FURTHER STUDIES OF ELECTRODE PHENOMENA IN TRANSIENT ARCS

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[*Manuscript received November* 13, 1952]

Summary

High current transient arcs in air at atmospheric pressure display radial contraction of the column near the anode. An examination of melting in the anode allows calculation of the anode spot temperature.

I. Introduction

It has been known for some time that the arc discharge column contracts radially near the *cathode* to give rise to very high current densities at that electrode (Cobine and Gallagher 1948; Froome 1948, 1949, 1950; Somerville and Blevin 1949). The phenomenon has usually been studied by photographing the luminous discharge and by examination of signs of melting and tarnishing left on the electrode by the discharge.

Both of these techniques have been employed by the author to study the behaviour of arcs at the *anode*. The discharges examined had durations varying from 1 μsec. to 1 msec., and were struck between metallic electrodes in air at atmospheric pressure by moving the electrodes together till sparking occurred. High constant current pulses were obtained by discharging artificial lines. The instantaneous potential across the gap was of the order of 30 V., showing that the discharge was an arc.

II. Contraction of Arcs at the Anode

Plate 1, Figure 1, is a photograph of a 200 μsec., 50 A. arc between a copper wire cathode (top) and a polished plane aluminium anode. The photograph was taken obliquely with the shutter held open throughout the duration of the arc. Considerable radial contraction of the discharge is seen to have occurred near the anode, and a highly luminous and circular " anode spot " is apparent. A Kerr cell shutter has been used to show that such a spot is established within the first few microseconds of the life of the arc, and does not alter significantly with time (Somerville, Blevin, and Fletcher 1952). Photographs similar to Plate 1, Figure 1, have been obtained for the low melting point metals tin and lead.

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Plate 1, Figure 2, is a photograph of a similar arc struck on a silver anode, and the absence of any anode spot is typical of the higher melting point metals. Contraction of the discharge at the anode is still apparent, however. The lower half of the photograph shows the reflection of the discharge in the anode. Measurement of the cross section of the discharge at the anode for different metals shows that the current density there may be as great as 50,000 A./cm.^{2}.

III. Temperature of the Anode Spot

The temperature of the anode spot is assumed to be constant with time. A similar assumption has been made for the cathode by previous authors (Holm 1947; Somerville, Blevin, and Fletcher, in press) chiefly because the problem of melting is more easily solved. Now, the arc characteristics show that the total rate of supply of energy to the arc is approximately constant, while the above assumption implies that the rate of supply of heat to the anode is inversely proportional to the square root of the time. These two situations are not incompatible, because the transient arcs examined have been characterized by an expanding cathode spot, which presumably uses energy at an increasing rate, and a comparatively static anode spot, which is consistent with a state of temperature equilibrium.

It has been possible to calculate the temperature of the anode surface in the central region of the active area by observation of the extent of melting of the electrode by each transient arc. Usually the depth of melting is small compared with the anode thickness and the theory of melting in a semi-infinite solid can be applied to the physical problem with reasonable accuracy. A technique for measuring depth of melting into thick anodes has been described previously (Somerville, Blevin, and Fletcher 1952). Unfortunately this method does not give sufficiently accurate measurements, and it has been found more satisfactory experimentally to study melting by arcs struck on metallic foils, and to develop a theory of melting for that case.

Consider the case when an arc of duration T has as anode the plane surface of a thin slab of metal of thickness α. If the diameter of the discharge greatly exceeds α, there is little radial conduction of heat in the metal from the centre of the active area, and heat entering the anode in that region is conducted linearly through the slab. Assume that for the duration of the arc the active anode surface is held at a constant temperature Φ (the initial temperature of the anode being zero), and that no heat is lost from the back of the anode slab. Let V be the melting point of the anode metal.

An analogous problem has been solved by Lightfoot (1930) to give the rate of solidification of a slab of molten steel. Small changes in Lightfoot's solution allow the rate of melting of the anode in the present problem to be determined. Although the solution is not exact, it is an extremely good approximation for the region used in the present case.

The position of the level at which the temperature is V, at time t, is given by

$$x = 2k\sqrt{\varkappa t}, \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where x = the coordinate of depth into the anode,
$\varkappa$ = the diffusivity = $K/c\rho$,
K = the thermal conductivity,
c = the specific heat,
ρ = the density,
and k is given by

$$\frac{\Phi}{V}=\frac{1}{1-\text{erf } k}+\frac{\lambda}{cV}\sqrt{\pi}ke^{k^2}\text{ erf } k, \quad \ldots\ldots\ldots\ldots (2)$$

where λ = the latent heat of fusion.

The temperature in the molten region $0<x<2k\sqrt{\varkappa t}$ is

$$v_1=\Phi-\frac{\Phi-V}{\text{erf } k}\text{ erf}\left(\frac{x}{2\sqrt{\varkappa t}}\right)-\frac{V}{1-\text{erf } k}\sum_{m=1}^{\infty}(-1)^m\left\{\text{erf}\left(\frac{2m\alpha+x}{2\sqrt{\varkappa t}}\right)-\text{erf}\left(\frac{2m\alpha-x}{2\sqrt{\varkappa t}}\right)\right\}, \quad \ldots\ldots\ldots\ldots (3)$$

and beyond this region, for $2k\sqrt{\varkappa t}<x<\alpha$, the temperature is

$$v_2=\frac{V}{1-\text{erf } k}\left[1-\text{erf}\left(\frac{x}{2\sqrt{\varkappa t}}\right)-\sum_{m=1}^{\infty}(-1)^m\left\{\text{erf}\left(\frac{2m\alpha+x}{2\sqrt{\varkappa t}}\right)-\text{erf}\left(\frac{2m\alpha-x}{2\sqrt{\varkappa t}}\right)\right\}\right]. \quad \ldots\ldots\ldots\ldots (4)$$

The quantity of heat entering the anode per unit area is

$$Q=\int_0^T \mathrm{K}\left(\frac{\partial v_1}{\partial x}\right)_{x=0}\mathrm{d}t. \quad \ldots\ldots\ldots\ldots (5)$$

Consider a slab of critical thickness α_0, such that melting just extends to its back surface. Then

$$Q=\alpha_0\rho(cV+\lambda). \quad \ldots\ldots\ldots\ldots (6)$$

If we now eliminate Q from (5) and (6), and substitute for v_1 from (3), we obtain

$$\frac{\lambda}{cV}=\frac{2}{\sqrt{\pi}}\frac{\sqrt{\varkappa T}}{\alpha_0}\left[\frac{\Phi/V-1}{\text{erf } k}+\frac{2}{1-\text{erf } k}\sum_{m=1}^{\infty}(-1)^m\left\{e^{-m^2\alpha_0^2/\varkappa T}-\frac{\sqrt{\pi}m\alpha_0}{\sqrt{\varkappa T}}\left(1-\text{erf}\left(\frac{m\alpha_0}{\sqrt{\varkappa T}}\right)\right)\right\}\right]-1.^* \quad \ldots\ldots\ldots\ldots (7)$$

Using (2) to eliminate k, we can obtain λ/cV in terms of $\sqrt{\varkappa T}/\alpha_0$ for given values of Φ/V. The solution is shown in Figure 1 for values of Φ/V in the range 1·2-10.

If the assumptions are approximately correct, Figure 1 enables the central anode spot temperature Φ to be determined. The abscissa λ/cV is a constant for a given metal and the ordinate $\sqrt{\varkappa T}/\alpha_0$ is determined by experiment. For some metals accurate measurement of α_0 is difficult, but in the cases mentioned

* A more elementary treatment (Somerville, Blevin, and Fletcher 1952) gives a similar result, but with the infinite series omitted. Errors due to this omission are not serious when $\sqrt{\varkappa T}/\alpha_0$ is small.

below the error is less than 5 per cent. (It is found that α_0 is independent of the arc current for values greater than 50 A., presumably because the spot diameter is then large enough for radial conduction of heat from the centre to be negligible.) Then Φ/V is read from the graph, and so Φ is known.

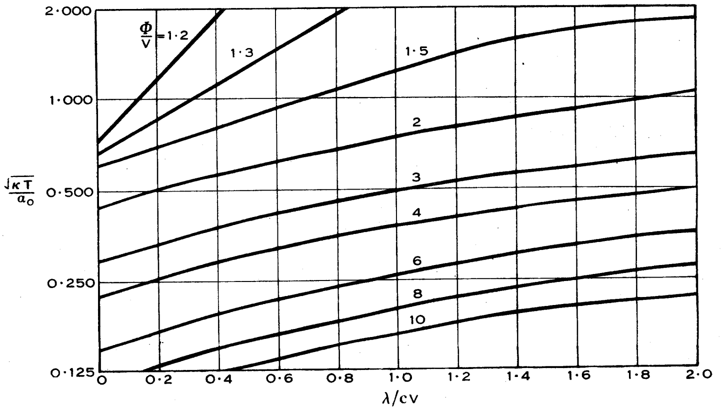

Fig. 1.—$\sqrt{\varkappa T}/\alpha_0$ is shown as a function of λ/cV for values of the parameter Φ/V in the range 1·2–10.

Results for anodes of nickel, aluminium, and tin are given in Table 1. If the anode spot temperature is not constant as assumed, Φ represents a mean value. However, the results for tin suggest that the assumption of constant temperature is approximately true. For each metal Φ is well below the boiling point.

TABLE 1

VALUES OF CENTRAL SPOT TEMPERATURE

Anode Metal	Arc Duration (μ sec.)	$\frac{\lambda}{cV}$	$\frac{\sqrt{\varkappa T}}{\alpha_0}$	$\frac{\Phi}{V}$	Spot Temperature (°C.)
Tin	27	1·06	0·22	7·5	1600
	50	1·06	0·24	6·8	1460
	250	1·06	0·25	6·5	1400
Aluminium	250	0·45	0·63	1·9	1250
Nickel	250	0·43	0·83	1·50	2300

The calculated average surface flux of heat is consistent with the value derived from the anode drop. Our solution gives values from 2 to 9 V. for the anode fall with the above metals (assuming that all the energy of the anode fall enters the anode), and accepted values for this quantity are of the same order (von Engel and Steenbeck 1932).

It is necessary to consider whether the values of Φ in Table 1 also hold for normal electrodes of much greater thickness than α_0, for it is possible that use of a thin slab as anode may have so limited the amount of heat conducted away that the surface temperature is considerably increased. The temperature at the back of the slab at time $t=T$ gives an indication of the extent to which the use of the slab has influenced the spot temperature. With $t=T$, and $x=\alpha_0$, (4) becomes

$$\bar{v}_2=\frac{2V}{1-\operatorname{erf} k}\left[1-\operatorname{erf}\left(\frac{\alpha_0}{2\sqrt{\varkappa T}}\right)+\sum_{m=1}^{\infty}(-1)^m\left\{1-\operatorname{erf}\left(\frac{(2m+1)\alpha_0}{2\sqrt{\varkappa T}}\right)\right\}\right].$$

For tin this temperature is less than 10 °C. and the boundary $x=\alpha_0$ therefore has negligible influence on Φ. However, for aluminium and nickel the values of $\bar{v}_2$ are not much less than V, and the values of Φ for these metals are somewhat greater than the spot temperatures on thicker anodes.

Indeed, experimental examination shows that the anode surface conditions alter when very thin metal foils are used for the electrode. The area of the molten spot increases when α falls below some critical value α_1. This is partly due to increased radial conduction of heat, but photographs of the discharge show that its cross section at the anode also increases, causing a decrease in the radial contraction. A tentative explanation is that high temperatures built up in very thin anodes cause appreciable thermionic emission of electrons, which

TABLE 2

COMPARISON OF THICKNESSES α_0 AND α_1

Anode Metal	α_0 (cm.)	α_1 (cm.)
Tin	0·030	0·007
Aluminium	0·018	0·016
Nickel	0·0071	0·016

decreases the total current density. Table 2 compares values of α_0 and α_1 for 250 μsec, 75 A. arcs. For tin $\alpha_0 \gg \alpha_1$, in agreement with the above conclusion that the boundary $x=\alpha_0$ does not significantly influence the state of the surface $x=0$. However, α_0 and α_1 are of the same order of magnitude for each of the other metals, and this again suggests that the thinness of the foil in these cases is affecting the anode spot temperature. For aluminium and nickel the spot temperature on normal anodes must therefore lie between their melting points (660 and 1455 °C., respectively) and the values given in Table 1.

IV. ACKNOWLEDGMENT

The author wishes to thank Dr. R. C. T. Smith for advice on the application to this problem of Lightfoot's solutions.

V. References

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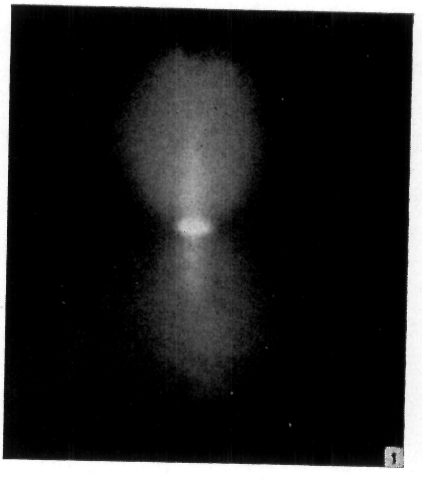

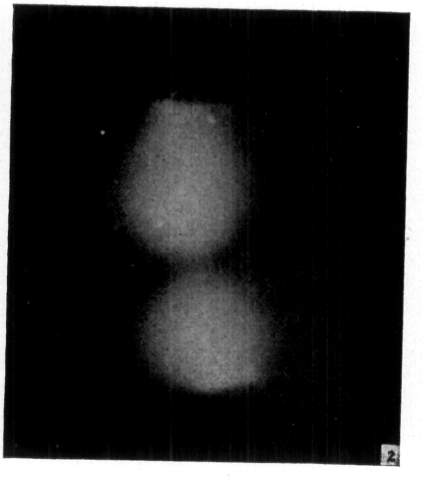

Fig. 1.—Radial contraction of an arc discharge at a low melting point anode. ×15.

Fig. 2.—Radial contraction of an arc discharge at a high melting point anode. ×15.