals which indicate the presence of defects in the welding process. Further, such a sensor should be able to differentiate between different types of defects so that the proper corrective action can be taken. These experiments evaluated the ability of signal processing to detect and differentiate various types of welding discontinuities. The weld discontinuities that were investigated were chosen to be representative of actual welding defects.

In these experiments, welds were made using the equipment and procedure described above. However, in each of these welds, a defect was made to occur. The defects or discontinuities that were studied were traveling weld size, humped bead formation, steel to aluminum base metal transition, and partial to full penetration.
weld transition. Upon completion of these welds, the system frequency response functions were examined to look for signatures of the various defects.

**Figures**

![Graph 1](image1.png)

**Figure 6.** Measured frequency for stationary welds on steel and copper compared to frequency predicted by each of the models.

**Results** — While the results for these experiments are too numerous to be included in detail here, they can be found in reference 13. However, one of the most important results is included. A comparison was made between observed and predicted weld pool frequency for traveling welds in steel and titanium. The predicted frequency of the steel welds is compared to the observed frequency in Figure 7 for both the lumped parameter and the distributed parameter model, while Figures 8 presents the same results for the titanium welds. Note that the general trend of increasing measured frequency with increasing predicted frequency is followed, but the scatter in the data prevents any prediction of the frequency of a particular weld pool.

![Graph 2](image2.png)

**Figure 7.** Predicted frequency compared with measured frequency for traveling welds in steel.

![Graph 3](image3.png)

**Figure 8.** Predicted frequency compared with measured frequency for traveling welds in titanium.

**DISCUSSION**

**SENSITIVITY ANALYSIS** — It was anticipated that as arc length increased, the relative amplitude of voltage oscillations would decrease due to the increase in average voltage. This could increase the difficulty of detecting the puddle oscillations. However, experiments performed showed that puddle oscillations could be detected up to the limits of arc stability. Thus, the technique described is effective for measuring the frequency of puddle oscillations of stationary welds at typical arc lengths with helium shielding gas.

As expected, the puddle frequency changed with weld pool size. As the pool size increased, the frequency decreased, which is consistent with the findings of Renwick and Richardson[10]. A detailed analysis of the dependence of natural frequency on weld pool size and shape is found in reference 13.

**OSCILLATION FREQUENCIES OF STATIONARY WELD POOLS** — As can be seen in Figure 6, good agreement between the predicted frequency and observed frequency was found for both models and both materials. The data for copper show less scatter than the data for steel. The values predicted by the distributed parameter model show better agreement than the values predicted by the lumped parameter model.

The scatter in the experimental data is due in part to the uncertainty in identifying the resonant frequency exactly. In many cases the resonance peak is more than five samples wide, which corresponds to a frequency uncertainty of
more than 35 Hz. Thus, there will be a certain amount of scatter simply due to the frequency measurement. In addition, there is some uncertainty in measuring the physical size of the weld pool. This is due to the necessity of sectioning the stationary weld exactly on the diameter in order to measure the correct width and depth. Thus, it is possible that the physical measurements of the welds are smaller than the actual size of the welds, thus leading to a predicted frequency which is too high. Nevertheless, the trend is established.

As can be seen from these figures, the distributed parameter model accurately predicts the weld pool frequency for weld pools of different geometries, densities, and surface tensions. This provides strong evidence for the correctness of this model.

These models predict that there will be significant problems in using signal analysis as a weld size monitor for welds of typical size. As can be seen in Figure 5, there is a very small change in weld pool frequency for welds varying in width from 0.5 to 1 cm. Therefore, in order to use weld pool frequency as an indicator of weld pool size, it is necessary to measure the weld pool frequency very precisely. As described above, it is difficult, if not impossible, to locate the weld pool resonant frequency this precisely using FFT techniques. The technique, therefore, is not likely to yield satisfactory results in real welds.

DETECTION OF WELD DEFECTS - The correlation between predicted and observed weld pool frequency is not very high, as is shown in Figures 7 and 8. The scatter in the experimental data is due in large part to the difficulty of measuring the puddle frequency in traveling welds. This is due to the measurement technique which is used to detect puddle frequencies.

The measurement technique used to detect puddle frequencies is optimized for use with underdamped systems. The longer the weld pool oscillations continue, the easier they are to measure. The oscillations will continue only if the system is underdamped. In a traveling weld, new material is continually being added to the system through melting, and old material is leaving the system through solidification. The material which is added to the system has no momentum at the time it melts; therefore it must be accelerated by the rest of the weld pool in order to oscillate. This has a damping effect on the oscillations, as the energy of the liquid metal is dissipated in accelerating this new material. Since the oscillations are damped out more rapidly, the resonant frequency is much more difficult to detect. This, in turn, leads to the scatter in Figures 7 and 8. Because of this problem, it is unlikely that signal analysis can serve as an adequate monitor of weld pool size in traveling welds.

In regard to the other discontinuities studied, changes in the frequency response function could generally be observed with some difficulty for each of these defects. However, there was no means of distinguishing between the various defects, and hence, no effective method of controlling the welding process to correct a particular defect. This fact, together with the difficulty of measuring puddle oscillations in traveling welds, indicates that this analysis technique will not serve as an effective weld process monitor. Other monitors must be found which show more selectivity between the various defects if adequate feedback control is to be instituted on the arc welding process.

CONCLUSION

The ability to use frequency spectral analysis as a means of detecting puddle oscillations in the GTA welding process has been demonstrated for stationary welds under carefully controlled conditions. The sensitivity of this technique to variations in arc length has been studied. For stationary welds on steel plate, with helium as a shielding gas, puddle oscillations were measured at arc lengths up to 33 mm. In addition, the change in oscillation frequency with change in puddle size was observed.

A model was developed to predict the resonant frequencies of the weld pool given the size of the weld pool. Experiments performed on steel and copper baseplates with stationary welds verified the ability of the model to predict weld pool frequencies. The model predicts that controlling weld pool size using digital signal analysis will be extremely difficult for typical weld sizes.

This analysis technique works much less well with traveling welds, due to the higher damping of the traveling weld pool. Although many changes in the weld cause changes in the frequency response of the arc–puddle system, the changes are not unique, and hence the defects cannot be distinguished from one another.

Difficulties still remain with measuring puddle oscillations with argon shielding gas. In addition, the input waveform affects calculations of the system transfer function due to the sequential nature of voltage and current sampling. Future work with simultaneous rather than sequential sampling may eliminate this problem, and lead to improved ability to sense puddle oscillations.

Digital signal processing has shown some promise as a laboratory diagnostic tool for gas tungsten arc welding. However, due to the careful setup required to obtain adequate results and the poor performance when applied to real welding problems even in the controlled laboratory environment, it seems unlikely that digital signal processing can serve as a practical sensor for GTA welding.
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REFERENCES

15. Ibid. B-223 to B-225.