Contact Tube Wear Detection in Gas Metal Arc Welding

With the development of an algorithm for detecting contact tube wear, an integrated system for measuring current, voltage and wear in real time is now possible

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ABSTRACT. A real-time algorithm has been developed to detect contact tube wear during gas metal arc welding. The integral from 0.3 to 4 Hz of the power spectral density of voltage (constant current and pulsed current power sources) or current (constant voltage power sources) is called the wear parameter and is used to measure wear. The contact tube is predicted to be worn when the parameter grows nonlinearly or exceeds a threshold. For 11 contact tubes worn by welding on a rotating pipe, the wear parameter predicted the observed increase in the area of the contact tube's exit bore of 140% of the original area within a standard deviation of 20%. Welds were made with a constant voltage power source and with a pulsed current power source at two different voltages. The pulsed current welds were made with and without automatic voltage control by wire feed speed and with and without weaving in a V-groove. No significant differences were detected between the wear parameters for all test welds, indicating that the algorithm can be used under these welding conditions.

Introduction

This paper describes a method for detecting contact tube wear in gas metal arc welding (GMAW) from measurements of the process current or voltage. In GMAW an arc is created between the continuously fed, consumable electrode and the workpiece. Current is transferred to the electrode as it slides through a tube (usually an alloy of copper) at the end of the welding gun. The tube also mechanically guides the wire. The tubes deteriorate because of the sliding contact between the electrode and the tube and are replaced relatively often (for example, every 120 min for steel electrodes, Ref. 1). In automatic (robotic) welding, it may be difficult for the operator to detect contact tube wear. If the tube is not replaced in time, defective welds may be produced, but premature replacement increases downtime. A sensor that predicts contact tube life is therefore necessary.

For steel electrodes and copper-alloy contact tubes, the bore of the tube gradually enlarges. Yamada and Tanaka (Ref. 2) found steel and copper debris indicating wear on the inside of the contact tube. They also found that there was a variation of up to 70% of the mean in the wire electrode feed speed (WFS) at the contact tube even though there was almost no variation in WFS at the wire feeder. Low frequency (< 4 Hz) variations in WFS will affect the distance the electrode extends from the contact tube before being melted (the electrode extension) (Ref. 3). The arc length and arc voltage (and therefore the weld consistency or quality) depend on the electrode extension for a given contact tube-to-work distance (CTWD) and arc current. As the bore of the contact tube enlarges, the position of the electrode relative to the workpiece is no longer concentric with the welding gun, the usual assumption in the design of an automatic welding station. Wadsworth (Ref. 4) found that, if the electrode was displaced from the center of the joint for a fillet weld by one electrode diameter, the strength of the joint was reduced by as much as 54%. Contact tube wear leads to detrimental effects: variations in the WFS or current transfer point, and dislocation of the electrode tip.

Zwickert and Krupp (Ref. 5) and Göthe, *et al.* (Ref. 6), describe a sensing system to detect contact tube wear. They measure the contact resistance between the contact tube and the electrode by first measuring the voltage drop between a roller in the electrode feeder and the contact tube, then measuring welding current, and finally, dividing them. They report a correlation between contact tube wear and contact resistance.

This paper presents a different method for detecting contact tube wear using the low-frequency (< 4 Hz) instabilities in the process. A wear parameter W is calculated in real time as the integral of the power spectral density of the normalized voltage for current-controlled power supplies (constant current or pulsed current) or normalized current for voltage-controlled power supplies (constant voltage) in the interval 0.3 to 4 Hz. W predicts the increase in the area of the exit bore of the contact tube.

KEY WORDS

Contact Tube Wear
Tube Wear Detection
Robotic Welding
Wire Tip Dislocation
Downtime Reduction
GMAW
Welding Current
Wire Feed Speed
Sliding Contact
Gas Metal Arc Welding

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The Wear Parameter

The voltage for current-controlled power supplies (or the current for voltage-controlled power supplies) is sampled continuously and processed in blocks of 2^N (here N = 10). The data in the block are first normalized.

$$V' = \frac{V - \bar{V}}{\bar{V}} \tag{1}$$

where V is the voltage (current), $\bar{V}$ is the mean voltage (current) in the block, and V' is the normalized voltage (current). The power spectral density P of V' is then calculated using the fast Fourier transform (Ref. 7), and P is integrated from 0.3 to 4 Hz.

$$a = \int_{0.3}^{4Hz} P(V')\,df \tag{2}$$

where f is frequency and *a* is the mean squared value of V' in this frequency range. *a* is normalized with its initial value calculated when the contact tube is first placed in the welding gun.

$$W(L) = \frac{a(L)}{a(L \approx 0)} \tag{3}$$

where L is the total length of electrode that has passed through the contact tube.

Oscillation of the welding gun perpendicular to the direction of travel (weaving) can cause a periodic variation in the welding voltage (current, for a constant voltage power source) if the joint geometry is not flat (V-grooves, for example). As the welding gun traverses the joint, the CTWD changes, which changes the voltage (current). The weaving frequency is often below 4 Hz. The resulting peaks in the power spectrum can distort the wear parameter calculation. To compensate for the effect of weaving, sharp peaks in the power spectrum are found and removed. The local maxima in P from 0.3 to 4 Hz are identified by sweeping an interval of length 0.9 Hz through the spectrum data and fitting a parabola to the data in the interval. If the maximum of the parabola lies within the interval and is at least two times greater than the end points, then the largest P in the interval is considered a local maximum. If a local maximum is greater than two times the standard deviation of P from 0.3 to 4 Hz, then the point is considered a (sharp) peak due to weaving. The data in the interval between the zero crossings of the parabola used to find the maximum are then discarded, and the end points of the interval are joined with a line. *a* is then calculated using the modified P.

An alternative method for measuring wear is to filter the analog signal with a pass-band between 0.3 Hz and 4 Hz, sample it, and then compute the rms value a_{rms}. The rms value calculated in this way is proportional to $a^{1/2}$ (Ref. 8). W_{rms} is defined similarly to W.

$$W_{rms}(L) = \frac{a_{rms}(L)}{a_{rms}(L \approx 0)} \tag{4}$$

Failure Criteria

In order to be used in real time, the wear detection algorithm must predict when the contact tube should be replaced. Since W is a measure of the stability of the process, an increase in W would indicate a decrease in stability and that the contact tube is wearing. Two criteria are used to test W to predict when a contact tube is worn. If W increases above a threshold W_T (for example, W_T = 6) or if W increases nonlinearly, then the contact tube is considered worn. To test whether W is increasing nonlinearly, a line is fitted to W(t) where t is the time since the contact tube was new. The confidence limits are calculated for the line at the next time increment according to Ref. 9. If the value of W calculated at the next time increment is at least twice as large as the upper confidence limit, W is considered to be growing nonlinearly.

Experiments

The first series of tests was designed to validate the algorithm in prediction of contact tube wear. Stringer beads were made on a mild steel pipe with a diameter of 0.5 m (1.6 ft) and a wall thickness of 9.5 mm (0.375 in.). The pipe rotated at 0.2 rpm, and after each rotation, the weld was offset one bead width. Contact tubes of two alloy compositions were tested using a pulsed current power source and a constant voltage power source. Composition A was designated as "standard" by the manufacturer; composition B was designated as "long life." The pulsed current source allowed for automatic voltage control (AVC) in which the WFS was varied according to the difference between the desired voltage and the voltage measured at the power source. The weld was shielded by 95% Ar-5% CO_2 flowing at 15 L/min (32 ft^3/h), and AWS E100S-1 electrode (bare, low-carbon steel), 1.2 mm (0.045 in.) in diameter, was used. A water-cooled, straight welding gun was used. The CTWD was 19 mm (0.75 in.); the other welding parameters are given in Table 1. The welding was continued until the area of the exit bore increased to at least 150% of the original area ($Area_0$) or the tube could no longer sustain the arc.

To compare W to W_{rms}, the voltage signal was processed two ways: 1) the signal was passed through a band-pass filter with a pass-band between 0.3 and 4 Hz and recorded at 18 samples/s, and 2) the signal was passed through a low-pass filter with a corner frequency of 100 Hz and recorded at 210 samples/s. The data collected at 18 samples/s were used to calculate the rms voltage between 0.3 and 4.0 Hz. The wear parameter was calculated in real time with the 210 samples/s data using a block size of 2^{10}. The wear parameter was then smoothed using a running average. Every 10 min the weld was stopped and an image of the exit bore of the contact tube was recorded with a video camera and a macro lens. The resolution of the image was 0.014 mm/pixel. The area of the exit bore was then calculated using a video frame digitizer and image analysis software as a measure of the actual wear in the contact tube.

A second series of tests was conducted to assure that the algorithm could be used during weaving and also to verify that the algorithm could be used under a variety of welding conditions. The rotating pipe was again used to wear the contact tubes, but no data were recorded while welding on the pipe. After welding on the pipe for 15 min with the pulsed current power source with AVC using the two nominal (pipe) welding conditions shown in Table 2, an image of the exit bore was taken as above. A series of 80-s test welds was then made on mild steel plates (Table 2) during which the current, voltage, and WFS signals were passed through a low-pass filter with a corner frequency of 100 Hz and recorded at 210 samples/s. Five different cases were used for these test welds. In test Case 1, the welding

Table 1 — The Welding Parameters and Number of Contact Tubes for Welding Series 1

	Mean Current (A)	Mean Voltage (V)	Mean WFS (m/s)	Number of Tubes Alloy A	Number of Tubes Alloy B
Pulsed Current	260	30.4	0.17	3	3
	233	29.6	0.15	3	—
Constant Voltage	246	29.2	0.15	2	—

A total of 11 contact tubes were tested in this series.

conditions were nominally the same as those during the pipe welds used to wear the contact tube. In test Case 2, conditions were nominally the same as Case 1, except that the voltage was increased as shown in Table 2. In test Case 3, the same nominal conditions as test Case 1 were used, except that the AVC was turned off. In test Case 4, the conditions were nominally the same as in Case 1, except that a 1.4 Hz weave (sinusoidal oscillation of the welding gun perpendicular to the direction of travel) was used to join 25.4-mm (1-in.) plate with a 60-deg included joint angle. In Case 5, a stringer weld was made with the power source in constant voltage mode. Test Cases 3 and 5 were undertaken for 8 of the 12 contact tubes (Table 2).

The W calculated for this second series were not used to predict when the contact tube was worn because of the granularity of the data (one sample every 15 min). The W calculated from the second series test conditions were compared with one another using a nonparametric, permutation test (Ref. 10).

The electrode was wound by the manufacturer on 200-mm (8-in.) diameter spools to a diameter of 300 mm (12 in.). As defined in Ref. 11, the cast of an electrode is the diameter that one loop of unrestrained electrode assumes; when the unrestrained loop of electrode is placed on a horizontal surface, the helix is the vertical distance between the end of the electrode and the surface. Here, the cast of the electrode varied from about 760 mm (30 in.) for electrode taken near the outside of the spool to about 660 mm (26 in.) for electrode taken near the inside. The helix of the electrode varied from about 6 mm (0.24 in.) for electrode taken near the outside of the spool to about 30 mm (1.2 in.) for wire taken near the inside.

The current was measured with a Hall effect transducer with an absolute error of 1%. The voltage between the welding gun and the base plate was measured within 0.5% absolute error. The WFS was measured as the electrode entered the wire feeder: a pinch roller (16-mm diameter) was attached to an optical encoder (5000 pulses/revolution) and the resulting pulse train was frequency converted to give a voltage signal proportional to the WFS. The rms uncertainty from calibration tests for the WFS transducer was 2 mm/s (5 in./min).

Table 2 — The Welding Parameters and Tube Designations for the Five Test Cases of Welding Series 2[a]

		Mean Current, Voltage, WFS and Tube Numbers	
Nominal Pipe Conditions		230 A 29 V 0.14 m/s 2A1[b]-2A3 2B1-2B3	256 A 31 V 0.16 m/s 2A4-2A6 2B4-2B6
Test cases	1. Pulsed current, AVC on, Bead-on-plate	231 A 29 V 0.14 m/s 2A1-2A3 2B1-2B3	256 A 31 V 0.16 m/s 2A4-2A6 2B4-2B6
	2. Pulsed current, AVC on, Bead-on-plate, High voltage	231 A 31 V 0.13 m/s 2A1-2A3 2B1-2B3	256 A 32 V 0.15 m/s 2A4-2A6 2B4-2B6
	3. Pulsed current, AVC off, Bead-on-plate	231 A 32 V 0.13 m/s 2B1-2B3	256 A 33 V 0.14 m/s 2A5,2A6 2B4-2B6
	4. Pulsed current, AVC on, 1.4 Hz weave in a 60 deg groove	231 A 30 V 0.14 m/s 2B1-2B3	256 A 31 V 0.15 m/s 2A5,2A6 2B4-2B6
	5. Constant voltage	242 A 29 V 0.14 m/s 2B1-2B3	249 A 30 V 0.13 m/s 2A5,2A6 2B4-2B6

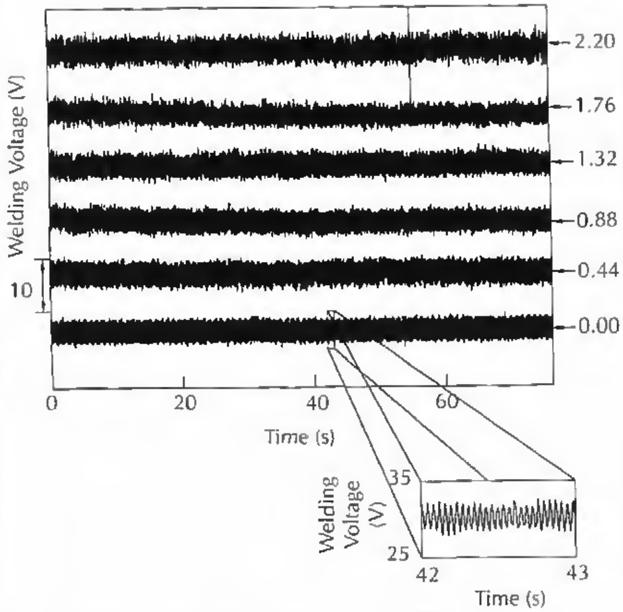
(a)A total of 12 contact tubes were tested in this series.
(b)The first numeral in the tube designation refers to the test series, the letter refers to tube composition and the final numeral is the tube number.

General Results

For all of the 23 contact tubes tested, as the contact tube wore, the voltage (current, in the constant voltage tests) became more erratic. In Fig. 1, the voltage recorded during the Case 2 welds for Tube 2B6 is shown at intervals as the tube was worn. Because the current was pulsed at 78 Hz, there was a 78-Hz oscillation in the voltage with an rms amplitude of 1.2 V; the noise on the envelope of the voltage oscillation increased as the contact tube wore.

The steel electrode wore into all 23 tubes a tapered slot whose width was just larger than the diameter of the electrode. The slot was widest at the exit and tapered back as far as the middle of the tube — Figs. 2 and 3. The exit bore area of the tube increased nearly linearly with the length L of electrode consumed — Figs. 3 and 4. The average correlation of the linear fit of the data (area vs. L) for the 23 contact tubes tested was 0.95. For the tubes tested (Series 1 and 2) at the nominal current of 230 A, the rate of increase in the exit bore area per unit length of electrode fed was 1.2 ± 0.7 mm^2/km for composition A, and 0.69 ±0.09 mm^2/km for composition B. The difference between the two rates was found not to be significant using a two-way analysis-of-variance test on the inverses. (Here, the quantities were considered to be significantly different if the significance level $p < 0.07$.) For 260 A the rate of increase was 2 ± 1 mm^2/km for composition A, and 0.8 ± 0.3 mm^2/km for composition B; the difference was significant, $p = 0.06$). There was no significant difference in the rate of increase for either tube composition between tubes tested at 230 A and tubes tested at 260 A.

As the slot was worn in the contact tube, the electrode tip was no longer positioned along the axis of the welding gun. The position of the electrode was measured for Tube 1B3 (260 A, pulsed current) using an optical comparator after the tube had been removed from service. The area of the exit bore had enlarged to 153% of that of the original. The tip of the electrode deviated from the axis of the welding gun by 1.4 mm (1.2 electrode diameters) at an electrode extension of 10 mm (0.4 in.).



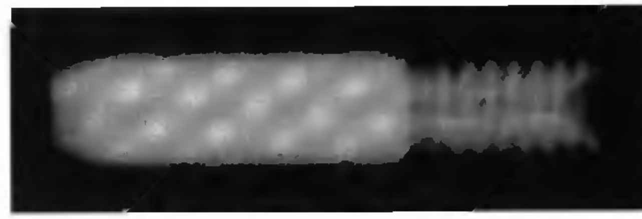


Fig. 2 — An x-ray image of contact Tube 2A1: the slot in the contact tube starts approximately half way along the tube and is widest at the exit.

Fig. 1 — The voltage recorded during the Case 2 test welds for Tube 2B6 using a pulsed current power source: as the contact tube wears out, the noise on the envelope of the voltage signal is enlarged. The voltage signal was passed through a low-pass filter with a corner frequency of 100 Hz and was sampled at 210 samples/s.

Results of Test Series 1

For the 11 tubes in test series 1, W increased with L until the exit bore area reached ~140% of its original area — Fig. 4. After the exit bore area increased to ~140% of its original area, W became erratic on some tubes — Fig. 4. The area and its standard deviation, when the contact tube was predicted to be worn, was 140% ± 20% of the original with $W_T = 6$. W_{rms} showed similar results to W — Fig. 5. Using $W_{T\,rms} = 1.6$, the algorithm again predicted the contact tube was worn with an area of 140% ± 20% of that of the original.

The two tubes welded with the constant voltage power source showed similar results for W calculated with the current — Fig. 6. With $W_T = 6$, the areas of the exit bores when the contact tube was predicted to be worn were 146% and 128% of the area of the original.

Results of Test Series 2

For the 12 tubes in test Series 2, W for the welds made on the flat plate had the same behavior as W monitored continuously on the pipe. W calculated from the 5 test conditions for each current was compared for significant differences using a nonparametric, permutation test (Ref. 10) and was not found to be significantly different ($p > 0.07$) for cases compared at approximately the same length of electrode fed. (W was calculated using the current signal when the constant voltage power source was used.) Therefore, in the ranges tested, changes in mean voltage, AVC, weaving, and type of power source did not affect W.

Discussion

The wear algorithm was shown to predict an increase in the area of the exit bore of the contact tube of 140% of its

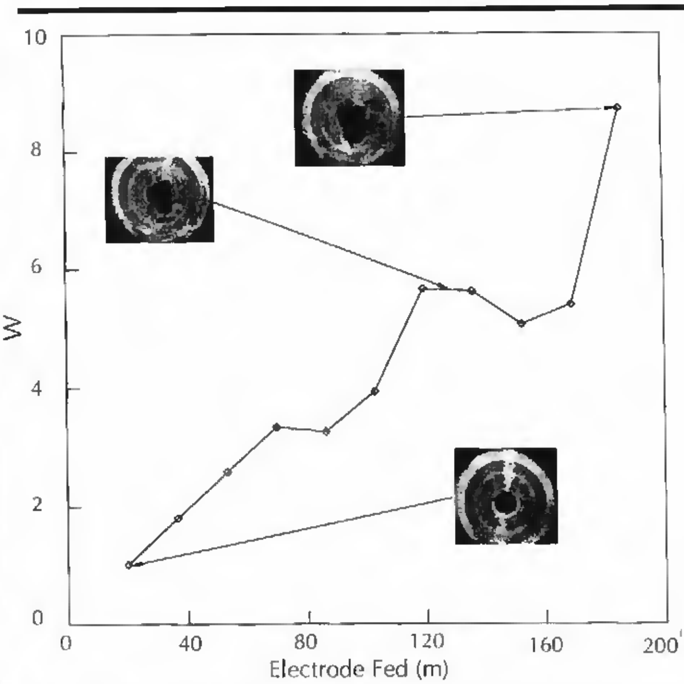


Fig. 3 — The wear parameter W for Tube 1A1 (260 A pulsed current) and images of the exit bore: W increases as the slot in the contact tube is enlarged.

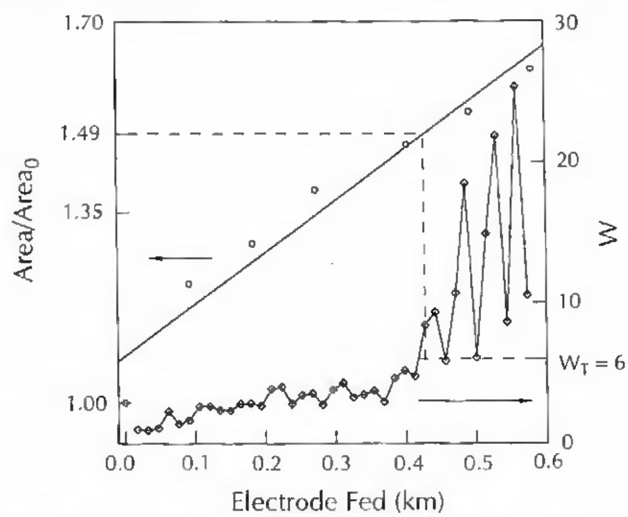


Fig. 4 — The wear parameter W for Tube 1A4 (230 A pulsed current) and the increase in area of the exit bore: W increases with the amount of electrode fed until the area is about 140% of the original area, after which W increases rapidly and becomes erratic.

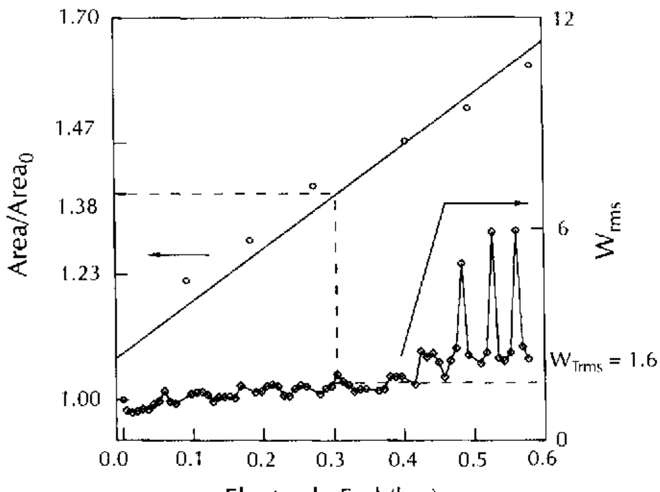


Fig. 5 — The wear parameter W_{rms} for Tube 1A4 (230 A pulsed current) and the increase in area of the exit bore: using an analog band-pass filter and calculating the rms value of the voltage gives results similar to those for W (Fig. 4) when weaving is not used.

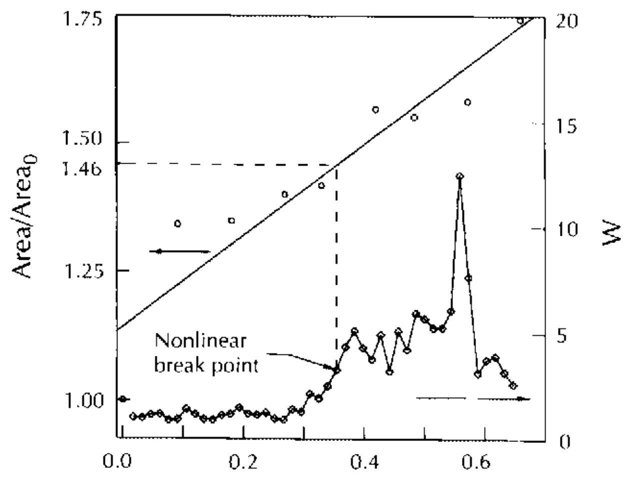


Fig. 6 — The wear parameter W for Tube 1A7 (constant voltage) and the increase in area of the exit bore: using the current signal to calculate W for a constant voltage power source gives results similar to those for W calculated with voltage for a current-controlled power source (Fig. 4).

original area within a standard deviation of 20% in test Series 1. The same nominal test conditions were used in Cases 1 and 2 of test Series 2. Because there was no significant differences between any of the cases in test Series 2, the wear algorithm has been shown to be able to predict an increase in the area of the exit bore of the contact tube of 140% to the same accuracy as for test Series 1 (20%) for all of the test conditions used in Series 2.

For Tube 1B3, the deviation in the electrode from the axis of the welding gun (1.2 electrode diameters) indicates the need for an automatic detection of contact tube wear for automatic welding. The deviation of this amount in the electrode could lead to a reduction in strength of as much as 54% in fillet welds (Ref. 4).

The variations in the voltage (current) may be caused by variations in the WFS; this mechanism was partially surmised by Yamada and Tanaka (Ref. 2). The cast in the electrode presses it against the bore of the contact tube and sliding contact occurs. When the contact tube is new, the machined surface of the tube contacts the wire at many small asperities (on the order of 1 μm, Ref. 12) . Assuming clean metal-on-metal contact or contact where the oxide film has been partially worn away, the contacting asperities will cold-weld to each other and form junctions. As the electrode is forced through the contact tube, the junctions are plastically deformed or the copper asperities shear and leave a small amount of copper on the surface of the electrode (Ref. 13). Because the electrode shears the copper asperities in many places, the WFS remains nearly constant. If the electrode wears a particular area long enough, the small asperity junctions that are plastically deformed will coalesce into superjunctions (Ref. 14). The superjunctions have a greater effect on the WFS since it requires a larger force to shear them (a condition of stick-slip). This may explain the nonuniformity in the WFS at the contact tube measured by Yamada and Tanaka. As the electrode wears a groove in the tube, "new," relatively smooth surfaces (small asperities) at the leading edge of the taper in the slot and at the original radius of the tube (Fig. 7) are exposed. Finally, when the radius of the slot reaches the radius of the electrode and little new material is being worn, the contact tube reaches a final state of stick-slip which causes irregularities in the WFS.

In Ref. 3 transfer functions were developed between WFS and the electrode extension. GMAW acts as a single-pole, low-pass filter with a cutoff frequency around 2 Hz for an electrode extension with respect to WFS. The variations in WFS cause variations that are measurable only in the low-frequency (< 4 Hz) part of the electrode extension spectrum. For a fixed CTWD, the electrode extension determines the voltage for a current-controlled power source, or the current for a constant voltage power source. When the amount of power in the voltage spectrum (current spectrum for a constant voltage power source) from 0.3 to 4 Hz is compared to the power when the contact tube was new, the change in the variation of the WFS and, hence, the amount of wear in the contact tube can be indirectly measured.

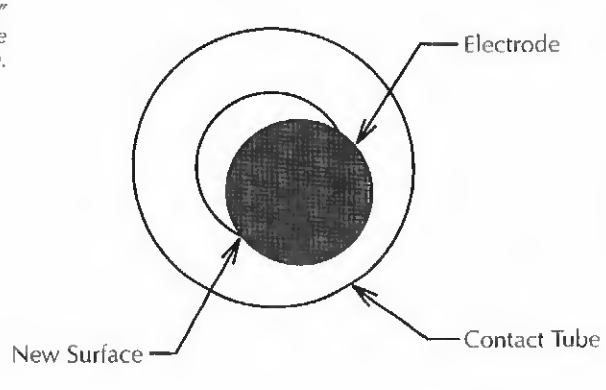
The wear rate of copper depends on temperature (Ref. 15). Therefore, any mechanism that increases the contact tube temperature (higher currents, smaller electrode extension, less efficient external cooling, etc.) will also increase the rate at which the contact tube wears.

The wear algorithm may not be suitable for all electrodes. When DeNale and Lukens (Ref. 1) were welding with titanium electrodes, intermetallic titanium-copper particles bonded to the interior of the contact tube and eventually caused the wire to seize. There may be no increase in the low-frequency variations of the current or voltage in this case.

It is difficult to fully compare the algorithm presented here with that of Refs. 5 and 6 since that process is patented and little information is given in Ref. 5. The algorithm presented here measures the stability of the process, which directly affects the quality of the weld; whereas, the method in Ref. 5 measures the contact resistance between the electrode and the contact tube. The algorithm presented here can easily be integrated into an arc monitoring system (Ref. 16) that is already measuring the current and voltage.

The method described here for sensing contact tube deterioration is best suited for automated welding. The variations in voltage (current for a constant voltage power source) introduced by the variations in CTWD during manual welding may mask the variations from the deteriorating contact tube. The use of the analog filter to calculate W (W_{rms}) is simpler to implement since only the rms

Fig. 7 — As the slot is worn in the contact tube, "new" material is exposed at the original radius of the tube.



values of the recorded signal need be calculated. To use W_{rms} during weaving, a similar power spectral density calculation would be necessary to remove the peaks in the spectrum. W_{rms} could be made more sensitive by measuring the unfiltered voltage or current in addition to the filtered voltage or current and then normalizing the signal as is done in Equation 1. A procedure for implementing both algorithms is given in the appendix.

Conclusions

1) A real-time algorithm that predicts contact tube wear in GMAW from the arc voltage for current-controlled power supplies or the arc current for constant voltage power supplies has been developed and implemented. The integral of the power spectral density of the normalized process signal from 0.3 to 4.0 Hz is divided by the initial value (new contact tube) of the integral to form the wear parameter. If the wear parameter grows nonlinearly with time or exceeds an empirically determined threshold value, the contact tube is considered worn.

2) For 11 of the tubes studied, the wear algorithm predicted an increase in the area of the exit bore of the contact tube of 140% of its original area within a standard deviation of 20%. Tests conducted on 12 more contact tubes showed no significant difference between the wear algorithm predictions using different voltages (29–33 V) or using automatic voltage control by the wire electrode feed speed or using different currents (230 and 260 A). The algorithm can be modified to account for peaks in the spectrum caused by weaving; when weaving was used in a V-type joint, the results were not affected. Therefore, for the ranges tested, the wear algorithm is independent of voltage, current, automatic voltage control, and weaving.

3) Contact tube composition can significantly affect the rate of wear of the contact tube.

Acknowledgements

This research was partially sponsored by the U.S. Navy. We thank A. J. Slifka for his discussions concerning the wear mechanism.

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Appendix

Implementation Procedure

This appendix details the practical construction and application of a contact tube wear detection sensor. The sensor can be realized almost entirely in software executing on a computer equipped with a analog-to-digital converter (ADC) by computing the wear parameter W. Alternatively, some signal processing can be completed in hardware before the signal enters the computer by using W_{rms}. In the following, the term "process signal" refers to the voltage for constant current and pulsed current power supplies and the current for constant voltage power supplies.

Hardware Requirements

A computer with an ADC is required. The ADC should have a minimum resolution of 12 bits and should have either a unipolar input range (W) or a bipolar input range (W_{rms}) depending on which implementation is chosen as described below. Either a low-pass or band-pass filter is also required. An analog isolation buffer should also be used between the ADC and the process signal.

Design 1: Minimum Amount of Hardware. The process signal is filtered using an analog low-pass filter with a corner frequency of one half of the sampling frequency (Nyquist criterion). Practically, a multipole low-pass filter with a corner frequency equal to 4 Hz is used with a sampling rate in the range of 10 to 20 samples/s. A unipolar ADC is required to digitize the process signal. The power spectral density (PSD) is then calculated after 2^N data points have been recorded (for a sampling frequency of 20 samples/s, $N = 8$ would be adequate). Signal analysis software or programs written with the use of software libraries such as Ref. 7 can be used. Then a in Equation 2 can be calculated by numerically integrating the PSD. Values of a are stored in an array.

Design 2: Minimum Amount of Software. The process signal is filtered using an analog band-pass filter with a passband between 0.3 Hz and 4 Hz. Again, the filtered signal is sampled at a rate f of 10 to 20 samples/s (Nyquist criterion) using a bipolar ADC. The root-mean-square (rms) of the samples from an interval of duration 10/f of the digitized signal is calculated and results in a_{rms}. The a_{rms} values are stored in an array.

Failure Judgement

The array of a or a_{rms} should be smoothed with a running average using enough points to account for about 100 s of continuous welding, which is used to calculate W or W_{rms} (Equations 3 and 4). Failure can be detected by a simple comparison of W or W_{rms} to an experimentally determined threshold value and by examining the linearity of W or W_{rms} as it grows with time. To determine whether W or W_{rms} is growing nonlinearly, a line should be fitted to the previously stored values of W or W_{rms} as outlined in the "Failure Criteria" section of this paper. The values for the simple threshold, used to determine contact tube failure, should be adjusted to the particular application; the values used here can be taken as guidelines.

Process Dependent Applications

For constant voltage, constant current, and pulsed current processes without torch weaving, Designs 1 and 2 can be applied directly. For processes including welding gun weaving, only Design 2 has been successfully applied by using the algorithm outlined in "The Wear Parameter" section of this paper.