MICROSTRUCTURE OF NON-REFRACTORY ARC CATHODE ROOTS IN PLASMA DEVICES WITH MAGNETIC ROTATION OF THE ARC

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ABSTRACT

Scanning electron microscopy of copper cathodes after a short-duration stationary arc or an arc driven magnetically once over the surface, has revealed details of the arc cathode root microstructure and its variation with oxide film thickness. This throws light on the complex changes in arc cathode erosion which have been found to occur in plasma devices with magnetic arc rotation.

1. INTRODUCTION

The work described in this paper arose out of an investigation into the erosion of non-refractory cathodes of plasma devices in which an arc is rotated magnetically. The erosion measurements (see paper by the same author in Session 3 of Round Table) showed non-linearities which appeared to arise from processes in the cathode oxide film, and no systematic investigation of these films had ever been reported in the literature.

The work described here involved scanning electron microscope (SEM) examination of arc cathode damage, mainly on oxygen-free-high-conductivity copper cathodes, with oxide layers of a wide range of thickness produced by heating in an oven after initial polishing to a finish of about 0.05μm. Fast rotation of arc roots in a plasma device avoids gross melting but multiple rotations obscure the detailed evidence which might be found by SEM examination, so that two techniques were employed in the present work to obtain quantitative data: (a) short-duration (3.8 ns to 3.5 μs) 4.5A "stationary" arcs and (b) a single passage of a magnetically-driven arc of up to 1.1 kA.

For both "stationary" and moving arcs, SEM examination at magnifications up to 100,000 x revealed craters of similar size and similar surface densities, and it is believed that each of these craters was left by expulsion of evaporated and/or molten material from one of the many electron emitting sites which together make up an arc cathode root, according to the following simple model which was developed during this work.

2. MODEL OF THE MICROSTRUCTURE OF THE CATHODE SPOT

Within the cathode spot which carries the total arc current I amperes, there are many separate emitting sites which on average carry a current I_s and each of which leaves behind a crater on the cathode surface. Thus

$$I_s = I/n \tag{1}$$

where n is the mean number of sites at any one instant, i.e. in one single generation of sites.

If each emitting site lasts on average t_s seconds then the mean number of generations of sites per second N is

$$N = 1/t_s \tag{2}$$

For an arc duration $t >> t_s$, the number of craters Z left by emitting sites may be expected to be

$$Z \simeq Nnt = It/I_s t_s \tag{3}$$

It has been possible to verify that equation (3) is approximately true by SEM measurements of Z for stationary arcs(1),(2) so that the product $I_s t_s$ may be evaluated. Two methods have been evolved of separating out the two values I_s and t_s from this product. The first involves a very large number of tests over a wide range of arc duration, so as to determine the duration below which the number of sites fall off rapidly with decreasing time(1). The second method(2) involves first determining $j_s t_s$ by dividing by $\pi D_{mc}^2/4$ where j_s is the mean current density in the cathode emitting sites and D_{mc} is the crater diameter at which there is a peak in the distribution given by plotting number of craters in a given narrow range of size against crater diameter. It has then been shown that writing down the energy balance terms at a single cathode emitting site yields

$$(j_s^2 d D_{mc}^2 K_1 + K_2 + K_3 - K_4) t_s = AdK_5 \tag{4}$$

where d is the thickness of the oxide film and K_1, K_2, K_3, K_4 and K_5 are constants involving physical parameters of the oxide and these constants have been evaluated for copper(3). From equations (3) and (4) it is possible to obtain values of j_s, I_s and t_s.

For an arc moving at a velocity U, with a track width W and leaving a crater density S, the number of craters produced per second is SUW and using equation (3) with t = 1 gives

$$W = \frac{1}{I_s t_s S} \cdot \frac{I}{U} \tag{5}$$

Equation (5), like equation (3) for stationary arcs, only gives a value of the $I_s t_s$ product, but approximate estimates of I_s and t_s may be obtained as follows(2),(4).

$$I_s = \frac{I}{W\,R\,\sqrt{S}} \qquad (6)$$

$$t_s = \frac{R}{U\sqrt{S}} \qquad (7)$$

where R is the number of rows of co-existing sites transverse to the direction of arc movement.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Table 1 shows the results of the experiments using stationary 4.5 A arcs on copper cathodes with varied oxide film thickness. It can be seen that at a thickness of ∿25-44 nm there is a minimum in the most common crater diameter D_{mc} and in the mean emitting site lifetime t_s, whilst there is a maximum in the density S of craters on the surface, in the number of craters after a given arc duration and in the mean current density at an emitting site j_s. Only the mean site current I_s remains almost unaffected by change in oxide thickness. This is clear evidence in support of the suggestion made by the authors(5) that the electron emission and erosion processes at a copper cathode of an arc must be divided into two distinct types; those for very thin films <10nm where electron tunnelling can occur and those of greater thickness. It was originally suggested(6) that for these thicker films each emitting site would occur where a filamentary conducting channel had appeared through the oxide film by switching or by electroforming. The very short lifetimes shown in Table 1, make it clear however, that there is no electroforming because this takes times of μs to ms to occur(7), but there is now a great deal of evidence(8) that there is switching (i.e. a thermal run-away process in which the electrical conductivity of the oxide film rapidly rises in a filamentary channel as the temperature increases).

In the case of the 2.5 nm films the craters have pronounced rims and are not uniformly distributed and often tend to form along scratches on the surface. On relatively thick films the craters are formed with a distribution which is remarkably uniform within an area from which the oxide has been stripped, and which for short duration (< 1 μs) is nearly circular. Measurements of the step around the edges of these areas showed that it was about equal to the thickness of the original films so that all the oxide was stripped away, together with metal removed from the craters within this stripped area.

When arcs of currents from 12 A to 68 A were moved magnetically along copper cathodes with oxide films of thickness 2.5 nm, 44 nm and 100 nm it was found(2),(4) that the cratering in the arc-tracks was generally similar in surface distribution, size distribution and appearance to that for stationary arcing, apart from when arcs were moved at speeds in excess of ∿80 m/s on 44 nm oxide films. Following a transition range of 80-120 m/s it was found(4) that for higher speeds (up to 241 m/s) on this thickness, a different mode of cratering with no oxide-stripping was in operation. The surface density was reduced by more than 4 orders of magnitude to $\sim 10^9/\mathrm{m}^2$ and the most common diameter of the craters rose to 1 μm compared with ∿0.1 μm for lower speeds.

In estimating site currents and site lifetimes from this moving arc data it was found necessary to assume that more than 1 row of sites co-existed at any instant. For 2.5 nm films(2) R in equations (6) and (7) was given a value of 2 to 3; for 44 nm films at velocities at which the normal oxide-stripping mode occurred its value was about 2; and for 100 nm films its value(4) was again about 2. For the unusual high velocity mode on 44 nm films, where only very approximate values of I_s and t_s (∿ 1 A and ∿1 µs respectively), could be calculated, it appears that R takes values between 1 and 5.

Recent experiments(9) suggest that emission from copper cathodes with various oxide films is not affected appreciably either when the pressure is reduced to ∿1 torr or when the moving arc currents are increased to ∿1 kA.

Erosion rate values may be estimated(10) from the SEM data obtained for short-duration stationary 4.5 A arcs(1),(2) and for moving arcs(2),(4) of currents from 12 A to 68 A. Fig 1 shows curves of estimated erosion rates corrected to 45 A for the two cases and they are seen to agree well. When these estimated erosion rates are compared with data for long duration rotating arcs, they are found to overestimate greatly the experimentally measured values. The reasons for this are believed to involve transfer of cathode material to the anode and back again to the cathode, and later electron emission occurring at the edges of old craters(10). However, the variation in erosion rate with oxide film thickness in Fig 1 does help to explain the complex changes in measured erosion rates reported in the paper in Session 3 of the Round Table.

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TABLE 1 Arc Cathode Root Parameters on Copper Cathodes with varied Cu_2O film thickness

Oxide Thickness	2.5 nm	25 nm	44 nm	100 nm	225 nm	340 nm
Most Common Crater Diameter μm	0.115	0.07	0.07	0.105	0.165	0.205
Crater Density on Cathode Surface S per m^2	4×10^{12}	2.7×10^{13}	3.2×10^{13}	1.8×10^{13}	8×10^{12}	4×10^{12}
Number of Craters at 1 μs	2.5×10^4	22×10^4	12×10^4	7.5×10^4	1.5×10^4	0.7×10^4
Mean Cathode Site Current I_s mA	17	15.3	11.3	11	13.1	14.5
Cathode Site Current Density j_s A/m^2	1.7×10^{12}	4×10^{12}	2.95×10^{12}	1.4×10^{12}	6.15×10^{11}	3.7×10^{11}
Mean Cathode Site Lifetime t_s ns	55	1.3	3.3	4.5	23	105

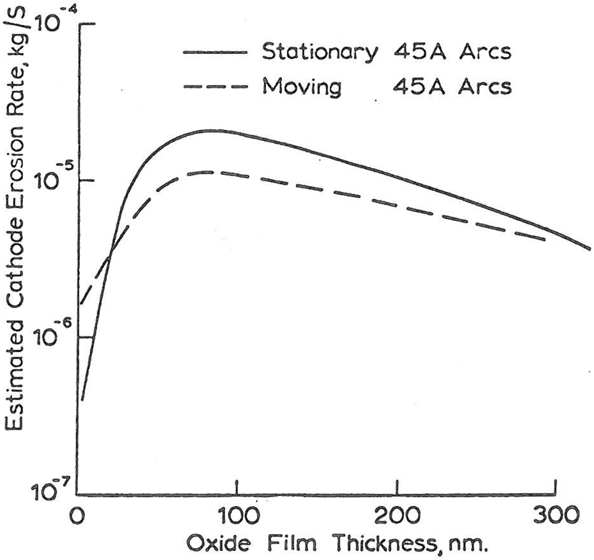

Fig.1 Comparison of calculated erosion rate/oxide film thickness curves for stationary and moving 45A arcs on copper cathodes