FACTORS IN EROSION OF NON-REFRACTORY CATHODES OF ELECTRIC ARC HEATERS

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ABSTRACT

It is shown that the transverse magnetic field causes successive minima and maxima in the erosion rate of water-cooled non-refractory cathodes in arc heaters. These and similar changes when the water flow rate is varied arise from phenomena in the cathode oxide films, and investigation of these shows why a small oxygen content in the heated gas can increase electrode life.

1. INTRODUCTION

Some of the electric arc heaters employed in plasma chemistry use non-refractory cathodes such as copper where electron emission cannot be thermionic. In some cases a three-phase arc may be used between three electrodes having consumable water-cooled tips[1]. In other cases magnetic rotation of the arc may be used to increase electrode life, either using a d.c. arc[2] or with three arc heaters connected to a three-phase supply[3]. It has been shown[4] that when both arc velocity and water cooling flow rate are increased, the erosion rate of oxygen-free-high-conductivity copper cathodes varies considerably. These and other non-linearities were attributed to processes in the cathode oxide film, and it has been shown[5] that the erosion rate reaches a peak at a particular oxide thickness and that it is possible to evaluate the important parameters of arc cathode emitting sites, such as current density, lifetime, crater density and diameter which have all been found to be functions of oxide thickness.

2. CATHODE MICROSTRUCTURE DEDUCED FROM SHORT-DURATION STATIONARY ARCS

Using scanning electron microscopy of damage on copper cathodes by stationary 4.5A arcs of duration t_a seconds where $3.8\text{ns} < t_a < 3.5\mu\text{s}$, it was possible to measure the total number of craters, their mean surface density and their radii and the most common radius r_{mc}. Using this data for various values of t_a, two methods were given[5] by which it was possible to obtain the parameters

I_s = mean emitting site current
$j_s = I_s/\pi r^2_{mc}$ = mean emitting site current density
t_s = mean emitting site lifetime.

These methods could only be applied to copper and steel because one required a vast number of photomicrographs, and the other values of oxide parameters up to the melting point which were not available for most oxides. A third method has now been developed[6] in which the

growth in r_{mc} with increasing arc duration t_a has been compared with the equation for heat generation by joule heating in a hemispherical region and outflow by conduction. Two conditions must be distinguished:-

(a) small radii and times: adiabatic heating

The time t_1 taken to raise the metal temperature from ambient T_o to the melting temperature T_m and to supply the heat of fusion is given by

$$t_1 = 4\pi^2 d\lambda f_1(T_m) r^4 / L I_s^2 \qquad (1)$$

where d = density of cathode metal; λ = thermal conductivity; L = Lorentz constant and $f_1(T_m)$ is the entropy increase up to and including melting.

(b) large radii and times: dominated by heat conduction

When the electron emission does not cease sufficiently quickly to leave a crater of radius r at a short time t_1 given by equation (1), then r can increase to a value r_c where the joule heating which diminishes as r grows is balanced by the increasing heat conduction as $\delta T/\delta r \to 0$ as $r \to r_c$ and

$$r_c = \sqrt{L} I_s / 2\pi\lambda \cos^{-1}(T_o/T_m). \qquad (2)$$

Since it has been shown[5] for copper cathodes that I_s is constant then equation (1) becomes

$$t_a = k_1 r^4. \qquad (3)$$

This equation will only hold for $t_a < t_s$ because for longer arc durations heat conduction will no longer be negligible and r_{mc} would tend towards a limiting value at high t_a as further generations of craters of similar size replace one another.

The measured growth in r_{mc} with increasing t_a does conform with equation (3) up to $t_a \simeq 0.5\ t_s$ and it has been possible to deduce for the following materials with a very thin oxide film of $\sim$2.5nm that the important parameters are:-

silver: $I_s \simeq 43$mA; $t_s \simeq 160$ns; $r_{mc} = 0.05\mu$m; $j_s \simeq (0.82\text{-}5.1) \times 10^{12}$A/m^2

aluminium: $I_s \simeq 25$mA; $t_s \simeq 11$ns; $r_{mc} = 0.045\mu$m; $j_s = (0.66\text{-}3.6) \times 10^{12}$A/m^2

silver/cadmium oxide: $I_s = (200\text{-}650)$mA; $t_s \sim 170$ns; $r_{mc} = 0.29\mu$m; $j_s = (0.13\text{-}2.5) \times 10^{12}$A/m^2.

These current densities are in the same high range[6] as for copper and mild steel cathodes having very thin and very thick oxide films.

3. EROSION RATES FOR ROTATING ARCS

It was shown[4] using a magnetic field to drive an arc between two concentric electrodes, the outer of which was a cathode ring removable from its water-cooled housing for weighing before and after arcing, that the erosion rate of o.f.h.c. copper varied in a switchback manner with increase in arc velocity. This kind of variation occurred for all the cathode materials tested and for some of them, as Fig 1 shows, there were a number of minima and maxima. Such a result does not show whether these turning points occur at critical velocities. However in the case of o.f.h.c. copper and a silver/copper alloy of 80%/20% composition with about 20ppm P_2O_5, sufficient results over the arc current range 45-800A were obtained to allow this to be checked. In the case of o.f.h.c. copper a particular turning point, e.g. the first minimum, occured over a velocity

range of 3 or 4:1 depending upon the current, but Fig 2 shows that each occurs at almost the same magnetic field for all currents. For Ag/Cu the velocities at which a given turning point in erosion occurred varied even more widely. Fig 3 shows that after the first maximum, the other minima and maxima do occur at about the same magnetic field in the current range up to a few hundred amperes. Figs 2 and 3 show that the factors of increase in magnetic field to go from one minimum or maximum to the next do not vary greatly with arc current. They range from 1.2 for aluminium bronze and 1.4 for copper zirconium up to 3 for 75%/25% tungsten/silver and 3.5 for silver. There seem however to be subtle differences, e.g. three coppers, o.f.h.c., phosphorus-deoxidised and electrolytic-tough-pitch gave factors of 2.1, 1.4 and 2.4 respectively. In the case of silver/copper the eutectic yielded 1.5 while the 80/20 alloy gave 1.75-2 with 20ppm of P_2O_5 and 2.8-3.6 with 500ppm of P_2O_5. It has been shown[4] that maxima and minima also occur in the erosion rate of o.f.h.c. copper cathodes when the flow rate of water through the housing is increased. Fig 4 shows that this happens also with Ag/Cu. Here however there is the additional feature that three cathodes from the same block of metal although showing similar variations in erosion do not all have a particular minimum or maximum at the same water flow rate. When the erosion rate was very close to a minimum the interference colours indicated an oxide film of about 50nm, whereas when it was near a maximum the film was clearly many hundreds of nanometres thick.

4. DISCUSSION OF RESULTS

The current densities on copper, mild steel, silver, silver/cadmium oxide and aluminium cathodes with a variety of oxide films, have been shown to be up to 50 times higher than the highest values shown in a recent review[7] of some aspects of electrode erosion in plasma arc reactors. The agreement of measured crater sizes with equation (3) confirms that electron emitting sites are due to the switching into conduction of filamentary channels through the oxide as a result of joule heating. Whereas the crater radii for copper in atmospheric air with very thin oxide film or thick film are only about 0.05μm and are independent of arc current I, the radii for a very clean surface in vacuum are typically 2-6μm[8]. For short-duration stationary arcs on o.f.h.c. copper cathodes the erosion rates are 1-10μg/C for very thin oxide films in air and in vacuum, 100-400μg/C for very thick films in air and about 100μg/C for clean cathodes in vacuum. This shows the need for a thin oxide film in order to have long electrode life of non-refractory cathodes, and explains why it has been found[1] using nitrogen that the minimum erosion rate occurred when about 1% of oxygen was added. The violent erosion with pronounced craters[1] and increased erosion rate[3] found when oxygen was excluded, can now be said to stem from the electron emission no longer arising from tunneling with thin oxide film or switching with a thick one, but changing when the surface oxide films are cleaned up to a vapour-type of arc cathode process similar to a vacuum arc. This progression from craters having radii of ~0.15μm on an oxidised surface, to ~1μm on a moderately cleaned area, to ~10μm for a clean surface, i.e. changing from equation (1) to (2), has recently been found for unipolar arcing on stainless steel surfaces in a tokamak[9]. This explains the range of 1.5-7.5μm found for crater radii on stainless steel[10]. From equation (2) the ratio r_c/I_s can be calculated using the material parameters, giving 0.05μm/A for copper and 1.55μm/A for stainless steel which explains the larger craters for the latter.

Exactly the same minimum cathode erosion rate of <1μg/C has been found by varying either the magnetic field or the cooling water flow rate, and it seems likely that related phenomena such as galvanomagnetic or thermo-magnetic effects in the oxide film are responsible, as suggested before for related phenomena[11]. It is possible that an effect such as the hot-electron magneto-phonon effect which can cause oscillations in the magnetoconductivity of semiconductors, may trigger the switched filaments from the 'normal' mode with density $\sim 10^{13}/m^2$ and radius $\sim 0.05\mu m$, into the mode having a density 10^8-$10^9/m^2$ and radius $\sim 0.5\mu m$. This latter mode was found[12] at the same oxide thickness of ~50nm as has been observed to occur on the cathodes having minimum erosion rate, and it was shown[13] that this mode would lead to a much reduced erosion rate. This suggests that it is not merely high arc rotation frequency and large feedstock throughput which leads to minimum erosion as is sometimes said[3]. A thin oxide film should be maintained and the magnetic field and water flow should be varied to check whether a lower erosion rate exists.

REFERENCES

(1) D. Gold, C. Bonet, G. Chauvin and A.D. Mathieu, Proc. 4th Int. Symp. on Plasma Chemistry, Zurich, 1, 265 (1979).
(2) K Arkless and D. Cleaver, British Patent 1035191, (1966).
(3) M.G. Fey, T.N. Meyer and W.H. Reed, Proc. 4th Int. Symp. on Plasma Chemistry, Zurich, 2, 708, (1979).
(4) A.E. Guile, Proc. 4th Int. Symp. on Plasma Chemistry, Zurich, 1, 305, (1979).
(5) A.E. Guile, Proc. 4th Int. Symp. on Plasma Chemistry, Zurich, 2, 629, (1979)
(6) A.E. Guile, Proc. IEE, PtA, No 7, 127, 452, (1980).
(7) C. Bonet, Pure and Appl. Chem. 52, 1707, (1980).
(8) A.E. Guile and B. Jüttner, IEEE Trans. Plasma Sci., P-S8, No3, 259, (1980).
(9) J.P. Datlov, A.E. Guile and B. Jüttner, Beitr. Plasmaphys, to be published.
(10) K. Höthker, K. Koizlik and E. Hintz, Proc. 4th Int. Symp. on Plasma Chemistry, Zurich, 1, 109, (1979).
(11) A.E. Guile, T.J. Lewis and S.F. Mehta, Brit. J. Appl. Phys., 8, 444, (1957).
(12) A.E. Guile, A.H. Hitchcock and J.M. Barlow, Proc. IEE, 124, 406 (1977).
(13) A.H. Hitchcock and A.E. Guile, J. Matls. Sci. 12, 1095 (1977).

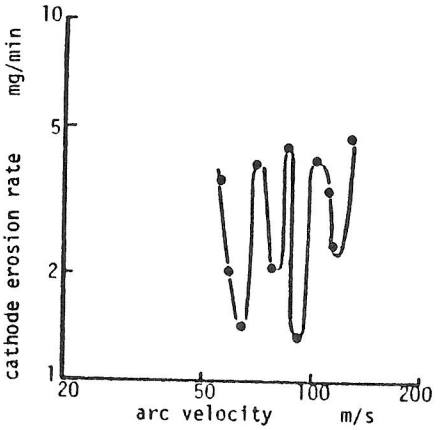

FIG 1. Cathode erosion rate as a function of arc velocity for 100 A arcs on aluminium bronze cathodes (92.5% Cu/7% Al/0.5% Co), in air at atmospheric pressure, 4.8 ℓ/min cooling water flow rate.

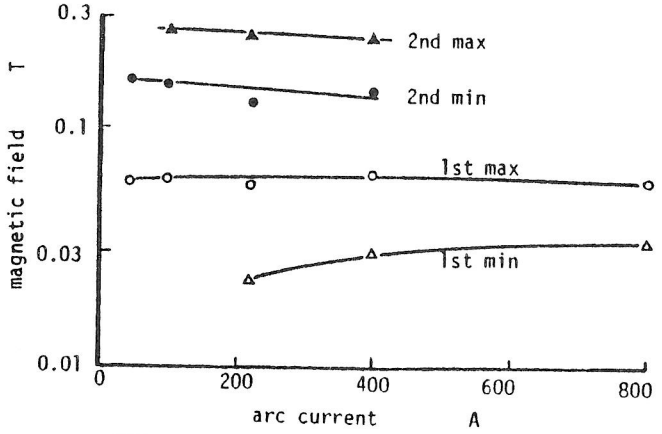

FIG 2. Magnetic field at a turning point in erosion rate for o.f.h.c. copper cathodes in air at atmospheric pressure. 4.8 ℓ/min cooling water flow rate.

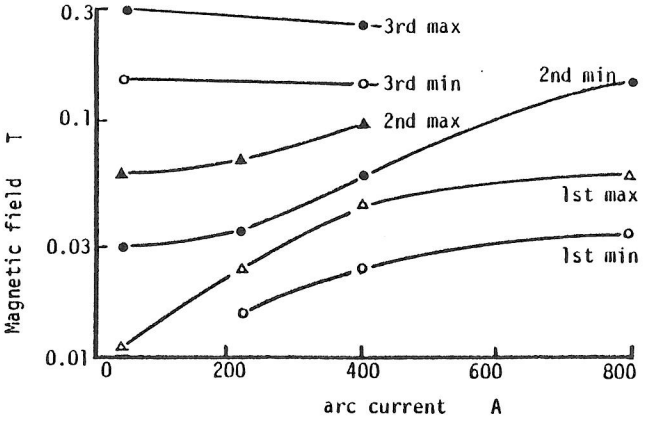

FIG 3. Magnetic field at a turning point in erosion rate for silver/copper cathodes (80%/20% with 20-60 ppm P_2O_5) in air at atmospheric pressure. 4.8 ℓ/min cooling water flow rate.

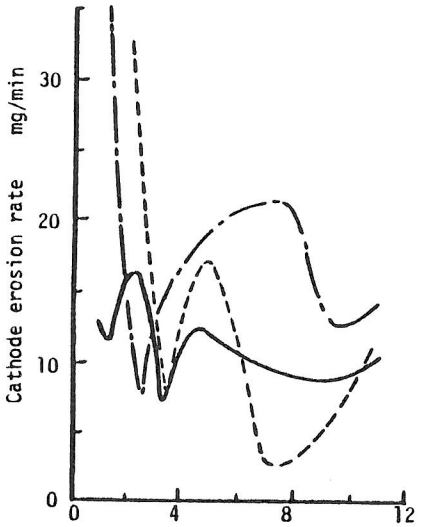

FIG 4. Erosion rate as a function of cathode cooling water flow rate for three silver/copper cathodes (80%/20% with 500 ppm P_2O_5) at 220 A and 110 m/s in air at one atmosphere