The Rationing of Power Between the Gas Tungsten Arc and Electrode

Electrode shape and background resistances have a profound effect on numerous variables in gas tungsten-arc welding

BY R. A. CHIHOSKI

SUMMARY. Potential drop in the familiar volt-ampere characteristic curve of a tungsten electrode–inert gas system decreases to a minimum at 150 to 200 amp and rises with further increasing current. Higher drops occur with sharper cone tipped electrodes than for broader cone tips (fixed psoition). The conversion of five *E* vs. *I* curves to *R* vs. *I* curves for five cone tips (30, 60, 90, 120 and 180 deg) on ⅛ in. 2% thoriated electrodes shows an initial rapid decline of resistance tapering to a nearly asymptotic level after 490 amp with the resistance of the finer tips always higher. This resistance, for each electrode, was mathematically separated into a resistance attributable to plasma effects which declines in a pattern like the total resistance, and a resistance attributable to the heating of the metal conductors and the electrode tip which rises from a low value steadily with increasing current.

The resistance in the finest electrode (30 deg) yields an insignificant potential drop at currents lower than 100 amp, but the drop increases at a rate of as much as 4 v per 100 amp. At 400 amp as much as 8 v will be dropped in this electrode's system. In a constant potential welding arrangement the increase in metal drop causes an equal reduction in arc drop as the servomechanism acts to shorten the arc and maintain the preset voltage. Thus, with higher currents or finer tips, the arc can be seen as significantly shortened. Although the voltmeter across the head may report an unchanged drop, the true arc drop is very much reduced. In extreme cases of fine tips and high currents, this may drive the electrode into the work or extinguish the arc.

The power fraction, by heat output, of the 30 deg electrode tip grows to such an extent with increasing current that the *IE* heat production attributed to the arc declines beyond 250 amp after peaking at 2250 watts (for a 12 v premise). The arc produced heat which was nearly 100% of the power input below 100 amp and 75% at 250 amp can sink to 30% of the heat output at 400 amp. 70% of the heat input power at 400 amp is being emitted from the electrode tip and the other conductors between the controlling volt sensor and voltmeter. Blunter electrodes demonstrate the same traits but to a lesser degree as the cone angle increases.

This begins to explain some arc efficiency problems. The relative dispensing of heat from each of the separate sources is dependent on the magnitude of the sources: the arc length, and the tip position; and these are altered by the tip shape, current, and metal drop. Observations suggest that the I^2R heating in the electrode is one of the largest useful sources of heat and that it is transported effectively to the anode. The anode benefits from electron kinetic energy acquired in the true arc drop, but an additional volt applied to that span would not increase anode receipts proportionately. Much previous research would be enhanced by reexamination with recognition of the metal or tip drop factor.

The functions employed to make the resistance separation, into metal and arc components, may bear some clues as to physical events and the sites of these phenomena. It appears that the true arc drop in the fixed position experiment decreases quickly up to 200 amp and remains a constant from there thru higher currents; the finer electrodes maintain a slightly higher arc drop throughout. The metal-tip drop function shows distinctly higher levels for finer tips but the growth of the function with current is nearly the same for all tips. The particular reactions of the cathode or anode surfaces or fields may be discernable in these functions.

R. A. CHIHOSKI is Unit Head, Advanced Manufacturing Engineering, Martin Marietta Corp., Denver Division, Denver, Colo.

Introduction

In October 1963 the prototype longitudinal welds for the Titan III fuel tank were being tested at the Denver Division of Martin-Marietta Corporation. Weld engineers and welders were optimizing the values of the parameters required by the process card. The process card lists set up conditions and weld parameters that must be followed by the welder on production parts. They had become satisfied that 260 amp, 12 volts dc, and 10 ipm travel "punched" penetration through the .320 in. thick 2014 T6 aluminum alloy. But on some later plates those settings produced only intermittent penetration. To improve penetration, one weld engineer would grind his tungsten electrodes to a finer cone and sharper tip. But often those electrodes would not supply the expected heat and sometimes would descend into the aluminum puddle and the arc would go out even while more current or voltage was applied to reverse that action. One blunter electrode tip that was tried improved penetration and stability.

If two pass welding experiments had not at that time shown more consistent welds and superior properties, the experience with the single pass process would have generated the kind of problems that demands some specific remedy. The paradoxes then were forgotten. Yet the influence of electrode geometry remains to subtly cause problems and raise consternation. In what less conspicuous forms does the welding operation suffer from shifting effects? The following study explains in part what tungsten electrode shapes can do to the weld operation despite apparently fixed weld parameters.

The discoveries given here explain many reactions in welding and arc physics that have for many years escaped explanation. Anomalies, inconsistencies, or contradictions that were found by comparing some parts of substantial competent research and reporting can now be resolved by recognizing in the gross behavior of arcs the independent behavior of the electrode and the plasma. Much difficulty has accrued from the ommission of electrode tip geometry from descriptions of historic experiments. This turns out to have a large effect on the electrode influence; which is itself a substantial influence on the gross current, potential drop, power and heat production, and distribution measurements of a given arc system.

Experimental Method

A familiar plot of voltage vs current for arc systems was supplied by a paper given by Canulette[1] at the Fall AWS Meeting in San Francisco, October

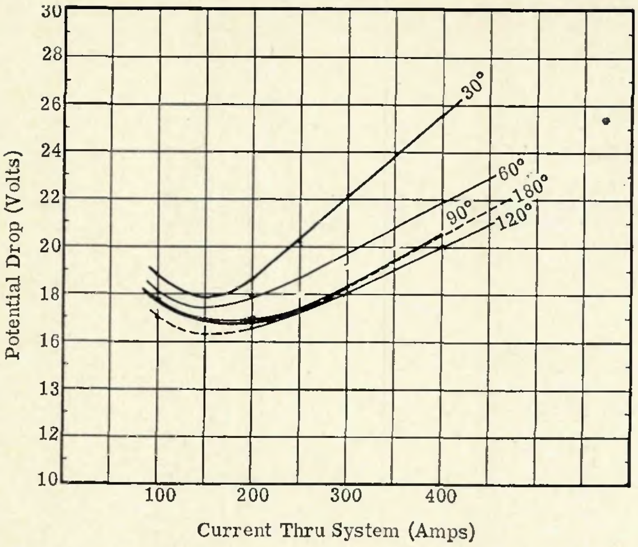


Fig. 1—The voltage vs. current characteristics curve for the fixed position dcsp electrode (.050 in. from the anode) shows the typical voltage drop before rise. The voltage across the conducting loop is dependent on the current passing through the power consumers and independent of the character of the power source before the voltmeter. The voltage is higher and reacts more to the sharper cone tipped electrodes in the five electrodes analyzed (see Table 1)

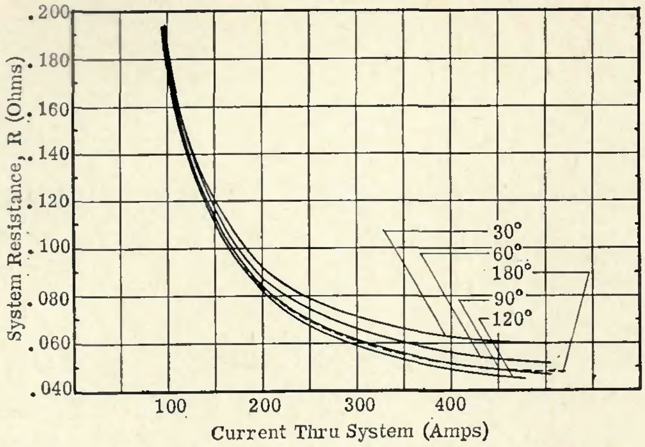


Fig. 2—The resistance of the conducting loop (the copper carriers, the electrode, the arc, the anode) decays with increasing current passing through that system. The finer electrodes maintain a higher resistance especially at higher currents (see Table 2)

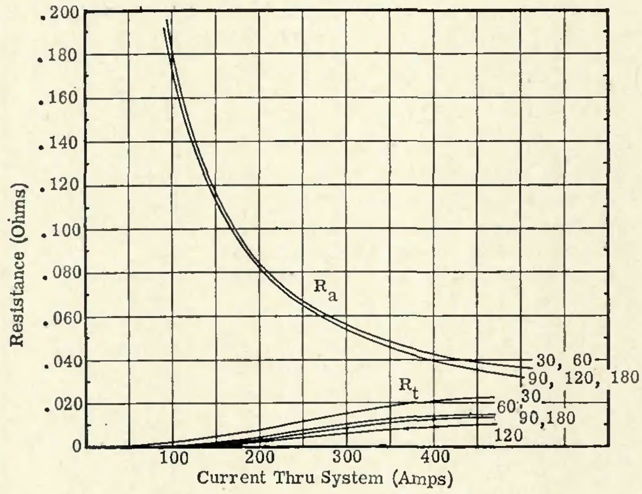


Fig. 3—The total resistance of the system after the power source may be divided into two resistive components—one which represents arc resistance R_a, and one for metal resistance R_t. As must physically be the resistance decrease must occur in the arc for metal conductors can only rise. Both R_o and R_t are higher for finer electrodes (see Table 2)

1964. He fixed a 1/8 in. diameter 2% thoriated electrode tip at a distance of 0.060 in. from a water cooled tungsten anode. Voltage readings were taken as the current was raised from 100 to 400 amp. Five tip configurations were tested in 40 cfh helium in this manner. They were pointed cone tips of 30, 60, 90, 120, or 180 deg included angle.

The voltage vs. current data furnished by the above experiment are presented in Fig. 1 and Table 1. This investigation mathematically treated that evidence to separate those effects into more meaningful and revealing components. All data curves in this paper except those in Fig. 9 are mathematical or logical derivatives of Fig. 1. The total resistance associated for each electrode vs each experimental current was caluclated by Ohm's Law, $R = E/I$, giving the results shown in Fig. 2. It was then reasoned that this resistance must be the summation of two resistance systems in series: the metallic resistance, R_t, and the arc resistance, R_a.

The resistance of the metallic conductors changes as the temperature rises (primarily the electrode) which, in the steady state will be a function of current. In order to employ a more fundamental dimension, a function r_t was defined such that $I \cdot r_t = R_t$.

On the other hand, since gas plasma conducting systems decrease in resistance with increase in temperature, it was more appropriate to define a function r_a for arc resistance such that R_a goes down with current rise: $r_a/I = R_a$. These functions r_t and r_a were employed in simultaneous equations.

For each electrode tip design the following was carried out. Four equations, one at each current level, were arrayed employing the total resistance and the described functions. For example, in the 30 deg electrode—

$$R_\Sigma 100 = .188 = 100 \cdot r_{t100} + r_{a100/100} \text{ ohms}$$

$$R_\Sigma 200 = .092 = 200 \cdot r_{t200} + r_{a200/200} \text{ ohms}$$

$$R_\Sigma 300 = .073 = 300 \cdot r_{t300} + r_{a300/300} \text{ ohms}$$

$$R_\Sigma 400 = .064 = 400 \cdot r_{t400} + r_{a400/400} \text{ ohms}$$

The Appendix* demonstrates how the 30 deg electrode was treated and how r_a was temporarily treated as a constant and subsequently eliminated to determine the average value of r_t at each current level. Then r_t was treated as a constant to determine r_a at each level. This process which involved some averaging proved itself when the values of r_t and r_a were put back into the right hand side of each equation and the calculated R_Σ at each level was not outside 1% of the original experimental value of resistance (R_Σ) in any of the 20 current-electrode combinations.

In effect, all resistive components which reacted by a resistance increases to a current increase were mathematically incorporated into a function called r_t. The numerical values of r_t that satisfied the premised formula were plotted to see if r_t behaved rationally. Likewise, any component of the system that reacted by a resistance decrease, as current rose, was mathematically segregated and incorporated into a function called r_a. These values were plotted (Figs. 10 and 11) to see if they behaved rationally. The values have only the validity of numerically satisfying the constructed formula. They have

*See Appendix on page 81.

the qualities, which are to be discussed, of being continuous, coherent and plausibly related to the physical situations.

Discussion

The Division of Resistance

The family of voltage vs. current curves for fixed electrodes illustrated in Fig. 1 shows a well known trait described as the volt-ampere characteristic of the arc:

1. At low current values the voltage across the cathode-anode span is high.
2. With an increase in current the potential drop is reduced.
3. Further increasing current causes the potential drop to grow again continuing with continuing increases in current.

When the voltage characteristic is changed to a resistance characteristic by Ohms Law ($R = E/I$) the reaction of the system is more comprehensible (Fig. 2); the resistance of the system is continuously dropping with increasing current. Initially the resistance decline is so fast (relative to current) that the voltage must decrease. Only after resistance approaches constancy (after 300 amp) does the ordinary voltage rise with current rise ($E = I \cdot R$) become evident.

The system can be considered as:

1. The conductors to and including the tungsten cathode.
2. The arc.
3. The anode and subsequent conductors.

The resistance of this system can be summed as the resistance of the arc in series with the resistance of all the metal circuitry in the remainder of the electrical loop. This may be expressed simply as $R_\Sigma = R_a + R_t \cdot R_t$ is composed of all copper losses, and anode (work and tooling) losses as well as tungsten losses. Each of the components of R_t, therefore R_t itself, will have a constant resistance or a resistance which rises somewhat with current and temperature.

The precipitous drop of R_Σ in Fig. 2 therefore is due to the drop of arc resistance, R_a, with increasing current. This is consonant with the character of hot gas plasmas, which conduct better as their temperatures rise or they increase in cross section. R_a may or may not include cathode and anode field effects. The power pumped into the system by the source is manifested as a heat production. Part is emitted from background circuitry, part from the electrode, and part from the arc. The division of power, or R_Σ, or E_Σ was considered important to know.

Of the two distinct components, R_t and R_a, each respond to current increase by separate physical laws. It should be an objective to find equations for R_t and R_a so that the sum of their values at any current level gives the total resistance R_Σ experienced in fact at that current level. The root equation for either should be composed of coefficients, representing a permanent physical character of the matter involved which remains constant with changing conditions such as of current. When R_a was described by r_a/I and R_t was described by $r_t \cdot I$, and the numerical values of r_a and r_t were derived for the five electrode and four current combinations. r_a turned out to be nominally constant between 200 and 400 amp: 17 ohm-amps for the 30 deg electrode, 16.7 for the 60 deg, 16.1 for the 90 deg, 16.3 for the 120 deg, 16.2 for the 180 deg (see Fig. 11). The coefficient r_t could be found from an equation of the form $r_t = C_2 + C_3 \cdot I$ between 100 amp and 300 amp (see Fig. 12). The total resistance R_Σ is soluble between 200 and 300 amp by the equation of the form:

$$R_\Sigma = \frac{C_1 + C_2 I^2 + C_3 I^3}{I}*$$

The constants are listed in Table 3 for the five electrode configurations. R_Σ calculated by the above formula and R_Σ experimentally obtained are compared in Table 4 for the 200 and 300 amp levels.

* $E\Sigma$ then would be equal to $C_1 + C_2 I^2 + C_3 I^3$.

Table 1—Current-Voltage Relationships for Five Electrode Geometries

Specific relationship	Electrode, deg[a]	Current level, amp 100 v	200 v	300 v	400 v
Voltage-ampere characteristics	30	18.8	18.6	22.0	25.5
	60	18.1	17.9	19.7	21.9
	90	18.8	16.9	18.2	20.5
	120	17.6	16.9	18.0	20.0
	180	17.0	16.6	18.2	20.5
Potential drops in metal system	30	.24	1.56	4.85	8.50
	60	.11	.88	3.06	5.60
	90	.00	.64	2.25	4.95
	120	.02	.32	1.72	3.84
	180	.14	.76	2.34	4.95

[a] Included angle for pointed cone tips.

Table 2—Current-Resistance Relationships for Five Electrode Geometries

Specific relationships	Electrode, deg[a]	Current level, amp 100 ohms	200 ohms	300 ohms	400 ohms
Total resistance decline, R_Σ	30	.188	.093	.173	.063
	60	.181	.089	.066	.055
	90	.178	.084	.061	.051
	120	.176	.084	.060	.050
	180	.170	.085	.061	.051
Arc resistance, R_a	30	.185	.084	.057	.043
	60	.180	.084	.056	.042
	90	.176	.082	.054	.040
	120	.176	.083	.054	.041
	180	.169	.081	.053	.040
Metallic resistance, R_t	30	.0024	.0078	.0162	.0212
	60	.0011	.0044	.0102	.0140
	90	.000	.0032	.0075	.0124
	120	.0002	.0016	.0057	.0096
	180	.0014	.0038	.0078	.0124

[a] Included angle for pointed cone tips.

Table 3—Constants for Electrode Configurations

Electrode Configuration	C_1 (ohm-amp)	C_2 (ohm/amp)	C_3 (ohm/amp^2)
30 deg	17.0	10×10^{-6}	14×10^{-8}
60 deg	16.7	0	11×10^{-8}
90 deg	16.1	-12×10^{-6}	13×10^{-8}
120 deg	16.3	-13×10^{-8}	11×10^{-8}
180 deg	16.2	8×10^{-6}	6×10^{-8}

Table 4—Comparisons of Calculated and Experimented Total Resistance

Electrode Configuration	200 amp Calc.	200 amp Exp.	300 amp Calc.	300 amp Exp.
30 deg	.093	.093	.073	.073
60 deg	.088	.089	.066	.066
90 deg	.084	.084	.062	.061
120 deg	.084	.084	.060	.060
180 deg	.085	.085	.062	.061

These reasonings prove that $R_\Sigma = r_a/I + R_t \cdot I$ is a solution to the analysis of R_Σ but unfortunately do not also serve to prove that the equation is the only mathematical analysis of R_Σ. The discussion will proceed as if it were the only valid analysis while conclusions are checked against experience or experiments.

Now the values of arc resistance R_a, may be taken from r_a/I and system resistance R_t from $r_t \cdot I$. This gives, for each electrode, the division of R_Σ into the arc and metal components (as defined). Each component behaves as expected (see Fig. 3). The metal resistance rises continuously and smoothly with current and temperature increase. The resistance decrease of the arc, which now must be greater at any point than the R_Σ decrease, is substantial at early current levels. From the establishment of this relationship begins the lessons of value to the welding engineer.

Two comparisons can be made to emphasize the effect of these data. First, the same electrode used at 100 amp will not produce triple the effect at 300 amp. At *100 amp only 1%* of the heat is emitted from the electrode, or the system behind it (99% from the arc). *At 300 amp 22%* is created in or behind the electrode. Second, *a 30 deg electrode* at 300 amp *creates 22%* of the total heat, whereas *a 120 deg electrode creates 10%* of the total heat. This is with a fixed position electrode and fixed current. The man who knows when he is not penetrating to the correct level usually only has to turn his heat (current) control up or down. The man, who does not know or see, must predict. That requires an understanding of his conditions such as the reaction of heat to a change in electrode configuration and the response of the given electrode to current changes.

It may be valuable to review momentarily some of the principles of heat creation and deployment before going into some practical cases. Electrical power is converted to heat by the resistance found in the power lines, electrode, arc, and work. A given input *IE*, shown by the current running through the loop and the potential drop in the consuming part of the loop below the voltmeter taps, is converted to heat in the four areas according to drop in each. The heat output from each will vary according to the fraction of the whole given drop that each takes. Whatever *IE* or I^2R heat the lines throw out is wasted to the air or the water jackets. The heat created in the electrode departs in four primary directions:

1. Back to the water cooled collet holding the electrode.
2. Into the surrounding purge gas.
3. Incandescent radiation to the environment.
4. Through the departure of hot electrons on their way to the anode.

The arc radiates (1) wastefully to the environment and (2) usefully to the anode, as well as (3) raising the temperature of the purging gas. Most recent data on the subject[3] indicate that 21 to 43% of the electrical energy is received by the weld metal. Knowledge of wastage then is very important to the understanding of the use of applied power. But before that the division of energy coming from the sources has to be organized. This is dealt with in more detail shortly.

The Division of Potential Drop

In practice, automatic welding can be conducted either as constant position (electrode fixed in height above work) or constant potential (where voltage is held constant by a servomotor which raises or lowers the electrode to change the arc length thus the voltage). So far the experiences are describing phenomenon expected in constant position welding for this was the character of the referenced experiment. Three reactions in this mode are not obviously predictable. Compare a 30 deg electrode whose current is doubled from 100 to 200 amp, at a fixed 0.060 in. separation—Table 5. Heat input raised 100% brings arc heat up 83% and metal circuitry heat up 670%. Also arc voltage has been reduced by 11% which can change arc force and puddling effects.

Next compare the conditions which accrue from replacing a 30 deg tip with a 120 deg tip at 300 amp, and a .060 in. separation—Table 6.

While the total heat input has been reduced to 82% by the change, the arc output has only been reduced to 95% The electrode and circuitry heat output is reduced to 28% of the previous level. Some significant effects should be expected in a weld. The operator may alter his current on the 120 deg electrode to recoup the conditions of the 30 deg electrode, but the results will never be quite the same. On a difficult weld this may make the difference between defects or trouble, and none.

Such a switch seems unlikely unless one considers that most of the controlling geometry exists in the extreme .080 in. of the electrode tip and the obvious greater electrode shape is not controlling. Further, most tips are prepared by the user manually on a local grinder and can include such personel choices as variously pointed, truncated, or balled tips. Therefore, one of the first conditions to check when welding with scheduled parameters produces inconsistent results is the conformity of electrodes used from piece to piece.

In constant potential welding the problem is more serious. To enter this subject with these data an important assumption must be made—that the conducting properties of a given electrode are essentially a function only of the electrode geometry and the current. So varying electrode to work distance between .090 and .025 in. would not change its resistance substantially. This would say that the metal potential drop illustrated by Fig. 4 is a largely correct response to current, and independent from arc lengths or controlled total voltages. This is borne out by Morris's research, which indicates that cathode heating (by caloric measurements) is independent of electrode-work separation.[6]

At this juncture belongs the question of what part of metal potential drop is in the power source, cables and connections, and what part is in the electrode itself. A test in the Martin Marietta Corporation's Denver Advanced Manufacturing Technology Laboratory on a 60 deg tip 1/8 in. diameter 2% thoriated tungsten electrode shorted to a tungsten block showed that distinction. Line 1 in Table 7 shows the d-c drop (V_s) across the 500 amp transformer-rectifier source as indicated by the voltmeter on the power source. Line 2 shows the drop (V_e) from weld

Table 5—Constant Potential Welding with a 30 deg Electrode

Current	Metal potential drop, v	Arc potential drop, v	Total heat input, watts	Heat from metal circuitry watts	Heat from arc, watts
100	.24	18.5	1880	24	1846
200	1.56	16.8	3720	312	3410

Table 6—Results of Replacing 30 deg Electrode with 120 deg Electrode at 300 Amp and 0.006 in. Separation

Electrode Configuration	Metal potential drop, v	Arc potential drop, v	Total heat input, watts	Heat from metal circuitry, watts	Heat from arc, watts
30 deg	4.85	17.2	6600	1456	5144
120 deg	1.72	16.3	5400	516	4880

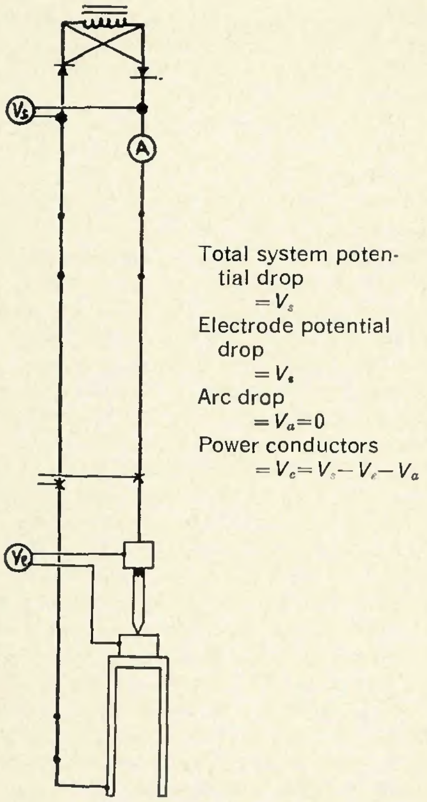


Fig. 4—A simple experimental division of potential drop of the whole metal system ($V_s = R_t \cdot I$) into the portion due to the head drop (electrode-work, V_e) and to the power conductors ($V_s - V_e$). The arc effects are excluded by shorting the electrode to the anode (see Table 7)

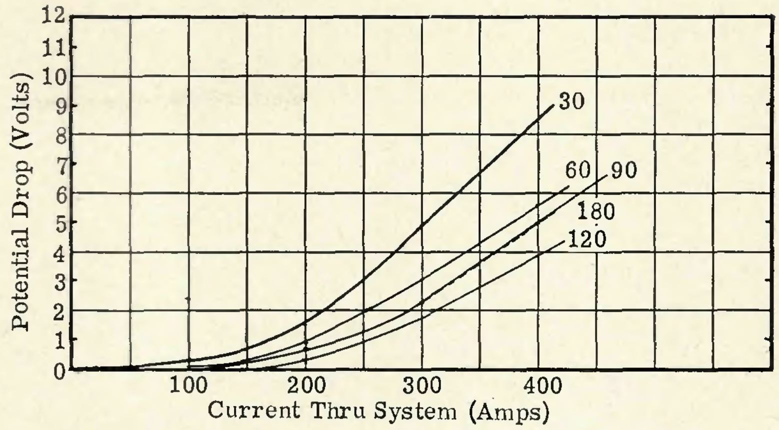


Fig. 5—The potential drop in the metal system rises significantly with increasing current through the loop. The drop in sharper tipped electrodes is a considerable value above that of blunter cone tips at higher currents (see Table 1)

head to ground (the tungsten-work drop). The difference in line 4 (V_b) is the characteristic voltage response in cables and connections—too often under estimated.

The test and its results are given to show how easily, with a well placed voltmeter, the characteristic voltage for the background power delivery system (line 4) can be identified. Since each system is peculiar, such backgrounds should be identified individually. The voltmeter on the power panel really gives bad advice to the welder who should be concerned during welding only with the voltage from weld head to ground. The meter visible to the welder during welding should be indicating this value. Servo-systems whose function is to maintain a constant potential weld, should have their sensor taps here as well. If they should be tapped upstream as at the x junctions, the heating of the lower lines will demand a drop over the arc in order to maintain the drop over the taps at a constant value. In this example, a meter at V_e will show a drop (the increased line drop to the x's) for no apparent reason.

The resistance R_t (in Table 2) of the metal system for any current and electrode tip tested, is easily converted to the potential drop in the metal sections by $E = IR$. So the metal drop characteristic of Canulette's set-up[1] is charted in Fig. 5 for any current on the five electrodes. Where the 120 deg electrode's curve must be closest to the volt-amp characteristic curve of the background system, which is not known, all the other electrode curves are clearly higher as a result of the larger resistance of their own tip.

Considering that the meters which provided voltage and current data in the original experiment for Table 1[1] would be the same meters which affected a welder's decision, it may be seen how misjudgment in constant potential welding may occur. A most obvious example will show the serious consequences of unawareness of the voltage rationing between the arc and the rest of the system. Take a 30 deg electrode set to operate at a constant 12 v and 200 amp. From Fig. 5, the metal drop should be 1.56 v; the arc then must be 10.44 v. Raise the current toward 400 amp and the metal drop moves toward 8.5 v. To maintain the constant 12 v drop, the arc will shorten until its drop would theoretically be 3.5 v. Somewhere along this route the electrode will stub out because arc length will head toward zero. In the case of fixed position welding, the arc will be have erratically or extinguish because the voltage remainder for the arc is less than the minimum required potential. It is later discussed that the heat produced and delivered to the work is affected by this changing power ratio.

Table 7—Comparative Potential Volts in a Practical System

Current, amp	100	200	300	400	430
System (V_s)	.5	2.0	4.0	6.0	6.6V
Electrode (V_e)	.2	1.0	2.0	2.4	2.9
Arc (V_a)	.0	.0	.0	.0	.0
Background drop in conductors	.3	1.0	2.0	3.6	3.7

Consider another example. A job has been accomplished satisfactorily with 300 amp, 12 v, and a 60 deg electrode. The metal and arc split is 3 + 9 v. A 30 deg electrode is substituted. The metal + arc split is now 5 + 7 volts. The charted voltage in Fig. 5 may be used to maintain the arc as a 9 v arc. Since it can be seen that the metal system is taking 2 more volts, the adjustments may be made to weld with 14 v giving the split 5 + 9 v. Other than the lesson that comes out of every illustration in this paper—that is, when effects must be duplicated in welding, it is necessary to duplicate electrodes—it is apparent that shifts toward either higher currents or finer tips from a given status can have the effect of greatly decreasing the arc generated heat. Arc voltage and arc length have important and difficult to describe effects on puddling and penetration. Heating efficiency, very important in its own right, now can be treated with some order.

The Metal-Arc Ratio of Heat Output

The efficiency of the subject electrodes with increasing current will be examined. The metal resistance values for five electrodes and four increasing current levels as given in Table 2 is by I^2R easily converted into power output, expressed as watts and manifested as heat. This is given in Table 8. The power input is the 12 v, the constant potential established for this example, times the current used. When the metal power output (P_m) is subtracted from the power input (P_I) the difference remaining must be the arc power output (P_a). This was done for each of the twenty cases. The power input is with constant potential welding a straight sloped line proportional to current at the rate of 12 watts per amp as shown by the dashed line in Fig. 6 or 7.

The theoretical rationing of resistance, or voltage, or power will be illus-

Table 8—Power-Current Level Relationships for Five Electrode Geometries

Specific relationship	Electrode, deg[a]	Type power[b]	Current level, amp: 100 watts	200 watts	300 watts	400 watts
Rise of metallic power output	30	P_m	24	312	1456	3400
	60	P_m	11	176	918	2240
	90	P_m	00	128	675	1980
	120	P_m	2	64	516	1737
	180	P_m	14	152	700	1980
Rise of arc power output	—	P_I	1200	2400	3600	4800
	30	P_a	1176	2088	2144	1400
	30	P_m	24	312	1456	3400
	60	P_a	1189	2224	2682	2560
	60	P_m	11	176	918	2240
	90	P_a	1200	2272	2925	2820
	90	P_m	00	128	675	1980
	120	P_a	1198	2336	3048	3265
	120	P_m	2	64	516	1537
	180	P_a	1186	2248	2900	2820
	180	P_m	14	152	700	1989

[a] Included angle for point cone tips
[b] P_m—metal power output; P_I—power input; P_a—arc power output

trated with the metal power output curve for the 30 deg electrode in Fig. 6. At 100 amp when the input is 1200 watts the metal resistance is so low (.0024 ohms, Table 2) that the metal potential drop is low (.24 v) and the metal puts out a small part of the 1200 watts put in (that is, 24 watts). At 200 amp the resistance has tripled (.0078 ohms), the potential drop (1.56 v) has become a significant part of the 12 v; and the heat output (312 watts) has become a significant 13% of the input (2400 watts). By 400 amp the resistamce is nearly ten times its value at 100 amp (.0212 ohms). The metal output has grown to 3400 watts, 70% of the input 4800 watts.

Before the 100 amp, while the power input rises at 12 watts for each amp increase, the metal output is nearly zero watts/amp. So the arc output rises at 12 watts/amp. At 200 amp, each amp increase raises the metal output 6 watts. By 250 amp, each amp increase raises the metal output 12 watts. Since this parallels the input the added input power all comes out of the metal and none is added to the arc output. After 250 amp, the watts/amp slope of metal output is greater than the input slope. So additional current causes a metal output increase greater than the input increase. By 400 amp, each 12 watts/amp input is reacted with a 20 watt/amp metal output. Each amp increase therefore is reducing the existing sum of arc power by 8 watts.

The behavior of arc power is clearly shown in Fig. 7 where, on the same ordinates as Fig. 6, the arc output is plotted. Here the near zero output of the metal is reflected when the arc output traces the input through 100 amp. Then as the temperature of the metal circuitry grows and its resistance grows irrepressibly, it takes a larger watt output and a larger fraction of the given input. At 250 amp any increase in current puts more watts out of the metal but none out of the arc. After 250 amp the watt output of the metal rises faster than the input, so that the arc output is actually decreased by more current. For example, at 400 amp the input is 4800 watts with the arc output being 1400 watts; then at 401 amp the input is 4812 watts and the arc output is 1392 watts. The electrode output has increased by 200 watts when the input was increased by 12 watts. Debits must be taken from the power balance of the arc. So with increasing current, arc power output declines until some part of the metal circuit burns out or the arc power or voltage becomes insufficient to maintain an arc, or arc length goes to zero.

The 30 deg electrode because it has the highest resistance and fastest resistance rise with current ($\Delta R/\Delta I$) steals more power from the arc and sooner. Therefore, its arc power always remains lower than the others and peaks

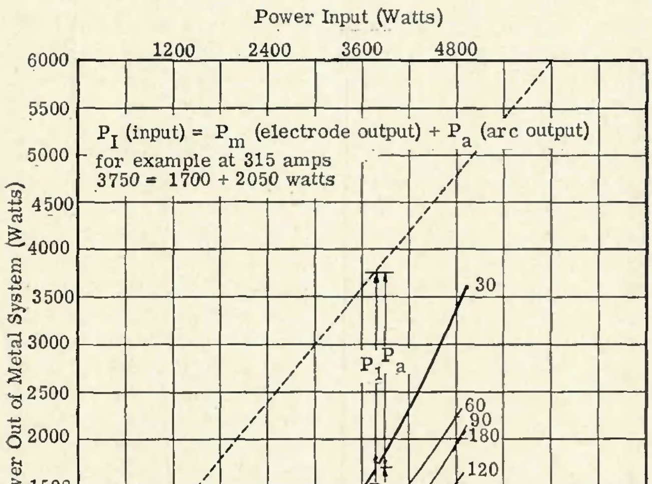


Fig. 6—The power out of the metal system vs. the power input (constant potential) showing the accelerating metal output as current, and input power, rise uniformly (see Table 8).

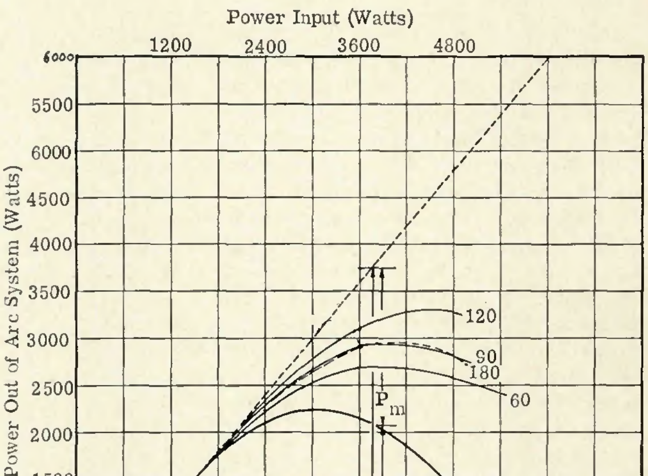


Fig. 7—Power put out by the arc as heat as input power rises showing how arc power peaks and declines with increasing current on a constant potential system. The peak occurs at lower currents and at lower power values for sharper electrodes (see Table 8)

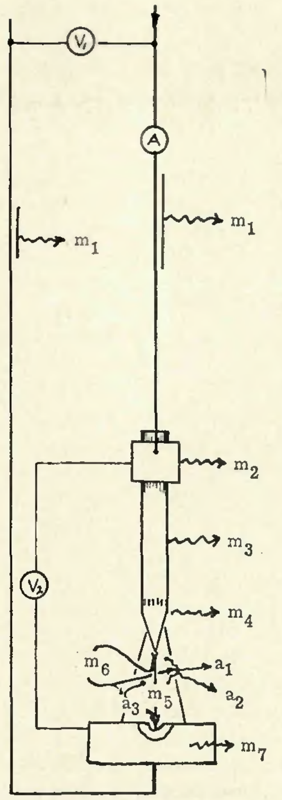
at a lower current, 2250 watts at 250 amp. The 60 deg electrode had a lower resistance and slower rise so its hottest arc occurs higher and later, 2700 watts at 325 amp. Now, if that peak did correspond to the hottest anode spot, then increasing the current to 400 amps would result in less penetration not more.

The immediate explanation of the higher resistance and quick resistance rise (with current) of the 30 deg electrode tip, compared to the lower values of the 60, 90, and 120 deg electrodes is the narrowing tungsten cross section in the tip before the electron emission extremity. The higher current density in the constriction increases the resistance and the temperature of the cone. Curiously, the coolest tip by this measure is the 120 deg rather than the 180 deg tip, which is really only the flat end of a cylinder. This may be related to a much earlier observation that at midrange currents the arc emerges from the corner of the cylinder end or revolves on it. Thus the tip geometry which was a cone extremity to current at 120 deg passed into a chisel extremity after 120 deg with consequent current funneling again. Thicker diameter electrodes would give higher arc output peaks but it is conceivable that a 30, 20, or 15 deg tip on a $^{3}/_{16}$ inch diameter electrode could peak sooner and lower than the 120 deg tip on the thinner $^{1}/_{8}$ inch electrode. It is enough of a possibility to guard against: larger diameter electrodes will not of themselves always guarantee lower electrode drops.

Heat Deployment

The ratio of power output between the metal system and the arc has been discussed on the basis of the correctness of the mathematical division of resistance of the "metal" and "arc" components. This well enough describes the two systems as separate origins of electrical heating. However, since their heat is deployed in various wasteful and useful ways, the heat output components must be identified before commentaries on penetration and efficiency can proceed. The I^2R heating of the lines passes into the air or water jacket and is completely wasted (m_1 in Fig. 8). This fraction can easily be separated from the head system (see Fig. 4, take V_e away from V_s).

The head system is the part of the loop enclosed by the closest voltage taps possible, such as V_e in Fig. 4. This can report the behavior of the electrode, the arc, and the anode which will be referred to as the head drop. 90 to 50% of the heating in the electrode shank flows through the water cooled holder, often located 1 in. up from the tip (m_2); some of the shank heat will heat the purge gas which flows by it (m_3); some of the shank and the tip heat will be broadcast as incandescent radiation (m_4); a great deal of heat produced in the electrode will depart on "hot" electrons which carry off energy (m_5 and m_6) into the arc column.



$P_I = P_m + P_a$
$P_m = m_1 + m_2 + m_3 + m_4 + m_5 + m_6 + m_7$
$P_a = a_1 + a_2 + a_3$
m_1 = line losses
m_2 = water cooled holder losses
m_3 = conduction losses to gas
m_4 = radiation losses
m_5 = heat transferred to anode
m_6 = some of m transferred to a
m_7 = work and tool losses
a_1 = arc radiation losses
a_2 = conduction losses to gas
a_3 = heat transferred to anode

Fig. 8—A welding system schematic showing where power input produces heat in the metal loop and in the arc and where these heat sources deploy their energy by several components

Savage[2] shows temperature profiles along the electrode length from tip to holder that suggests that nearly half the heat created in the shank, at very high currents, will leave from the tip. That means that much of the I^2R heating of the shank will be transplanted to the anode. Some portion of the electron energy (m_6) is transferred to the arc by collisions within the plasma. This creates and maintains the arc's high temperature. I^2R heating of the workpiece beyond the weld at the moment of the weld is dissipated (m_7). The IE heating in the arc departs essentially three ways: radiation to the environment (a_1); raising the temperature of the shielding gas (a_2); and radiation to the anode (a_3). The plasma of the arc conveys the "hot" electrons (m_5) from the electrode to the anode.

The electrode tip looses much heat on a departing electron (which now bears an energy increment sometimes called the "heat of evaporation"). The electron is now carrying heat in a kind of potential form. In falling from the higher to the lower potential electrode, it also acquires kinetic energy equivalent to the true arc drop. The anode redeems both forms of energy by getting hot. In the fall some electrons will loose their energy by collisions and energy exchanges with other atomic particles. This contributes to arc heat. That heat will be radiated and conducted away. Some of it will benefit the anode. A longer arc (greater drop) increases the kinetic amount of energy in the electron stream. But that proportional increase is taxed by frictional losses also proportional to a longer path. This seems to say a watt added by current may be more useful than one added by voltage.

In Fig. 8 the cathode escaping electrons carry out energies, $m_5 + m_6$, whose sum grows in the fall; m_6 is defined as the energy which is transferred to the arc heat. All energy put into this defined system (between meters) must be equalled by the sum of heat dispersed by the various components. The ratios of heat in each component may change in a variety of ways even when the input power does not. When it is useful components that grow, at the expense of others, the welding efficiency increases.

There is an inference in Fig. 7 that the heat to the work will decrease as arc heat (P_a) decreases. But since metallic heat (P_m) is increasing the heat to the work will depend on whether the decrease of arc delivered heat (a_3) is more or less than compensated by the rising delivered electron heat (m_5). Does the sum of anode collected heat

($m_5 + a_3$) fall when arc heat passes its peak?

The caloric pickup of the anode is the best measure for ascerting the change of this sum. This has been accomplished by many with a disconcerting scatter of results. For a comparison to the calculations set forth here the energy input was measured in terms of the area of weld nugget cross sections on specimens made in the AMT Laboratory. The voltage was set for a constantly maintained 12 v with 60 cfh of the helium as purge gas. Eight current values through a 60 deg tip were run on mild steel at 35 ipm.

The welds were sectioned, and the areas are presented in Fig. 9. The area results were a little unusual so the depth of penetration was also plotted, and the character of the first curve was reinterated. Some penetration data from Canulette's experiment on 6061 aluminum[1] were overlayed with the steel penetration, and it became clear that the staircase climb of energy received by the anode in the constant potential welding was a phenomenon associated with the arc and electrode and not with experimental observations. Other information sources which ran penetration effects through these current ranges carry hints of the same characteristic, even in argon or nitrogen. It is clearly apparent on the steel penetration in Fig. 9 that there are four zones which require individual explanation. The 100–200 amp range has a slow increase with current. The 200–300 amp range has a very steep penetration per amp response. The 300–400 amp range shows almost no response, although 100 amp have been added. The 450–600 amp range shows a uniform moderate increase of penetration with current.

Before offering an explanation for this, another observation with its own explanation must be completed. Even with constant potential it was observed, but not measured, that at 100 amp the 60 deg electrode was close to the work, at 200 amp it is separated to a much longer arc length, at 300 amp the arc was quite long, at 400 amp it had shortened to nearly half that, and at 500 and 600 amp it was nearly touching the anode. This has been sketched at the top of Fig. 9 as it might appear over a tungsten anode.

This is a constant potential system which adjusts itself by changing arc length through a servo-motor. The greater discussion supports the following rationale. At 100 amp the arc drop is highest, its resistance is highest while the electrode resistance is insignificant. A short length of high resistance arc is enough to make the essentially 12 v. At 200 and 300 amps the arc has become very conductive so the servomotor raised the head and lengthened the arc until the 12 v total was reached. Now by 400 amp while the arc resistance has not increased since 200 amp, the electrode resistance has grown to a point where it has a large part of the potential drop (perhaps 5.5 v) and the arc length is based on the remainder (now 6.5 v instead of 12 as at the start). At 500 and 600 amp as the electrode drop increases toward 12 v, the arc length heads toward zero. (Two investigators[6,8] have shown that the fields in front of the cathode and anode surfaces may be interacting at separations less than .020 in. Voltage previously declining with shrinking separation rises again, thus giving the arc an increased resistance just before tip work contact). This all is best summarized by Table 9.

Electrode and arc behavior have not been well understood, either in an engineering or scientific sense. Because arcs of equal drop were expected to be of equal length, the very close tip to work separation of sharp cone electrode tips vs. the larger separation of wider cones or truncated tips in a constant potential comparison was attributed to a constant distant from the anode surface to the average center of the emission surface on the cathode. The geometric tip, of course, extended much lower than the emission area centroid putting it very close to the work. Curiously, that explanation nearly fit the observations.[4]

Now it seems that the high drop in the fine tip, leaving only a small drop for the arc, requires the servomechanism to maintain a short arc. With the small drop in blunter tips, the arc drop must be increased to make the given total drop and so the arc length must be greater, all other conditions being equal. It seems now that this phenomenon will explain much, if not all, of the observed separation variance between different design electrode tips. Certainly now, although the head voltage may read the same, the true arc drop values are very different between the finer and the blunter tip, and this must be taken into account in any future generalizations.

In Fig. 9, the 100 amp added between 200 and 300 amp produced the largest increase in penetration. The input P_I rose 1200 watts, the metal power P_m rose 742 watts the arc power P_a 454 watts (per Fig. 7). Not a great change occurred in arc length. Either or both sources could have made the evident contribution (to increase $m_5 + a_3$). On the other hand the 1200 watts added between 100 and 200 amp made only a small contribution to penetration. The arc lengthened considerably, metal power P_m rose 165 watts, arc power P_a 1035 watts.

Compared to 200–300 amp, this suggests that arc power is a small contributor to anode heating or that the lengthening arc dissipates most of its power (through a disproportionate increase of $a_1 + a_2$). The latter has some credit because in going from 100 to 200 amps the nugget width increased 330% the depth increased 20%, suggesting a dispersion of the heat in the arc column. So the small increase in penetration (100 to 200 amp) is attributed to the electron heat and the surviving arc heat ($m_5 + a_3$) that reaches the anode. The 1200 watts added between 300 and 400 amp caused almost no increase in penetration. Metal heat rises 1322 watts, arc heat falls 122 watts, and the arc has become shorter. Delivered heat ($m_5 + a_3$) has apparently failed to rise significantly. It is feasible to attribute much of this to the reapportionment of power to largely unproductive metal losses (m_1, m_2, m_3, m_4, and m_7) especially in the now highly incandescent shank.

Canulette[1] and Savage[2] report that the shank midway between holder and tip can exceed 6000° F with currents greater than 300 amp. (The tip reaches its ultimate temperature, 5300° F before 250 amp, after which the mid-point, between tip and holder, rises up through 6000° F). With current increases after 450 amp, the line losses (m_1, m_2, m_3, and m_7) continue to be increasingly wasted but by now the tip has found a position below the plate surface so now two former conspicuous wasters (m_4 and a_1) now contribute some of their heat with the rising electron delivery (m_5) and declining arc delivery (a_3). This has some support in the nugget dimensions where the width-to-depth ratio turns down at 450 amp and, in fact, becomes less than 2.0 at 550 amp. (A standard might be set around a half circle shaped nugget whose width should be twice the depth. A larger ratio should suggest a heat impingement relatively broad. A smaller ratio suggests a subsurface deposit of heat).

The width actually declines from 500 amp. The nearby point source of heat found in the electron emitting tip is a very powerful element. This point has been shown to not rise above 5300° F while prodigious amounts of current are pumped through it.[2] That energy is directed primarily into the ellctron stream (m_5 and m_6). After 450 amp penetration increases in some proportion to energy input P_I but not so well as the rate between 200 and 300 amp, because now the metal circuit wasters (m_1, m_2, m_3, m_4/n, and m_7) are much larger tax on the input. Furthermore, after the arc is practically immersed, the hot anode in the puddle is clipsed by the electrode tip and the radiation normally seen by the environment is cast back on the arc and tip and conserved (especially at high speeds where the puddle is small.)

This bright radiation may be a significant distinction between the weld metals which are rarely reported to receive more than 50% of the input energy and those water-cooled anodes sometimes reported to receive up to 90% of input energy. It might be added here that Savage's curves[2] which show a temperature rise from 5300° at the tip to 6000° halfway to the water-cooled holder, then decline to the holder indicate that ion bombardment of the tip long considered the prime source of the tip heating must yield the majority of credit to the growing I^2R heating in the tungsten conductor.

There is a high degree of speculation in these preceding descriptions. Yet the tools supplied—the division of heat production, the arc length observations, respective potential drops—allow a coherent picture to be seen in what to a large degree has been a puzzle. The propositions are worthy enough to be clarified or modified. Many investigators and instructors argue that penetration rises in proportion to current or voltage, or is proportional to wattt input (IE) yet face conflicting experiences. It is safe to say the solution lies in the identification and weighing of energy distributed to useful ends (m_5, a_3) or wasted ends (m_1, m_2, m_3, m_4, m_6, m_7, a_1, a_2).

The prior explanations herein try to supply a format with some tools, primarily in a new practical recognition of the heat production category. The distribution is a large multi-faceted subject, which is not dealt with in depth here. However, it is hoped that the aspects explored here may provide some rationale to those remaining unexplainable correlations evident in works such as those by Salter, Wilkinson and Milner,[9,5] Lancaster,[8] and Morris and Gore.[6] It remains for improved calculations and incisive measurement techniques to correctly adjust the balance of energy factors as qualities and rules change with increasing current or voltage. The ideal report will be able to show for a given condition the values of each energy input and each energy disbursement (see Fig. 8). Then the coherent reapportionment evident in a changed condition will provide valuable clues to the several physical happenings.

Time as a Factor

Recall Fig. 5. If the 30 deg electrode has a drop of .24 v at 100 amp because it is cold, then it should have a very low drop also at 400 amp just at the moment when it is cold. If 12 v and 400 amp are being run through the system, the arc and the immediate electrode surfaces (cathode and anode) are the sites for essentially the entire potential drop and I^2R heat production (4800 watts). The flare seen in the first one-half second may be an expression of this. About three minutes later the power ratio has settled to near the theorized figure of 3600 watts in the metal system (from the 9 v for the sake of discussion) and down to 1200 watts in the arc related system.

In a weld of thin material with a fine electrode, this can have a disastrous effect for, the instant the arc plasma is formed, the power surge in the arc can be sufficient to blow a hole in the part before the very large drop forms in a thin electrode. Such a surge will not be reported by the meter except as a needle whip as the servosystem attempts to maintain a constant current while the resistance climbs quickly. In a heavier weld the surge is usually unnoticed, but it is almost an asset since a mass is to be brought up in temperature before the weld proceeds. The surge is related to the electrode and work dimensions rather than the power source. It can be

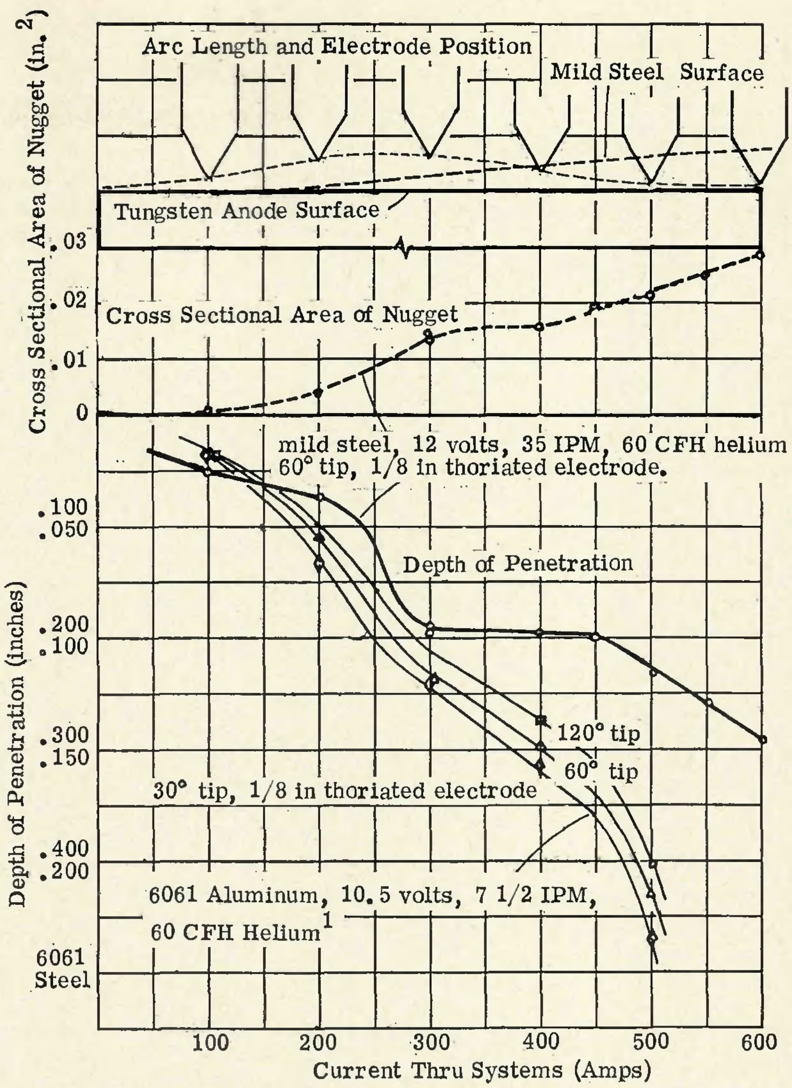


Fig. 9—The effect of current increase on penetration in steel and aluminum shows three distinct changes in the rate at which penetration reacts to current increase. The arc length and electrode position illustrates some of the reasons for this varying response to current at the constant potential

Table 9—Constant Potential Electrode Behavior (Servo Sensors at V_2 in Fig. 8)[a]

Current, amp	Arc resistance	Electrode resistance	Arc length
0–200	High	Low	Short
200–300	Low	Increasing	Long
300–450	Low	High	Shorter
450–600	Low	Very high	Shortest

[a] The so-called constant potential arc is in reality at high currents a very much reduced potential arc which might in practice warrant some increase to separate the very close electrode tip and work.

countered by programmed or preprogrammed start reactions in the welding equipment.

If a plot was to be constructed of metal potential drop vs. time at 400 amp, the curve would incorporate events at several different sites and different times. The first point immediately after current establishment should be an insignificant potential drop. The heating of the cone tip and the immediate surface of the anode, in less than 1 sec, should give a rise of a certain rate (based on the electrode tip shape). This curve would be blending into a drop rise rate which is dependent on the shank and anode temperature rise and reaches its max slope between 3 and 30 sec. The cone tip itself would have stabilized to a constant resistance during that period. The shank rise rate would be blending into a drop rise rate dependent on the heating of the power line and connections, which is dependent on the line temperatures and reaches its maximum slope between one and three minutes. The total drop would end up at 9 v (per Fig. 4) if the sum stabilized after three minutes.

There is then in the single E vs. time curve at least three probably "S" shaped curves whose max slopes occur one after the other. Reports on the arc experiments are usually assumed to give results for the stable time status. It is clear that conscious recognition of these effects are essential. Gross effects that sum the behavior of shank, tip, arc, and anode have usually been measured and reported. Just as an eledtrode tip change may give effects that reveal fundamental behaviors of electrode volumes or electrode surfaces or fields, this resistance time-rise factor may be exploited to make visible important effects. For example, by changing shank configuration or length or its material, the effect of this section may be identified and subtracted from the total behavior so that the tip behavior only may be shown.

Some reports on anode behavior in time under a starting arc may be heavily influenced by the cathode-side behavior in the time period when the majority heat production moves from the arc to the cathode (from a_3 to m_5). The electrode behavior in time should be isolated or fixed so that the time change of the anode stands out by itself.

Physical Aspects

Perhaps some physical aspects of these interacting phenonena may be revealed in the behavior of the coefficients r_a and r_t. The scope of this examination will include and distinguish (1) the lines, (2) the electrode shank, (3) the cone tip, (4) the conical emission surface, (5) its cathode field, (6) the arc with its electron plasma core, (7) its ion sheath, (8) the anode field, (9) the anode surface and (10) its volume. The point will be that the resistance of each one of these sections must fall either under the r_a (a function created as an incorporation of all functions which cause a decrease in resistance with increasing current, by $R_a = r_a/I$) or under the r_t (a function created as an incorporation of all functions which cause an increase in resistance with increasing current, by $R_t = r_t \cdot I$). Clearly the lines (1), the electrode shank (2), the cone tip (3) and the anode volume (10) belong under the r_t function. Also the arc (6 and 7) clearly belongs under r_a. The province that incorporates the cathode emission surface (4) the cathode field (5), the anode field (8) or anode surface (9), is not so obvious.

With the dimensions ohm-amp r_a is the same as potential drop (volts) across its components. For each electrode t_a appears to be constant at currents greater than 200 amp (Fig. 10). In a system expected to be current sensitive this potential drop remains constant although the conducting loop carries current ranging from 200 to 400 amp. This is an unusual and interesting condition. As an aside, it says that in a volt-ampere characteristic curve, such as Fig. 1, all voltage increases after 200 amp are added only by the metal conductors.

This would be a very useful rule since these curves are very easy to produce (just by noting voltage across a fixed position electrode as current is raised). As an example, between 200 and 400 amp the voltage over the whole system with a 30 deg electrode installed went from 18.6 to 25.5 v, or rose 6.9 v. The data presented by Fig. 5 show that the metal voltage went from 1.56 to 8.50 v, or rose 6.94 v. So data like that shown in Fig. 1 may be used to roughly ascertain the voltage rise of a particular metal system between 200 and I amp by the formula $VR = V_S - C$.

The constant potential drop phenomenon in an arc which is growing in diameter as current is raised from 200 amp suggests an arc core which has a very low resistance compared to the sum of the other possible sources of resistance—the cathode interface, the arc sheath, the anode interface. It is quite easy to see below 200 amp a low current core that, because of low heating and high heat loss, will have a high resistance. It is interesting to consider that above 200 amp the core may have reached a plasma state and temperature across its cross section and length that gives an insignificant resistance.

Physically, the Figure 10 curves indicate a constantly decreasing resistance of the r_a category. Resistance R_a might be comprised of $R_{ca} + R_c + R_{sh} + R_{an}$, which is the resistance of cathode end, arc core, arc sheath, and anode end. Any one of these must be either proportionally decreasing or be zero with respect to the r_a category (except the possibility of one going up decreasing the impact of one going down). Resistance is the physical attribute of the system with a current flow.

For a moment study an example just to make a practical point. Potential drop across the electrode and anode is changed by changing arc length. So the drop of the end effects alone might be found by extrapolating arc length to zero (thus $R_{co} + R_{sh}$ are theoretically eliminated without actually reducing the arc length to zero). Several investigators have done this and give an answer for tungsten to copper in helium of 8.5 v. Tungsten to aluminum in helium appears to be near this. Assuming this to be a good technique (that is, R_{ca} and R_{an} are not altered), it would give in a constant potential system set at 12 v a true arc drop of 2.5 v. For an example from Fig. 10, if end effects constituted 8.5 v a 90 deg electrode operating with 350 amp (16 v) would have a true arc voltage of 7.5 v. It is essentially this voltage or watt fraction, 2.5 out of 12 v in the first example above 7.5 out of 16 v in the second, that can be altered by the arc length; also it is the part most likely to be wasted by radiation and conduction (a_1 and a_2) so least likely to proportionately heat the anode. Further, it is the factor in a constant potential welding system which is diminished by increases in metal circuitry drops. This may provide some more of the answer as to why heat does not go up in direct proportion to voltage, or up by the same proportion under different conditions.

The total arc resistance, R_a, is at 400 amp half of its value at 200 amp (.040 ohms vs. .080 ohms, see Table 2). If the drop is to stay near constant, the resistance must continue to drop. Which of the possible components is primarily responsible fot this? It is likely that the arc column is accommodating the larger current by expanding the diameter such a way as to maintain a constant drop, or so as to have resistance when current is doubled. Why should $R_2 = R_1 (I_1/I_2)$ in the arc? Or is this constancy a manifestation of the work function?

How likely is it that the anode end effect is a part of the r_a behavior? It is generally agreed that just above the anode surface is a space filled with a majority of low velocity electrons. This is the phenomenon which is credited with the distinct potential drop reported for the arc just before the surface. After that, authorities tend to differ on the reason for this cloud of electrons which impedes the high velocity electrons streaming from the cathode. It may be a shortage of ions due to insufficiency of ions near the cold anode surface. This is akin to more thermionically produced electrons than ions. It may be due to a jet action which selectively blows ions from the space.

Different methods of deduction or experimentation provide different conclusions for the magnitude of the anode field drop. Anode heating does not provide a means of answering the question since the I^2R heating in this short drop is essentially added only to the anode. With its other larger receipts of heat the drop effect will be lost if small. Data agree though that the longer the arc the more heat received by the anode. This may be only due to the deposit of increased kinetic energy acquired by each electron in the longer drop. Such a bombardment might tend to compress the field so as to make it thinner and even harder to measure. Driven closer to the anode surface it might be indistinguishable from interface effects thus justifying one researcher's conclusion that it is negligibly small. Some organization of this subject would be helpful.

Now, is the anode field behavior expressed in curves of Fig. 10? It is proposed that it is not (discounting the possibility that it enjoys a compensation like the one offered for the arc). The reason for this position can be found in the work of Savage.[2] He shows that the bead width in steel will be increased 50% (to .540 in. from .320 in.) by using a sharp electrode such as a 30 deg tip in lieu of a 120 deg tip at 300 amp. (This was an experiment set up similarily to Canulette's[1] in which a thoriated electrode in argon was fixed at .050 from a steel anode).

It is hard to imagine the surface of the anode and the current and heat flux density changing by a factor of two when changing the arc voltage so little unless it is a very small factor. In figure 10, the 17 vs. 16.2 v arc for the 30 vs. 120 deg electrode (at 300 amp) should be primarily attributed to a slightly greater arc, especially sheath, length. The .4 v parallelism between the 30 and 120 deg curves up to 200 amp may be from that. The extra divergence, after 200 amp, that grows to .6 v at 400 amp, might be an anode related increase. This is a good subject for careful experiments. If the mathematics are valid, the curves are purer in the sense that probes or artificial circumstance are not present to add their own influences contaminating numbers or trends.

The argument for not associating the cathode field with the r_a function is analogous. Chihoski[4] reports an experience where current density of the emmission surface varied from 41,000 amp/in.[2] on a 30 deg electrode to 151,000 amp/in.[2] on a 90 deg electrode. This suggests that there should be some substantial consequence in cathode field or emmission surface resistance with an electrode change. His experiment was run with constant potential in a melting aluminum anode so several conditions have changed from the fixed distance experiment. Considering the amazing things happening at the cathode, this is another subject in need of more investigation. The cathodic surface and field resistance could be going down with increasing current and temperature, which would give a trend that conforms with the change of r_a in Fig. 10.

The behavior of the function r_t which gives the metal resistance ($R_t = r_t \cdot I$) is illustrated in Fig. 11. The resistance of the conductor is ordinarily taken as a constant quality of the conductor not usually responsive to the current level passing thru. But the resistance is responsive to the conductor's temperature. So the change of resistance (R_t) in response to current is essentially a change attributable to the temperature resulting from that current. The formula $R_t = C_2I + C_3I^2$ contains the heat production evidence $I^2R = C_2I^3 + C_3I^4$. The heat production rate matched with the heat loss rate of the conductor settles into an equilibrium and stabilization at some temperature and so to some steady resistance value.

The coefficient r_t, whose trends are illustrated in Fig. 11, represents a property of the subject conductors, a property that varies with current. But in r_t are two constant properties of a given electrode system—$r_t = C_2 + C_3I$. C_2 compared between electrodes shows the 30 deg electrode to contain the highest initial resistance followed by 60, 90, and 120 deg. The 180 deg electrode has the inordinate quality of being, at low current, less than 30 deg but greater than 60 deg electrode. These differences are attributed to the narrower cross section of metal at the tip of the sharper electrode, including the chisel tip before the emmission site on the 180 deg tip. It is especially interesting to note, however, that the difference between the initial values of r_t, (C_2), hardly grows as r_t grows in each electrode with increasing current load (because the slopes of all electrodes, C_3, are nearly the same). This suggests that the initial and maintained difference of r_t (C_2) between electrodes is essentially attributable to the tip (C_2 is dependent on the tip) but the increase of r_t with current (C_3) is primarily a function of the temperature of the electrode shank and system beyond the tip.

Does either the cathode or anode end show itself in this function, r_t? Would either rise with a decreasing electrode cone angle? Would either rise with an increasing current? The possibilities here will be viewed again compared to two accepted (at least for the sake of this discussion) conditions:

1. Anode spot area increases with decreased tip angle.

2. Cathode area increases with decreased tip angle.

The effect of those two trends is to describe an arc which is broader from cathode to anode for finer electrodes. Since the higher resistance of the finer electrodes is easy to assign to the narrower cross section of their tips, the additive or subtractive influence of a changed cathodic surface or field does not stand out. A broader anodic field, it might be suggested, will increase resistance because it will be cooler for

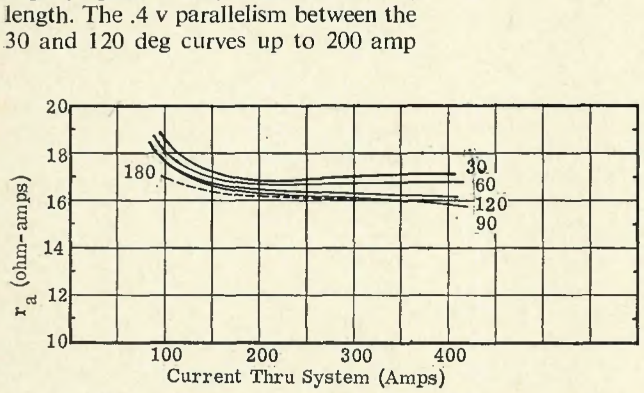


Fig. 10—The function r_a which is also the arc potential drop decreases from 100 amp to a constant value at 200 amp and higher. Finer electrodes have a higher arc drop

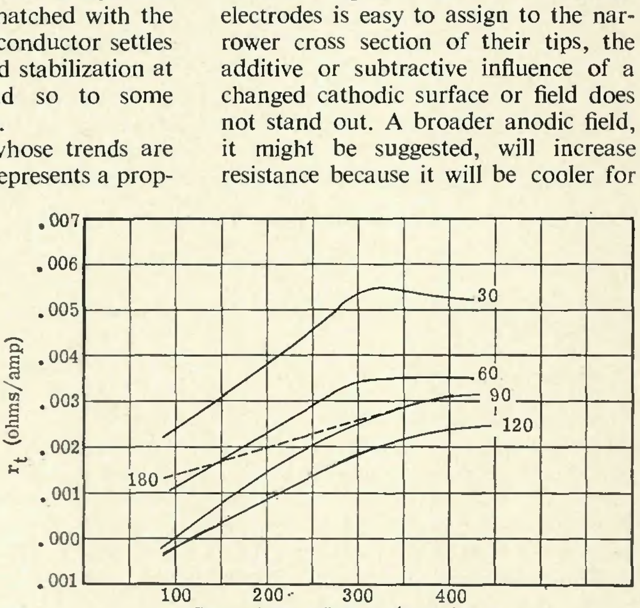


Fig. 11—The function of r_t increases in proportion to current Although it is higher for finer electrodes the increase slope is largely constant for all electrodes

lower current density, but a broader anodic surface will decrease in resistance because the current density will be down, lowering the temperature of the immediate metal subsurface. Then how does that net break down? If the two anode reactions could be isolated, would their net be rising or falling? Slight differences in the true slopes (C_3) might show the net because the anode-area to current ratio might be different for different electrodes.

The cathode is indeed the most interesting and vital sector of the whole system. Such a high density electron departure occurs on a tungsten electrode that thermionic emmission has long been recognized as not able to provide that quantity of electrons (at the most 10^4 amp/in.[2]). There is a plasma emmission concept which is associated with a contracted cathode spot and arc column (said to be able to account for emission up to 10^{-8} amp/in.[2]) and the field emmission concept (said to be able to account for emmission up to 10^{-9} amp/in.[2]).

Although the concept of an electron removing heat by its departure from the metal surface is thermodynamically sound, the accepted commentaries on work function and Fermi escape levels seem subordinate to larger effects. If the surface and field effects could be discerned in curves, such as Fig. 11, would the resistance of the emmission area of finer tips be lower or higher? The highly concentrated emmission area of the 120 deg cone (perhaps 150,000 amp/in.[2]) undoubtedly is being cooled by the high rate of electron departure (Savage[3] reports the 120 deg tip at 5300° F, the 60 deg tip at 5550° F).

It is imaginable at least that one physical distinction—electron mobility—between a conducting metal and a conducting gas diminishes as the temperature of the two rises. This could be resolved if the resistance of the 120 deg emmission interface would be found to be greater than the surface of the 30 deg tip interface. Hotter metal just back of the interface could give a greater resistance, and contaminate experimental data. An intensive analysis for the sub components of curves, such as those in Fig. 11, may suggest answers to these questions.

Conclusion

A paper such as this has several uses. To a welder or welding engineer it provides an improved sense of the reaction of his system to electrode, current, or voltage changes; to a welding researcher it provides a coherency and rationale to data and correlations that could not be explained; to a physicist it may clarify old data and exemplify some new approaches which permit the analysis of gross effects into their separate components.

The welding engineer should be conscious of the rise of potential drop in his system and in his electrode as current rises. The finer, 30 deg cone tip, electrodes may increase their potential drop at the rate of 4 v per 100 amp. They may demand as much as 8 v at 400 amp. In a constant potential system this is at the expense of the arc which may shorten to zero, or extinguish. The blunter, larger cone angle, electrodes are proportionately less demanding. The behavior and efficiency of each electrode should be respected as peculiar to that electrode. Transferability of weld parameters is first dependent on replication of electrode tops.

Most of the voltage and watt reaction can be appreciated by the construction of a curve like Fig. 1, for a particular conducting system including the electrode. The rise from minimum voltage in such a curve will provide an indication of heat lost to metal resistance. A short circuited set-up will identify the circuitry potential drop without the peculiar tip-plasma effects. The rise of voltage in the metal system back from the center of the electrode grip to the tip span makes no contribution to work heating and should be recognized as such.

For the sake of transferability of parameters, any two systems which give the same volt-amp characteristic with the same electrodes may be shown to enjoy the same weld parameters for the same work. The voltmeter used by a welder should be connected from head to ground since this is the voltage representing most nearly the condition of his arc. Certainly, the voltmeter on the source is not relevant since it responds to all the losses in the lines, connections, and tools. Constant potential servosystem taps should be connected here also. A few feet of separation of on the power loop of servosystem taps and voltmeter taps can have interesting results. If the servosystem taps are farther back from the head-work taps, copper losses will be added to electrode losses and the arc will be even more deprived in a constant potential system; also the changes will occur in time with the heating rate of the system. If the voltmeter is back of the servo taps by much, the arc position may be more nearly correct in fact but the voltmeter will report a droop in one to three minutes as the copper conductors heat. The system may be set to 12 v and the voltmeter will report 12 volts initially, but then droop to a lower value in the long run. The electrode, which is inside the taps, will take a larger fraction of volts as it heats in time—the more so with higher currents.

Tungsten extension (distance from grip to tip) will affect the arc voltage since the longer tungsten conductor will take a higher potential drop, and get hotter, at the expense of the true arc voltage and length. The higher the voltage drop in the electrode the shorter, and less voltage, will be the arc. This is extreme with fine tip electrodes or high currents. These things will be so although the head-work voltage reads the same.

When the system is cold, a power surge may be seen at arc initiation because the entire preset voltage is dropping at the arc. Within 0.5 to 2 seconds the electrode has heated, trimming the *IE* at the arc some; within 2 minutes most of the copper line has heated and the arc heat will be trimmed to the steady state of heat input that is expected for the long run. This phenomenon is not a fault of equipment design, although it may be designed out of the start sequence. That could be necessary in thin material welding.

Since the arc grows very short when the voltage is dropped in the electrode at high current, increased voltage could be appropriate since the arc itself is far from constant potential.

The welding researcher is interested in inventing, answering anomalies (beneficial or harmful), discovering or calculating best methods, isolating the causes of trouble and providing substantiated answers and advice to weld engineers. This paper has tried to some measure to do these things.

Much research on the arc characteristics has not considered even categorically the rise of resistance in the conductor and electrode section between instrument taps. The volt-ampere characteristic curve that falls to a minimum and then rises is the consequence of a falling resistance with increasing current. Total resistance is composed of a greatly dropping plasma resistance and a slowly rising electrode resistance. These resistances were separated here mathematically into the category that falls as a function of current (plasma) and one that rises with current (heating metal). In the end a formulation is the only way to make a pure separation.

There are large numbers of volt-ampere charactreistic curves reported in arc research. Those that only fall with increasing current have minimized the considered metal circuit rise. However, since instruments must be tapped at some point on the electrode, the metal or surface effects will always be incorporated into measured results. The arc effects may never be measured by themselves. If the mathematical method can be verified, the sources of heat can be identified, thus leading to a clearer understanding of the deployment of heat and efficiencies. The behavior of the arc stands out clearer when the influences of current on the electrode are separated. In a constant potential system the arc may actually decrease as a source of heat after a certain current value because of an increasing potential drop in the metal circuitry, but without loss of penetration since the I^2R heat from the shank and tip which are transported to the anode by hot electrons may be the major source of anode heating.

Weld heat cannot be said to be continuously related to current or reported watts (IE). The watts received by the anode per watt put in (according to head to work instruments) will vary according to the proportion of heat generated primarily in the electrode shank, tip, and arc. There may be four distinct efficiencies at different current levels between 100 and 600 amp. This recognition with a respect for arc

APPENDIX

The method by which the values of r_a and r_t were determined for the 30 deg electrode tip. (The 60, 90, 120 and 180 deg tip data were solved in the same manner)

$$\begin{array}{lllll}
a) & R_{\Sigma 100} = 100 r_t + \dfrac{r_a}{100} & = 188 \\
b) & R_{\Sigma 200} = 200 r_t + \dfrac{r_a}{200} & = 92 \\
c) & R_{\Sigma 300} = 300 r_t + \dfrac{r_a}{300} & = 73 \\
d & R_{\Sigma 400} = 400 r_t + \dfrac{r_a}{400} & = 64
\end{array}$$

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$$\begin{array}{ll}
a & r_a = 1(188)\,10^2 - r_t\,10^4 \\
b & r_a = 2(92)\,10^2 - 4r_t\,10^4 \\
c & r_a = 3(73)\,10^2 - 9r_t\,10^4 \\
d & r_a = 4(64)\,10^2 - 16r_t\,10^4
\end{array}$$

$$\begin{array}{l}
r_t = [1(188)\,10^{-2} - r_a\,10^{-4}]/1 \\
r_t = [2(92)\,10^{-2} - r_a\,10^{-4}]/4 \\
r_t = [3(73)\,10^{-2} - r_a\,10^{-4}]/9 \\
r_t = [4(64)\,10^{-2} - r_a\,10^{-4}]/16
\end{array}$$

$$\begin{array}{ll}
ab & (188)\,10^2 - r_t\,10^4 = (184)\,10^2 - 4r_t\,10^4 \\
ac & (188)\,10^2 - r_t\,10^4 = (219)\,10^2 - 9r_t\,10^4 \\
ad & (188)\,10^2 - r_t\,10^4 = (256)\,10^2 - 16r_t\,10^4 \\
bc & (184)\,10^2 - 4r_t\,10^4 = (219)\,10^2 - 9r_t\,10^4 \\
bd & (184)\,10^2 - 4r_t\,10^4 = (256)\,10^2 - 16r_t\,10^4 \\
cd & (219)\,10^2 - 9r_t\,10^4 = (256)\,10^2 - 16r_t\,10^4
\end{array}$$

$$\begin{array}{l}
4[(188)\,10^{-2} - r_a 10^{-4}] = [(184)\,10^{-2} - r_a 10^{-4}] \\
9[(188)\,10^{-2} - r_a 10^{-4}] = [(219)\,10^{-2} - r_a 10^{-4}] \\
16[(188)\,10^{-2} - r_a 10^{-4}] = [(256)\,10^{-2} - r_a 10^{-4}] \\
9[(184)\,10^{-2} - r_a 10^{-4}] = 4[(219)\,10^{-2} - r_a 10^{-4}] \\
16[(184)\,10^{-2} - r_a 10^{-4}] = 4[(256)\,10^{-2} - r_a 10^{-4}] \\
16[(219)\,10^{-2} - r_a 10^{-4}] = 4[(256)\,10^{-2} - r_a 10^{-4}]
\end{array}$$

$$\begin{array}{llll}
ab & 3r_t = (-4)\,10^{-2}, & r_t = & -1.3 \\
ac & 8r_t = (31)\,10^{-2}, & r_t = & 3.9 \\
ad & 15r_t = (68)\,10^{-2}, & r_t = & 4.5 \\
bc & 5r_t = (35)\,10^{-2}, & r_t = & 7.0 \\
bd & 12r_t = (72)\,10^{-2}, & r_t = & 6.0 \\
cd & 7r_t = (37)\,10^{-2}, & r_t = & 5.3
\end{array}$$

$$\begin{array}{l}
8r_a\,10^{-2} = [(752) - (184)] = 568, \quad r_a = 189\cdot 10^2 \\
8r_a\,10^{-2} = [(1692) - (219)] = 1473, \quad r_a = 184\cdot 10^2 \\
15r_a\,10^{-2} = [(3008) - (256)] = 2752, \quad r_a = 183\cdot 10^2 \\
5r_a\,10^{-2} = [(1656) - (876)] = 780, \quad r_a = 156\cdot 10^2 \\
12r_a\,10^{-2} = [(2944) - (1024)] = 1920, \quad r_a = 160\cdot 10^2 \\
7r_a\,10^{-2} = [(3504) - (2304)] = 1200, \quad r_a = 171\cdot 10^2
\end{array}$$

$$\begin{array}{llll}
r_{t\,a} = & \text{average of} & ab, ac, ad & = 2.4\cdot 10^{-2} \\
r_{t\,b} = & \text{"} & ba, bc, bd & = 3.9\cdot 10^{-2} \\
r_{t\,c} = & \text{"} & ca, cb, cd & = 5.4\cdot 10^{-2} \\
r_{t\,d} = & \text{"} & da, db, dc & = 5.3\cdot 10^{-2}
\end{array}$$

$$\begin{array}{llll}
r_{a\,a} = & \text{average of} & ab, ac, ad & = 185.3\cdot 10^{2} \\
r_{a\,b} = & \text{"} & ba, bc, bd & = 168\cdot 10^{2} \\
r_{a\,c} = & \text{"} & ca, cb, cd & = 170\cdot 10^{2} \\
r_{a\,d} = & \text{"} & da, db, dc & = 171\cdot 10^{2}
\end{array}$$

$$\begin{array}{ll}
a & 100(2.4)\,10^{-2} + (185.3)\cdot 10^2/100 = R_{\Sigma 100} = 187.7 \\
b & 200(3.9)\,10^{-2} + (168)\cdot 10^2/200 = R_{\Sigma 200} = 91.8 \\
c & 300(5.4)\,10^{-2} + (170)\cdot 10^2/300 = R_{\Sigma 300} = 72.9 \\
d & 400(5.3)\,10^{-2} + (171)\cdot 10^2/400 = R_{\Sigma 400} = 64.0
\end{array}$$

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length and tip position will be found to be vital to a programmed penetration control system.

Some of the considerations may point the way toward improved parameter combinations in pulsed gas tungsten-arc welding, where electrode heating, when it is the prime source of directed heat, does not rise instantaneously but lags the current pulse.

It is clear that generalities about electrode or arc behaviors cannot be made without identification of the electrode shape and background resistances. Transferability of weld parameters from machine to machine in a plant or between plants for a given job has met with problems and scattered results. This has been discouraging since a volt or an ampere should be a fixed quantity anywhere. The position of the instrumentation taps, the resistance drops in the power loop between the instrumentation taps, and the reaction of the resistance to current and time are vital standards for this purpose. The work completed herein has been exploratory. The accuracy of absolute numbers could not be a prime goal of this study. However, the examples, the comparisons, the several cause and effect trends are expected to survive the results of carefully controlled specialized experiments. Some of what is conjecture or spuculation can be measured by specific tests.

The influence of electrode shape on the cathode emmission surface, the arc and the anode, surface is so significant that those experiments which have failed to specify electrode shape, the length to holder, the cold and hot resistance, or the time of data taking, can only report varieties of trends. In some experiments the failure to recognize resistive heating of the cathode has confounded conclusions. Yet it may be of advantage to the serious scientist to exploit the difference in electrode shapes to isolate the behavior of those sub-systems that ate of so much interest to physicists and welding researches, or to exploit the difference in results given from a cold electrode or a hot electrode, or the resistance rise-rate of various electrode systems.

The resistive components that react negatively to current increase, give a function which drops to a level at 200 amp and is nearly constant through higher currents. The difference in levels for different electrodes and the sublte tendencies with increasing current may contain clues that expose more laws governing cathode emission or the arc.

The resistive components which rise with current give a function r_t which rises at a constant rate with current. The finer electrodes start and remain higher than the blunter. Each of these functions may be further analyzed and tested for their representation of real sites of physical events and for their own several components that tell separate stories.

References

1. Canulette, W. N., "Effect of Tungsten Tip Shape on Welding Parameters and Fusion Patterns," talk presented at AWS National Fall Meeting, San Francisco, 1964.
2. Savage, W. F., Strunck, S. S., and Ishikawa, Y., "The Effect of Electrode Geometry in Gas Tungsten-Arc Welding," WELDING JOURNAL, 44 (11), Research Suppl., 489-s to 496-s (1965).
3. Christensen, N. Davies, V. del., Gjermundsen, "Distribution of Temperatures in Arc Welding," *British Welding Journal*, 12 (2), 54-74 (1965).
4. Chihoski, R. A., "The Effects of Varying Electrode Shape on Arc, Operations, and Qualities of Welds in 2014-T6 Aluminum," WELDING JOURNAL, 47 (5), Research Suppl., 210-s to 223-s (1968).
5. Milner, D. R., Salter, G. R., and Wilkinson, J. B., "Arc Characteristic and Their Significance in Welding," *British Welding Journal*, Vol 7 (2), February 1969, 74-88 (1968).
6. Morris, A. D., and Gore, W. C., "Analysis of the Direct Current Arc," WELDING JOURNAL, 35 (3), Research Supplement, 153-s to 160-s (1956).
7. Skolnik, M., and Jones, T. B., "High Current Tungsten Arc in Argon, Helium and Their Mixtures," WELDING JOURNAL, 32 (1), Research Suppl., 55-s to 64-s (1953).
8. Lancaster, J. F., "Energy Distribution in Argon Shielded Welding Arcs, *British Welding Journal*, 1 (9), 412-426 (1953).
9. Wilkinson, J. B., Milner, D. R., "Heat Transfer from Arcs," *British Welding Journal*, Vol 7 (2), 115-125, (1960).
10. Spraragen, W., and Lengyel, B. A., "Physics of the Arc and the Transfer of Metal in Arc Welding," WELDING JOURNAL, 22 (1), Research Suppl., 2-s to 43-s (1943).

Technical Note

(*Continued from page* 60-s)

Test Results

Table 1 lists the stress waves that were recorded over a period of approximately 87 hr of continuous monitoring. Note that count rate (highest sensitivity seting) recorded the first burst of stress waves 9 minutes after activating the counter system. Note also that the greatest stress-wave activity occurred in the first seven hours (cumulative count of 7078). In the next 24-hour period, the cumulative count increased by only 29, and in the following 24-hour period, the cumulative count increased by only 1. There were no stress waves recorded in the 3rd 24-hr period. Thus, for all practical purposes, the cracking occurred in the first 24 hr after welding was completed.

Discussion of Results

The weldment for this test was designed to crack. The square butt joint involved incomplete penetration, and the initial fusion passes were small and cracked before the filler passes were deposited. Thus, the cracking that occurred during welding may have resulted in some degree of stress relief and thereby shortened the period of delayed cracking. Therefore, a quantitative measurement of the duration of delayed cracking will require monitoring restrained joints that are representative of shipyard practice and free of hot cracking.

References

1. Hartbower, C. E., Gerberich, W. W., and Crimmins, P. P., "Monitoring Subcritical Crack Growth by an Acoustic Technique," *Weld Imperfections*, Proceedings of a Symposium at Lockheed Palo Alto Research Laboratory, Calif., Sept. 19-21, 1966, pp. 371-389, Addison-Wesley, Reading, Mass.
2. Hartbower, C. E., Gerberich, W. W., and Crimmins P. P., "Monitoring Subcritical Crack Growth by Detection of Elastic Stress Waves," WELDING JOURNAL, 47(1), Research Suppl., 1-s to 18-s (1968).
3. Dunegan, H. L., Harris, D. O., and Tatro, C. A., "Fracture Analysis by Use of Acoustic Emission," *Eng'r'g Fracture Mechanics*, Vol. 1, pp. 105-122, June 1968.
4. Hartbower, C. E., Gerberich, W. W., and Liebowitz, H., "Investigations of Crack-Growth Stress-Wave Relationships," *Ibid.*, pp. 291-308, Aug. 1968.
5. Gerberich, W. W., Hartbower, C. E., and Crimmins, P. P., 'Spontaneous Strain Aging as a Mechanism of Slow Crack Growth," WELDING JOURNAL, 47(10), Research Suppl., 433-s to 443-s (1968).
6. Green, A. T., "Detection of Incipient Failures in Pressure Vessels by Stress-Wave Emissions," *Nuclear Safety*, Vol. 10(1), Jan-Feb, 1969.
7. Jolly, W. D., "Acoustic Emission Exposes Cracks During Welding," WELDING JOURNAL, 48(1), 21 to 27 (1969).