Fundamental Processes of the Short Arc

With Applications to Contact Erosion and Percussion Welding

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The short arc develops an instability when certain critical conditions of power input to the arc are not satisfied. In this unstable condition the arc is momentarily extinguished, a molten filament of metal is drawn between the electrodes and this may permanently bridge the electrodes. Semi-empirical expressions have been derived which predict at what time in the life of an arc it becomes unstable.

These expressions give a simple explanation of some of the erosion characteristics of relay contacts. In addition, the analysis is useful in determining the optimum current waveform for percussion welding, where a stable arc is desirable.

I. INTRODUCTION

When charged electrodes are brought together, an electric arc is formed before they touch. For potentials below about 300 volts, the arc is both initiated and maintained by field emission currents. The initiation and sustaining mechanisms are quite well understood and have been treated in considerable detail in papers by L. H. Germer and his co-workers.

Recently Germer and Boyle[1] have presented experimental evidence that two distinct types of short arcs exist. One of them, called the cathode arc, obtains the predominant supply of ions necessary to maintain an arc by continuously exploding small points on the cathode surface. This type of arc does not weld the electrodes together and will not be treated in this paper. The second type of arc, which derives its ions from metal vaporized from the anode by electron bombardment, is appropriately called an anode arc. If sufficient energy is supplied to this arc, the electrodes will be welded together. We have obtained experimental information which clarifies the physical processes that give rise

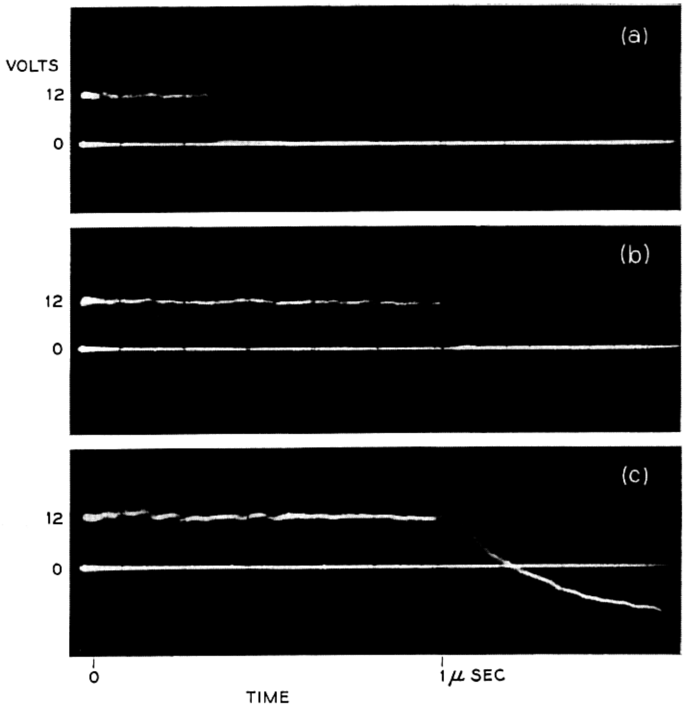

Fig. 1 — Oscilloscopic records of the potential across a constant-current arc: (a) electrodes welded at 0.35 microsecond, *before* complete discharge of the source of energy; (b) electrodes welded at 1 microsecond, just as the available energy was exhausted; (c) electrodes not welded.

to electrode welding and have developed a theory which enables one to predict under what conditions welding will take place. This information proves to be useful either for predicting the erosion of relay contacts in terms of the associated circuit parameters or, conversely, for designing the optimum circuit for percussion welding.

To illustrate what is meant by a weld in the present context, Fig. 1 shows three oscillograms of the potential across a pair of approaching gold electrodes as a function of time after the initiation of an arc. The electrodes were connected to 400 feet of RG58U transmission line charged to 200 volts. The transmission line supplied approximately 2 amperes of constant current to the arc for a duration of 1 microsecond. Each oscillogram shows a plateau voltage of approximately 12 volts, which is characteristic of a short arc between gold electrodes. The instant when closure (or welding) of the electrodes took place is indicated by a sudden change of potential reducing the voltage across the contacts to zero.

In the uppermost oscillogram, closure occurred before the transmission line was completely discharged; i.e., the electrodes were welded. In the middle oscillogram, a weld occurred at the instant the line was completely discharged. In the lower oscillogram, there was no weld, the contacts closing sometime after the line was completely discharged. Closures of the type illustrated by the upper and middle oscillograms predominate for anode arcs. Furthermore, if the power input to the arc is large and of short duration, such as a discharge of a transmission line or an *LC* circuit, the majority of the closures will take place at the end of the discharge period. This is shown quite clearly in Fig. 2, which was obtained by replotting the data from Fig. 7 of an earlier paper by Germer and Smith.[2] An explanation for this preference to weld just as the circuit is completely discharged will now be given.

II. WELDING MECHANISM OF THE ANODE ARC

The initiation process for short arcs must differ from that of the usual breakdown process in air, since arcs can be initiated between electrodes with a potential difference considerably below the "minimum" sparking potential. To initiate this arc, an electric field is required of the order of 10^7 volts per cm, which has suggested a field emission process for obtaining the initial electrons. Kisliuk[3] has developed a model which shows that field emission currents can both initiate and maintain the short arc.

Because of the small electrode gap (~1000 Å), most of the initial electrons cross without collision, dissipating their energy on the anode surface. This raises a small spot on the anode surface to the boiling point.

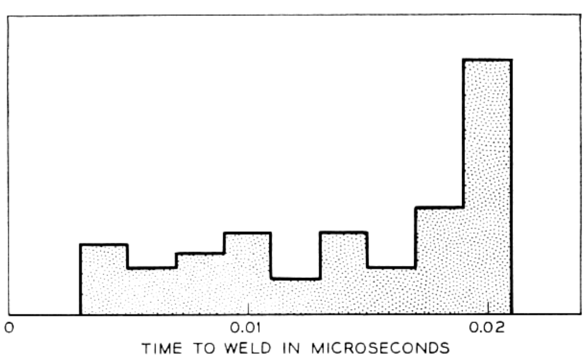

Fig. 2 — Statistical distribution of observed closure times at the discharge of an *LC* circuit having a discharge time of 0.02 microsecond ($L = 0.10\ \mu h$, $C = 400\ \mu\mu f$).

creating a vapor that, when ionized, supplies the arc with ions. The ions form a space charge in front of the cathode. This produces a sufficiently large field to maintain by field emission the high current densities ($>3 \times 10^7$ amps/cm^2) necessary for the arc. Kisliuk has shown that this type of arc is very efficient in its use of ions to produce electrons and that more than 90 per cent of the current is carried by electrons. Since many of these electrons cross the gap without collision, a large portion of the total arc energy is dissipated on the anode by electron bombardment. Some of this energy is carried away by conduction, and the rest melts and vaporizes metal. During the arc, there is therefore a molten pool of metal on the anode.

The ionic space charge in front of the cathode increases the field at the cathode and lowers the field at the anode. A simple sketch of the potential distribution in the arc is shown by curve A in Fig. 3. With the low electrostatic field at the anode during the arc, the molten pool of metal remains intact — at least there are no large forces tending to pull it towards the cathode. When the arc is extinguished, there is a redistribution of the potential between the electrodes, with the potential attempting to approach that of curve B of Fig. 3. With this redistribution, there is an increase in the electric field at the anode, tending to pull a filament of the molten pool of metal across the gap, thus welding the electrodes.

When the power input to the arc is too low to vaporize sufficient metal to maintain the required number of ions, the arc will be extinguished. Boyle and Germer[4] have shown that the power needed to main-

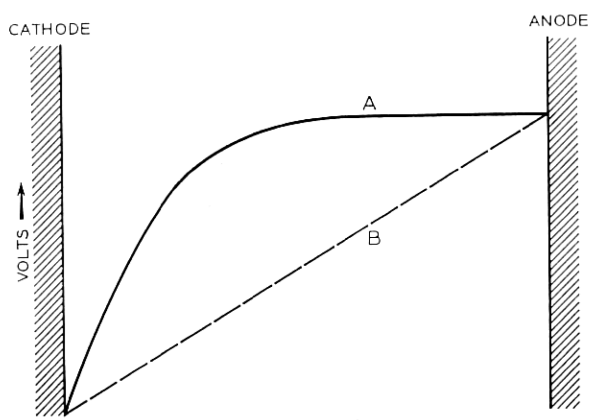

Fig. 3 — Potential distribution between electrodes: A — during arc; B — after end of arc.

tain the arc increases with the total energy which has been delivered to the arc. In a low-energy, high-power circuit, the arc will be extinguished when the supply of energy is completely exhausted. In higher-energy circuits the arc may be extinguished considerably before this point is reached and, because of the welding phenomenon, the remainder of the energy will be dissipated in the resistance of the circuit.

Fig. 4 is a photomicrograph of a single pit produced on the anode of a gold electrode by a discharge of a constant-current 3-ampere source for 0.3 microsecond. The shape of the pit is approximately that of a half hemisphere although the depth is usually less than that of the radius. Germer and Haworth[5] have shown that the diameter of the pit varies as the cube root of the energy.

Since the power lost in conduction increases with the diameter, one expects that, for a given power input, the arc will grow to some maximum diameter at which time the power available for evaporation of metal will be insufficient to produce the number of ions needed to maintain the arc. This is indeed the case, and Boyle and Germer have shown that the maximum pit diameter is quite sensitive to the input power.

The clearest demonstration of the nature of the welding process comes from a study of the welding characteristics of a constant-current circuit.

Fig. 4 — Pit made on the anode by a single arc of the anode type.

TABLE I — WELDING TIMES WITH SHORT CABLES

Trial	Time to Weld/Maximum Time of Cable Discharge, for Cable Length of		
	10 ft.	50 ft.	150 ft.
1	1.0	1.0	0.9
2	1.0	1.0	0.9
3	1.0	1.0	1.0
4	1.0	1.0	1.0
5	open	0.9	0.9
6	1.0	1.0	0.8
7	1.0	1.0	0.9
8	1.0	0.9	0.8
9	1.0	1.0	1.0
10	1.0	1.0	1.0

If various lengths of transmission line are discharged through a pair of electrodes in a short arc, it is found, as remarked earlier, that, for the short lengths of cable, there is a great tendency for the weld to occur at a time when the cable has just been completely discharged. In other words, the weld occurs under those conditions when the arc has just been terminated by the discharge of the circuit, in agreement with the idea that the gap is bridged when the field is redistributed.

By way of further illustration of the fact that, for short discharge times, the weld always occurs when the circuit is discharged, some data on welding times for polished palladium electrodes are presented in Table I. These data were obtained by discharging various short lengths of 50-ohm cable charged to 50 volts. Experimental details are given as a footnote in Ref. 1, p. 33.

From this it is quite clear that, even though 10 feet of cable provides enough energy to weld the electrodes, in many cases the arc lasted for the full period of the 150-foot cable, with the dissipation of 15 times as much energy.

With longer cables or in an RC circuit, the weld will occur before the arc has been terminated by the external circuit. Once again this is due to the fact that the arc goes out. In these cases, the extinction of the arc is due to an instability in the arc itself; i.e., the pit diameter grows too large to be maintained by the available power. To establish this point, we shall give the appropriate calculations for the times of extinction of an arc carrying a steady or exponentially decaying current. Then it will be shown that these times agree well with experimentally observed welding times.

To make the calculations we start with the empirical expression $d = AE^{1/3}$, where d is the diameter of the anode hot spot, E the total arc energy and A a proportionality constant determined experimentally in Ref. 4 for gold electrodes. The conduction loss from the anode is $P_c = 2\,KdT_B$, where K is the thermal conductivity of the electrodes (at a temperature approximately midway between the boiling temperature T_B and room temperature). The power input to the anode, P_i, is approximately, Iv, where I is the arc current and v is the arc voltage. (Actually, P_i is somewhat less than this, since some energy is delivered to the cathode.) Eliminating d from these two expressions and using $P_i > P_c$ for our condition of stability, we obtain

$$I > GE^{1/3}, \tag{1}$$

with $G = 2\,KT_B\,A/v$, which is a semi-empirical constant to be evaluated. The arc is extinguished when the condition of (1) is no longer satisfied.

In a constant-current circuit $E = I\tau v$, where τ is the time to extinction of the arc, and is therefore given by

$$\tau = I^2/G^3 v. \tag{2}$$

In an RC circuit with $I = I_0 \exp(-t/RC)$ the criterion for stability is

$$I > G\left(\int_0^t Iv\,dt\right)^{1/3}$$

and the time to extinction τ is a solution of the equation

$$\exp(3\tau/RC) - \exp(2\tau/RC) = (V_0 - v)^2/G^3R^3Cv, \tag{3}$$

where V_0 is the initial potential difference across the capacitor C.

To demonstrate the validity of the above analysis, we shall consider separately below a series of experiments with long cables and with various RC circuits.

All of the measurements were made with a pair of gold electrodes mounted on a standard telephone relay. The welding time was measured visually on an oscilloscope (see Fig. 1) and each measurement presented in Tables II and III represents the average of some 50 observations. The precision of the average welding time τ is not great — not because of any instrumental error, but because of slow variations of τ over many operations, presumably because of uncontrolled changes in the surface condition of the electrodes.

In Table II, where the results of the experiments on long cables are summarized, V is the voltage on the cable; Z is the effective cable impedance, including the termination, which was chosen so that the cable was matched at the electrode end; τ is the observed average welding

TABLE II — WELDING TIMES WITH LONG CABLES

V, volts	Z, ohms	I, amp	τ, μsec	E, ergs	I^2/τ, amp²/sec
250	100	2.4	1.95	560	2.9×10^6
200	100	1.9	1.29	290	2.7×10^6
170	100	1.6	1.15	220	2.2×10^6
140	100	1.3	0.80	120	2.1×10^6
121	186	0.59	0.12	8.5	2.9×10^6
100	100	0.88	0.25	27	3.2×10^6

time; and E is the total arc energy $Iv\tau$, with $v = 12$ volts appropriate for gold. The last column gives the quotient I^2/τ, which, according to (2), should be constant. In all cases the discharge time of the cable was much longer than the average welding time.

The average of the I^2/τ values is 2.7×10^6, and there is a maximum deviation of 23 per cent about this mean. It should be noted that the energy to weld over this same range varied by a factor of 64. From (2), we determine $G = 61$.

In Table III are given the results of welding experiments using an RC network in place of the transmission cable, and a capacitor potential of 170 volts. Results are given for various combinations of three values of R and four values of C. These data can be used to test (3) by plotting $\exp(3\tau/RC) - \exp(2\tau/RC)$ against $1/R^3C$. Such a plot on logarithmic scales is given in Fig. 5. The line is drawn as the best fit of the points by a straight line of unit slope. Although the deviation of some of the points from the line is quite large, in no case is this an indication of more than 30 per cent error in the predicted value of τ. The value of G obtained from the line is 41.

It is apparent that (2) and (3) agree well with the experimental re-

TABLE III — WELDING TIMES WITH AN RC NETWORK

C, μf	R, ohms	τ, μsec	E, ergs
0.03	21	1.3	495
0.03	51	1.1	290
0.03	121	0.7	99
0.09	21	2.4	1230
0.09	51	2.6	742
0.09	121	1.1	171
0.3	21	4.7	2550
0.2	51	2.9	937
0.2	121	2.3	340
0.5	21	8.2	5120
0.5	51	3.3	1170
0.5	121	2.6	407

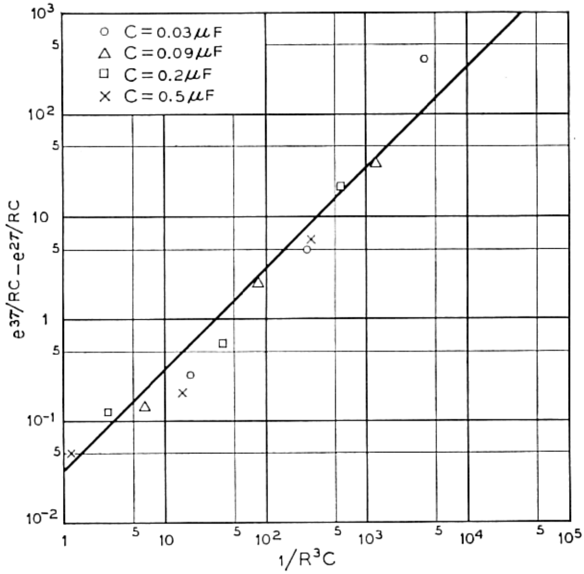

Fig. 5 — Plot of experimental values of welding time τ for gold electrodes and various RC circuits, affording confirmation of (3) (V = 170 volts, v = 12 volts).

sults. It remains now to compare the values of the factor G obtained experimentally with its computed value, $G = 2\ KT_B\ A/v$.

From Ref. 4 we may obtain $A = 0.05$ cm/joule$^{1/3}$ for gold. Combining this with $K = 2.9$ watts/cm°C, $T_B = 2600$°C and $v = 12$ volts, we obtain $G = 62$. This is to be compared with $G = 41$ obtained from arcs on the discharge of RC circuits, and with $G = 61$ obtained from the experiments with long cables.

All the evidence supports the theory for the welding time which has just been presented. The agreement is better than one might expect, considering that all the experiments were performed with rough electrodes and that the theory does not take this into account. In addition, we have used the empirical expression $d = AE^{1/3}$ for the arc diameter, and certainly this must hold only for short-duration arcs for which conduction losses are inappreciable.

III. APPLICATIONS

3.1 *Contact Erosion*

In early work on the erosion of relay contacts on closure, it was observed that the volume of metal transferred per unit of available arc energy was constant. These experiments were carried out by discharging a small capacitor, which was connected to the contacts by short lead wires. When resistance was inserted between the contacts and the capacitor, the results were not so simple. Fig. 6 is a reproduction of a curve from Fig. 4 of Ref. 5, and shows clearly the effect of introducing the resistance in series with the capacitor. The previous explanation ascribed the reduction in erosion to a reduced circuit current. This is substantially correct; what we are concerned with here is deducing why the reduction in circuit current is of importance.

In a previous section it was shown that the contacts weld together at the end of the arc, the end being brought about by the power input becoming too low to maintain the necessary supply of ions. Once the weld occurs, the remainder of the source energy is dissipated in the resistance of the circuit and does not result in further damage to the electrodes.

The analysis given earlier for the time to weld in a constant current circuit, or an RC circuit, can be applied directly to the case of contact erosion if it is assumed that the erosion is proportional to the energy dissipated in the arc. For the short arc, the potential across the arc remains constant and the dissipated energy is simply $E = Qv$, where Q is the charge passed through the arc and v the arc voltage.

In an RC discharge the maximum energy which can be dissipated in the arc is $E_0 = C(V_0 - v)v$. The actual energy dissipated, because of

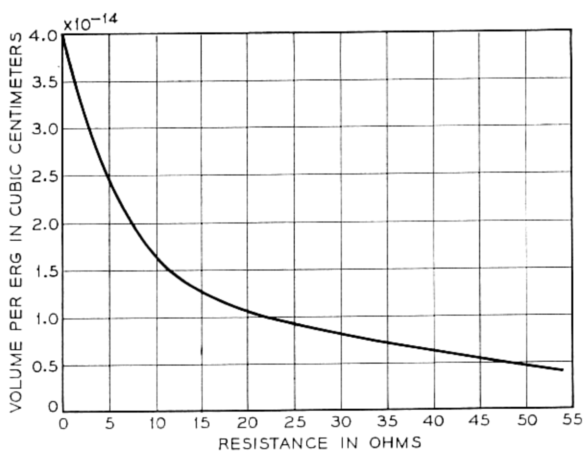

Fig. 6 — Metal transferred at the discharge of a capacitor, as a function of circuit resistance.

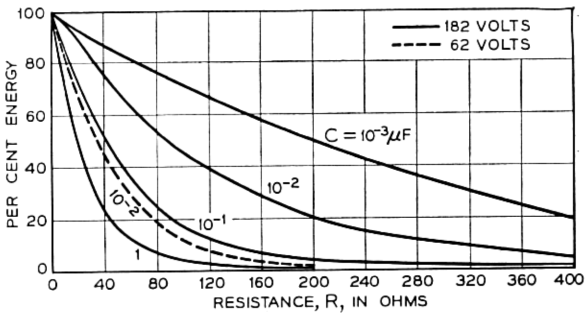

Fig. 7 — Arc energy E in various RC circuits, for gold electrodes.

early extinction, is only $E = C(V_0 - v)v\,[1 - \exp(-\tau/RC)]$. By eliminating τ between this expression and (3) we obtain,

$$(E/E_0)/(1 - E/E_0)^3 = (V_0 - v)^2/G^3R^3Cv. \qquad (4)$$

For the transmission line case, the corresponding formula is

$$E/E_0 = I^2/G^3\,Tv, \qquad (5)$$

where T is the discharge time of the line. Curves calculated from (4) for gold are plotted in Fig. 7.

Recently Germer has published erosion measurements for silver electrodes that discharged either a capacitor through a resistor or a transmission line.[6] Some of these measurements (Fig. 6 of Ref. 7) are reproduced here as Fig. 8 and serve as further confirmation of the above theory. The plotted points represent measurements and the heavy line the predicted behavior from (4) and (5). The agreement is better than the theory warrants, since the theoretical curves depend quite strongly on some parameters, such as the thermal conductivity at high temperatures, which are not precisely known.

The most interesting region of the erosion curves is near 1 ampere, where the erosion decreases rapidly to zero. Such a region is common, and the magnitude of the current at which it occurs is known as the minimum arc current. The theory presented here predicts the erosion behavior in this region, and that the minimum arc current is not a fixed value but depends upon the energy already dissipated in the arc. In the next section on percussion welding it will be shown that, for large dissipated energies, the arc may fail at currents as large as several hundred amperes. The minimum arc current is a property of both the contact materials and also of the circuit parameters.

The strong impression of a constant minimum arc current in the past is largely because the total energy which will be dissipated in the contacts is very strongly dependent on the circuit current.* For instance, from (5) for a constant-current circuit, the energy dissipated at the contacts is $E = (I/G)^3$. This same relationship holds for an RC circuit if C and R are quite large, since this circuit then approaches a constant-current circuit. Now, for a particular relay contact application, there is a rather narrow range of energies which, if dissipated per operation, will be just tolerable. Energies greatly above this value will lead to too short a contact life, whereas energies greatly below this value will appear to give negligible contact erosion.

3.2 *Percussion Welding*

In percussion welding the surfaces to be joined are melted by an arc discharging a large capacitor, and they are then brought together before they have solidified. After contact, the molten zone solidifies and the weld is complete.[7]

In the previous sections of this paper we have discussed a welding phenomenon which takes place when the arc is extinguished. This weld is caused by molten metal bridging the gap and solidifying, creating a weld of small cross sectional area. One would expect this weld to be weak, and this has been verified by unpublished work of P. Kisliuk and J.

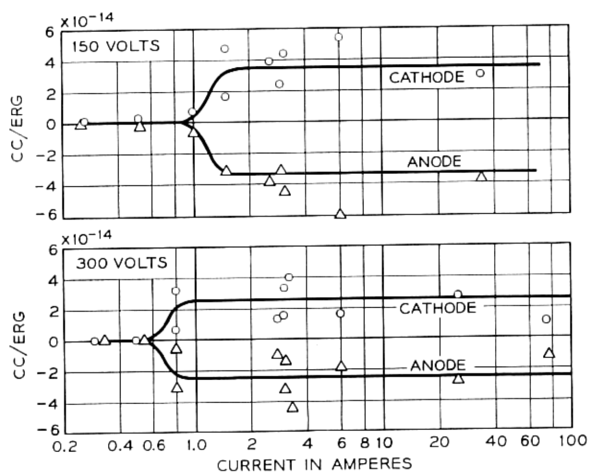

Fig. 8 — Calculated erosion per unit of available energy as a function of current (solid lines) and comparison with experimental values.

* As pointed out earlier in this paper, all these considerations apply only to "clean" electrodes, where anode arcs predominate.

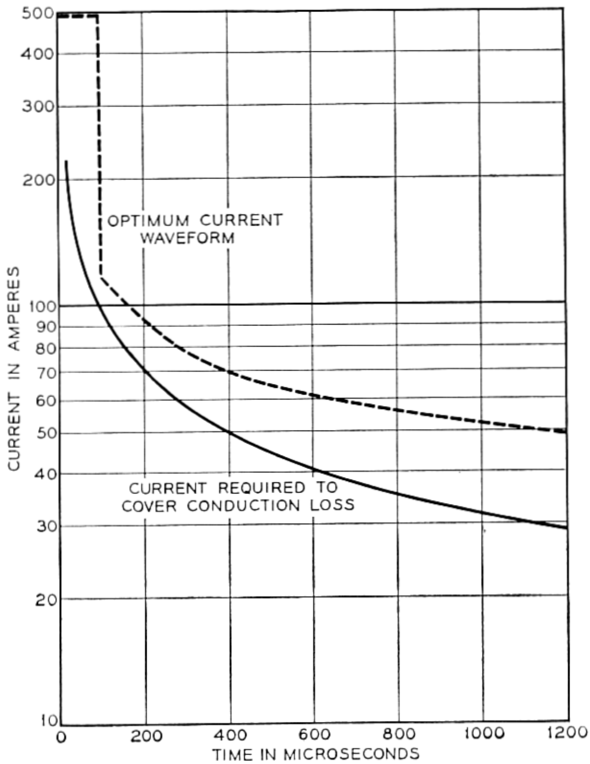

Fig. 9 — Calculated current required for percussion welding a 0.05 cm diameter copper wire to a copper plate.

Ammons. A much larger area and consequently stronger weld is obtained if the surfaces are held at the melting point until mechanical closure of the electrodes takes place. It is easy to show that the expected solidification time of the molten film is so short that this condition requires the arc to be maintained until the time of mechanical closure. It is required also that the arc power at all times exceed the rate of loss of energy by thermal conduction.

For calculating the conduction losses, the model is necessarily different from that used for the conduction-loss calculations made earlier. Let us consider the particular case of joining the end of a cylindrical wire to a flat surface. For welding, it is desirable to have the entire end of the wire held above the melting point, but in a short arc the surface will, in fact, be held more nearly at the boiling point. Radiation losses from the wire are negligible, so that, at least for a model of a right circular cylinder opposed to a thick plate, we have one-dimensional heat flow. The power loss by thermal conduction is $P_t = KT_B\, a/\pi kt$, where K is the thermal conductivity, a is the area of the electrode, k is the diffusivity, and t is the time.

For the long-duration arcs ($\sim 10^{-4}$ sec) with which we are concerned here, the power input is divided between the two electrodes. Assuming the division to be even, the power delivered by the arc to each electrode is $Iv/2$. The current needed to supply power equal to the conduction loss is then

$$I = 2\, KT_B\, a/\pi ktv. \tag{6}$$

Fig. 9 is a plot of I versus t from this equation, for a copper electrode of 0.05-cm diameter. For a satisfactory weld the current should exceed by only a small factor that needed to supply the energy lost by conduction for the entire time of the arc.

In Fig. 10 are shown oscilloscope traces of the currents for three test welds, with different values of the current waveform obtained in each case from an RC circuit in parallel with a simulated transmission line.

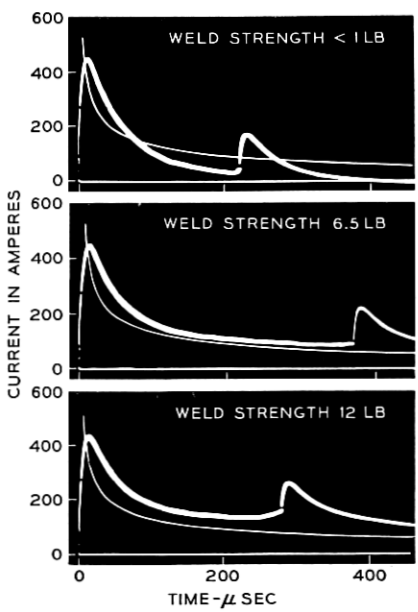

Fig. 10 — Oscilloscope traces of current for three experimental welds, with calculated values of the current required for a sound weld plotted upon each trace and strengths of the welds found in destructive tests.

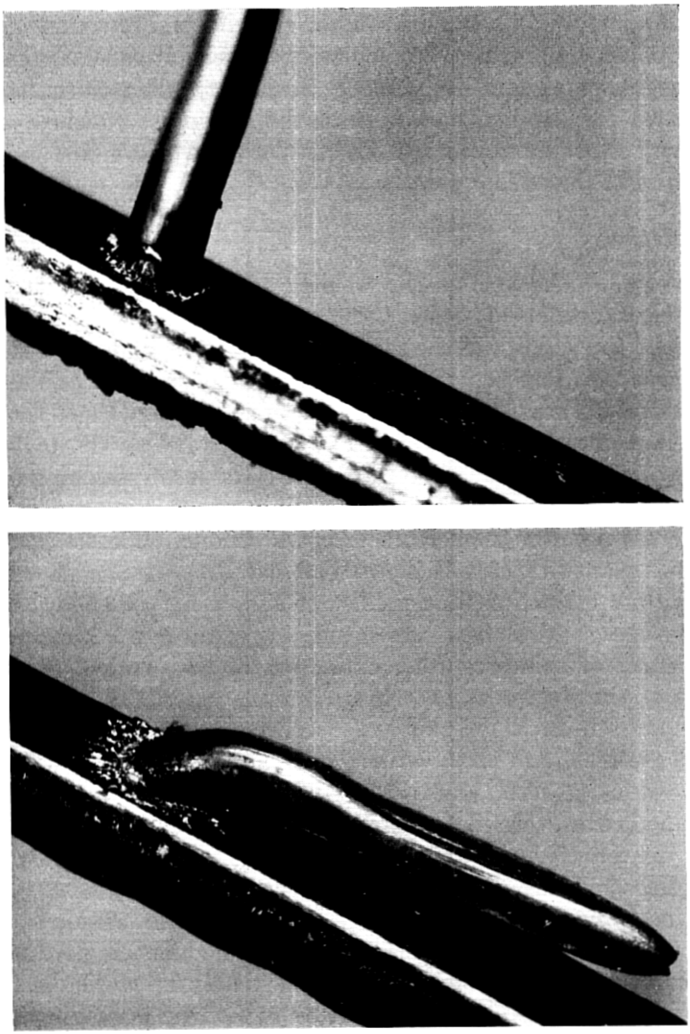

Fig. 11 — Photographs of sound welds, as made (top) and after a destructive test in which the wire broke (bottom).

The second peak on each trace is the sudden increase of current just as the contacts touch. Superposed on each trace is the calculated curve representing the current required to maintain the end of the wire at the boiling point. For each weld the breaking strength was measured by holding the large block fixed (Fig. 11) and pulling the wire with a force parallel to the surface of the block. The breaking strength of the wire was approximately 12 pounds. From the experimental breaking strengths written down underneath the oscilloscope traces, it can be noted that the strength was that of the wire only in the case where the current was maintained for the entire time until the electrodes touched, and at values well above those which, from calculation, would maintain the end of the wire at the boiling point.

IV. CONCLUSION

A theory which explains the welding phenomenon associated with short arcs of the anode type has been presented, along with experimental evidence of the validity of the theory. The theory is based on the simple assumption that a molten pool of metal remains on the anode until the arc is extinguished. At the instant the arc is extinguished, the redistribution of the electric field creates a force at the anode, pulling the molten metal from the anode towards the cathode and bridging the gap.

Extinction of the arc is due to insufficient power being supplied from the external circuitry to overcome thermal conduction losses away from the growing anode pit. It is shown that excellent agreement exists between an arc extinction time predicated simply on the conduction loss basis and measured times at which bridging of the gap takes place.

The effect of this premature extinction of the arc and subsequent welding of the electrodes on the erosion characteristics has been predicted for both an *RC* circuit and a constant-current circuit, and excellent agreement has been obtained with Germer's published measurements.

For anode arcs, this effect determines the minimum arc current. The theory yields a minimum arc current for gold electrodes near 0.5 ampere, for circuits which are in common use in the telephone plant.

The theory has been used also to calculate the optimum current waveform for percussion welding, where it is of fundamental importance that the electrode be maintained molten immediately up until the time of mechanical closure. Welding experiments to test the theory have shown the quality of the weld to be in excellent agreement with predictions made from the current waveform.

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