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A scanning electron microscope study of the role of copper oxide layers on arc cathode erosion rates

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The results are described of scanning electron microscopy of copper surfaces covered initially with oxide films of thickness from 2.5 to 340 nm, which have been the cathodes of electric arcs. The objective of the work has been to learn more about the mechanisms of electrical conduction through oxide films on non-refractory arc cathodes, electron emission into the arc and the erosion of the cathode. It is the latter aspect upon which this paper concentrates. Cathode erosion is a major problem when arcs rotate over electrode surfaces for very long times in certain industrial processes. Erosion rates are calculated here using SEMs, both for stationary 4.5 A arcs of duration 1 μsec, and for higher current arcs which were magnetically driven once over the cathode surface. Making allowance for the effect of current, these erosion rates are shown to be similar in magnitude and in their variation with oxide thickness, and reasons for this are given. Comparison is then made with erosion rates measured by weight loss for long-duration rotating arcs. In the light of the new data given here, it is now possible to understand better the remarkable changes which have occurred for long-duration arcs when varying arc velocity, water-cooling flow rate and arcing duration.

1. Introduction

Electrode erosion can be a major problem in industrial processes where an electric arc is used to heat gases, even when the arc roots are moved quite rapidly over the electrodes by means of a transverse magnetic field and possibly also by gas flow. To understand the processes involved, and find ways of reducing erosion, an extensive programme of research was undertaken by the authors on cathode erosion for magnetically-rotated arcs in atmospheric pressure air. Erosion rates were measured [1–3] for cathodes of various materials as a function of arc velocity at 45 A. Further experiments with an improved water-cooled electrode system were carried out to study the effect on the cathode erosion rate of arc current up to 800 A [4], arcing duration [5] and cathode cooling-water flow rate [6], mainly for copper cathodes. It was difficult to give more than a qualitative explanation of many of the results, all of which showed erosion rate to be a non-linear function of each variable, with large rises and falls when arc velocity or water flow rate were increased. The significant role of cathode surface oxide films was recognised early on, however, and a quantitative model of the erosion process was put forward [3] to explain the results of the erosion rate measurements at 45 A on copper cathodes. In this model, some evidence from photographs obtained from the SEM was used, and the erosion of material from sub-micron sized craters was attributed to joule heating in the oxide film [7]. The authors predicted [8] that the electron emission and the erosion processes on a copper cathode would differ greatly if the oxide was <10 nm or >10 nm thick. It was suggested from evidence on surface potential difference changes at arc cathode tracks [9] that switching within the oxide film occurred to form a number of filamentary conducting channels [10] each of which gave rise to one of the multiple electron

emitting sites which together make up the cathode root on a non-refractory cathode [11]. Switching (thermal run-away to a high electrical conductivity state) can occur within nanoseconds when sufficient over-voltage and temperature are applied to an oxide film [10], and there is now considerable evidence that this occurs in the oxide film on arc cathodes, and the resulting build up of current causes sufficient joule heating to destroy the efficient electron emission within nanoseconds by ejection of molten material to form a crater, typically below 1 μm diameter [12–15].

Interpretations of SEMs of the damage caused by rotating arcs, whose durations are a few minutes or more, on a relatively small cathode surface area 10^{-3} m^2 (the conditions operating in [1–6]) must be very tentative, even when the arc is moving rapidly. This is mainly because some of the surface details are obscured by debris transferred from other parts of the cathode (or even from the anode), and because the thickness of the oxide film changes considerably during the duration of the arc due to heating of the cathode. In an attempt to circumvent these problems and obtain further information, not only on the erosion but also on the electron emission process from copper arc cathodes with various oxide films, further investigations [13–15] have recently been carried out. In some experiments [13–14], copper cathodes having oxide thicknesses in the range 2.5 to 340 nm were subjected in air at atmospheric pressure to stationary arcs of current, normally 4.5 A, and of durations 4 nsec to 3.5 μsec. In other experiments [15] copper cathodes with various oxide thicknesses in the range 2.5 to 100 nm were subjected, again in air at atmospheric pressure, to magnetically moved single-traverse arcs of currents 12 to 68 A and velocities 19 to 241 m sec^{-1}.

This paper examines the evidence on erosion provided by SEM during these experiments [13–15], and others described here, and shows that it is now necessary to modify many of the aspects and assumptions of the model of erosion proposed earlier [3], for long-duration arcs rotating on copper cathodes on which the oxide films are not of constant thickness but vary during arcing from an initial thickness of about 2.5 nm up to tens or even hundreds of nm. Erosion rates are calculated in this paper using SEM data for short-duration "stationary" arcs and for single-traverse moving arcs; and the two are shown to be similar and are compared with those measured for long-duration rotating arcs. The effects of a number of factors are examined, and results of SEM and electron probe microanalysis are given showing that erosion of a copper cathode where the oxide layer varies appreciably during arcing, is far more complex than has been hitherto supposed.

2. Estimation of erosion rates

2.1. Stationary arcing

The arcs considered here were produced by the discharge of a cable with the gap between the oxygen-free high-conductivity (OFHC) copper anode and cathode set at about 20 μm to give the breakdown near the Paschen minimum, and were of current 4.5 A and duration 1 μsec. This technique has been described in greater detail elsewhere [13–14]. The cathode arcing surface was of 3 to 6 mm diameter for direct insertion into a Cambridge stereoscan 600 and was given a surface finish nominally flat to 0.05 μm. This was done by successive lapping in a lathe at 3000 rev min^{-1}, first with powdered silicon carbide and then with three successively finer grades of alumina powder impregnated into wet leather laps. SEM examination of the polished but un-arced cathodes, which had not been heated in an oven, indicated that surface melting had not occurred to any resolvable level during the polishing process because

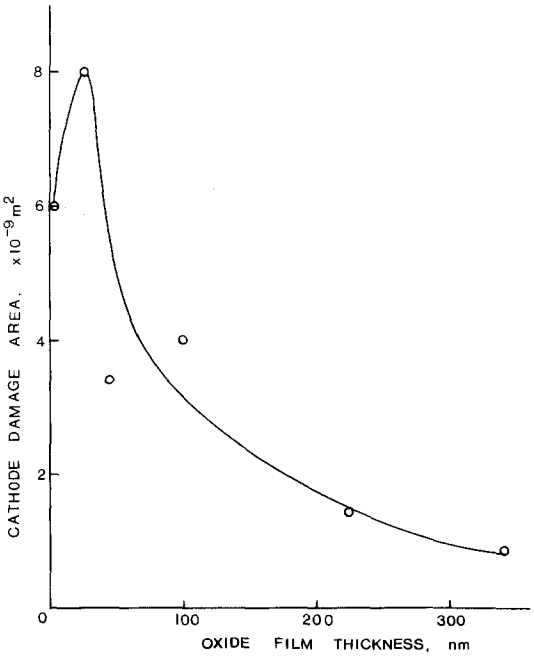

Figure 1 Mean cathode damage areas produced by 1 μsec 4.5 A arcs as a function of copper oxide thickness.

the laps were cooled with distilled de-ionized water. A cuprous oxide film was then formed by heating the cathode in atmospheric pressure air in an oven for various times at temperatures between 120 and 200° C. The thickness of cuprous oxide was estimated to an accuracy ± 10% or better, from the interference colours which were recognizable [16] in the range 38 to 125 nm. Some thicknesses outside this range were estimated by assuming that the thickness was proportional to (oxidation time)$^{1/3}$ for a given temperature [17]. The lowest thickness of oxide was that formed in air at atmospheric temperature and pressure after polishing, and this was estimated to be about 2.5 nm.

Fig. 1 shows the area of cathode damage produced by 1 μsec arcs as a function of oxide thickness. Each point is the mean of several experimentally determined areas at that oxide thickness. For thicknesses of 25 nm or greater, the damage area is the area stripped of oxide, while for 2.5 nm it is just the area containing craters, since there is no sign that stripping occurs for such very thin oxide films. Fig. 2 shows a typical example of an SEM of an area of the oxide film that has been stripped away by a 1 μsec arc (using a sputtered 20 nm film of gold–palladium alloy to reduce the tendency for charging up in the oxide film on the specimen and so improve the resolution). This particular cathode had an initial oxide film 225 nm thick, and by tilting it and those with different film thicknesses, it was possible to measure the step between the stirpped area and the surrounding surface, which was found to be about equal to the oxide thickness. Further evidence that melting of material in the stripped area does not occur to any great depth, is provided by the two scratches shown in Fig. 2, which are only about 0.1 to 0.2 μm deep but can be seen running right across the damaged area as well as across the unarced surrounding oxide film (from top to bottom and at an angle of about 30°). The stripped areas were found to be almost circular at small arc durations, but as the arcing duration was increased (by discharging a longer cable) beyond about 300 nsec, the areas became progressively less regular. At the boundary of this region, Fig. 2 shows molten oxide globules displaced by forces in the cathode region of the arc. A number of crystal grain boundaries can be seen in Fig. 2, running across unarced oxide film and the stripped area. It is clear that these crystal grain boundaries have not been preferentially eroded away by the emitting sites, and it appears that the reverse may be true in the stripped area. The underlying copper surface, with its very thin oxide film grown after arcing, was found to be covered more or less uniformly with sub-μm sized craters. The diameter distribution and the surface density of these craters had both been found to vary with oxide thickness [14]. The surface density, which was in the range 0.5 to 3.2 × 10^{13} m^{-2}, was found to be the same as that of "pores" or "hollows" which have been found by the authors to occur in the unarced oxide film. The diameters of pores and of craters found after arcing were also very similar. No detailed reference to those "pores" in copper oxide has been found but they may be the areas between oxidation nucleation sites [16], and by having a thinner film than the latter, they may have a higher electric field across them due to positive ion bombardment [18] and thus they form more efficient emitting sites.

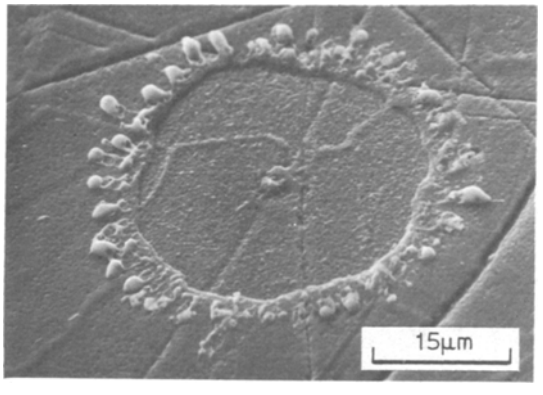

Figure 2 Stripped area produced by a 1 μsec 4.5 A arc on a copper cathode with a 225 nm oxide film.

In estimating the erosion rate for the films of thickness 25 nm and above, the mass of stripped oxide and the mass of copper leaving the craters which remain in the underlying copper in the stripped area must first be calculated. The crater depths, which are difficult to determine with any great accuracy from the SEMs, are assumed to be similar to their diameters, while the crater shape appears to be approximately cylindrical. The mean crater diameter and the mean number of craters produced in 1 μsec have been obtained earlier [14] as functions of oxide thickness. In comparing the results of these calculated erosion rates for short duration arcing at 4.5 A with the measured values [1–3] for long-duration arcing at 45 A, it must be remembered that the whole mass of oxide stripped here would not be measured as a weight

loss in the long-duration tests. In these tests the oxide is formed by reaction of the hot cathode with oxygen in the cell atmosphere and the oxygen of the oxide is obviously not included in the pre-arc weighing of the cathode. Thus, in the present tests only the mass of copper in the stripped oxide is considered to have been eroded. The estimation is further complicated by the fact that not all of the stripped oxide left the cathode in these short durations; considerable quantities of it were scattered around the stripped regions as may be seen in Fig. 2, and estimates from many SEMs suggested that as the oxide film thickness increased from 25 to 340 nm, the percentage of the stripped oxide actually leaving the cathode decreased from about 90% to as little as 5%.

The erosion rates estimated in the first instance were for a current of 4.5 A. It was found earlier [13] that for short duration arcing on 100 nm oxide films on copper, both the stripped area and the number of craters in the stripped area were proportional to arc current in the range 4.5 A to 14 A (the widest range that could be explored with the cable discharge technique) for an arcing duration of 12 nsec. It was reasonable, therefore, to scale up the estimated erosion rates for 4.5 A by a factor of 10, to allow a more direct comparison with erosion rates monitored previously [1–3] for long-duration 45 A arcing.

In the case of the cathodes with a 2.5 nm oxide film there was no sign of oxide stripping. The craters were again of sub-μm size but they differed in appearance from those for the much thicker films, by having pronounced rims. Furthermore, they were not uniformly distributed at constant density as for the thicker films, but instead there was some tendency to form along scratches as may

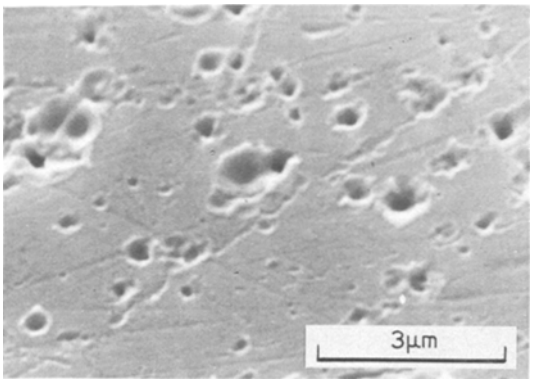

Figure 3 Surface distribution of craters due to a stationary 4.5 A arc on a copper cathode with a 2.5 nm oxide film.

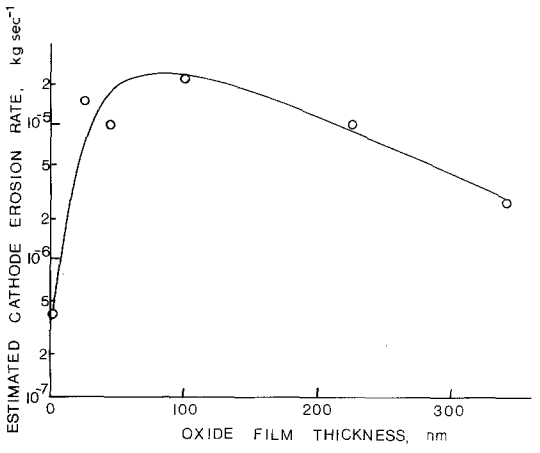

Figure 4 Estimated erosion rates for stationary 45 A arcs of duration1 μsec, as a function of oxide film thickness.

be seen in Fig. 3. The erosion rate estimated for the very thin film of 2.5 nm was obtained by considering only material lost from the craters, there being no oxide stripping apparent. The mean number of craters produced by a stationary 1 μsec 4.5 A arc on the 2.5 nm film and their mean diameter has been obtained previously [14]. SEMs suggest that the craters are approximately hemispherical in shape, with rims containing about 60% of the crater material, and an estimate of the possible erosion rate was thus obtained which was scaled up to 45 A using the same method as for the thicker films.

The scaled-up erosion rates corresponding to 45 A were plotted as the continuous line in Fig. 4 for all the oxide thicknesses used in the stationary arcing. It can be seen that there is a peak in the estimated erosion rates at an oxide thickness of about 80 nm.

2.2. Single-traverse magnetically moved arcs

Similar erosion-rate estimates were made for the moving arcs. Here oxide-stripping normally occurred, as illustrated in Fig. 5, at the thicknesses explored of 44, 100 and 275 nm, except for arcs moving at velocities above about 120 m sec^{-1} on 44 nm oxide films, where a new type of damage was found [15] which consisted of relatively few large craters ~ 1 μm diameter (about 10 times the mean diameter of the craters in stripped areas) penetrating the oxide film, without large areas of oxide being stripped. These large craters had pronounced rims and their surface density was between 4 and 5 orders of magnitude below that of the craters in the oxide-stripping mode. At an

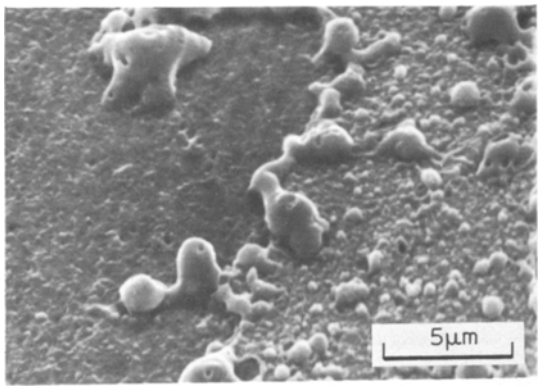

Figure 5 Boundary of stripped area produced by a moving 40 A arc on a copper oxide film of thickness 275 nm.

oxide thickness of 2.5 nm the situation was similar to that for stationary arcing in that large numbers of small rimmed craters were seen and there was apparently no oxide stripping present. A number of these craters could run into one another to form part of a cathode root track, and Fig. 6 illustrates this for an extremely short length of track formed by about 4 craters.

The erosion rate estimates for the oxide-stripping cathodes followed the procedure used for the stationary arcs. The area of oxide stripped per second is approximately the product of the arc velocity and the mean track width, and the calculation of the number of craters produced per second follows from a knowledge of the mean crater density. Again SEMs suggest that the assumption that the craters are cylindrical with depths similar to their diameters is reasonable. In estimating how much of the stripped oxide left the surface, the procedure used was different to that employed for stationary arcing, because it would have been extremely difficult to estimate the percentage of the stripped oxide remaining on the cathode, due to the extent of the damage and nature of the track. The tracks in the stripping mode can be of width up to 1 mm or more [15], much larger than the dimensions produced by the stationary short-duration arcing, and the particles being sought are often of sub-μm dimensions. These particles tend to be more widely scattered by the magnetically-moved arcs than by the stationary arcs. It was assumed that all the stripped oxide which did leave the cathode crossed the inter-electrode gap and landed on the anode. This is a reasonable approximation, as the arc usually ran near to the cathode centre and the cathode and anode widths were about 4 times the inter-electrode gap [15]. SEM examination of an anode surface, used in conjunction with a cathode having an oxide film of thickness 44 nm, together with estimation of oxide stripped away from the cathode as revealed by SEM, showed that only about 30% of the material stripped from the cathode actually left its surface, and Fig. 7 shows cathode material found on the anode. This percentage is considerably smaller than the 90% estimated for the same thickness when stationary arcing was employed, and although the inter-electrode gap is larger for the moving arcs which may affect the process of transfer from cathode to anode, it seems likely that the arc movement itself can appreciably affect the amount of stirpped oxide leaving the cathode. It follows that the percentage of stripped oxide leaving the cathode is likely to depend on arc velocity and that a considerable amount of work would be required to quantify the situation. The estimates of these percentages are subject to large scatter, so that as a first approx-

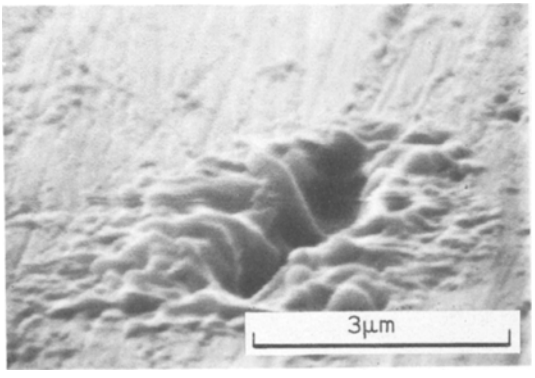

Figure 6 String of several craters produced by a moving 50 A arc on an oxide film of thickness 2.5 nm.

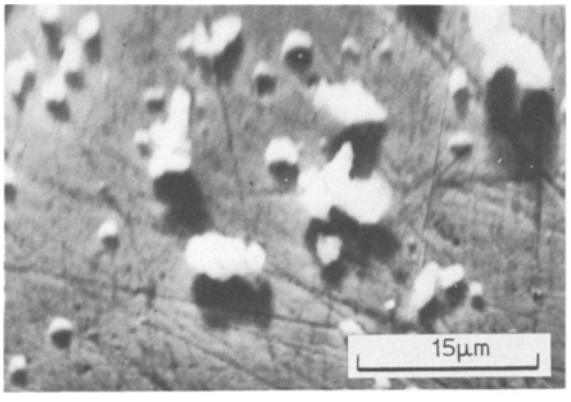

Figure 7 Particles of stripped oxide deposited on an anode from the copper cathode of a moving arc, original cathode oxide layer of 44 nm thickness.

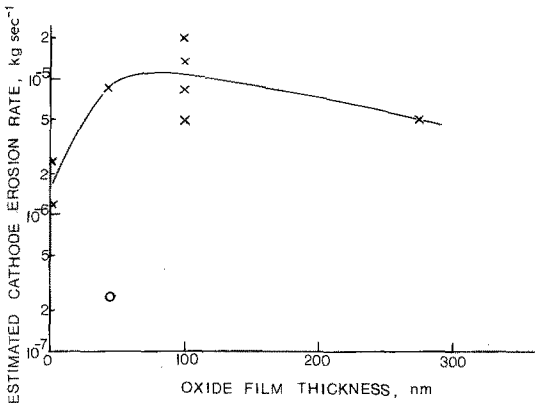

Figure 8 Estimated erosion rates for single-traverse 45 A arcs as a function of oxide film thickness.

imation it was assumed that for the 100 and 275 nm oxide films the percentage of stripped oxide leaving the cathode was similar to the approximate value for 44 nm, i.e. 30%. The calculated erosion rates were all normalized to 45 A, assuming an approximate dependence of erosion rate on arc current, as was found [4] for currents from 45 to 800 A. The values obtained for electrodes with 44, 100 and 275 nm oxide films are shown in Fig. 8.

Estimates of the erosion rates for moving arcs on 2.5 nm oxide films need only take into account material leaving the craters and, as for stationary arcs on this film thickness, the craters appeared to be approximately hemispherical in shape. However, for the moving arcs it was found that on average only 20% of a crater volume was contained in its rim, whereas for the stationary arcs it averaged 60%. The number of craters occurring per second was considered to be approximately the product of the mean crater density and the area of track swept out per second. The results of these calculations for two cathodes with 2.5 nm oxide films are plotted in Fig. 8 along with the results for the thicker films for which oxide stripping occurred.

An erosion rate was also estimated for a cathode with a 44 nm oxide film which did not show oxide-stripping. It was more difficult to estimate the mean crater density in this case because it is four to five orders of magnitude lower than those obtained for the other types of damage described, and the high magnifications required on the SEM to distinguish the μm-sized craters restricted the field of view to such small areas that only a small number of craters could be seen at once. Allowance was made for the crater rimming, which was estimated from observation of several craters to contain about 50% of the crater volume. The craters appear to be approximately cylindrical with mean depths of about 0.5 μm. The erosion rate obtained, normalized to 45 A, is plotted as a circle in Fig. 8 and is some 15 to 70 times lower than erosion rates calculated for moving arcs on the same oxide thickness, where stripping occurs. Comparison with Fig. 4 shows that it is also considerably lower than most of the erosion rates estimated for stationary arcing, the exception being that calculated for the 2.5 nm oxide film which is only about 60% higher than that for the non-stripping mode.

3. Discussion

3.1. Comparison of erosion rates for stationary and single-traverse arcs

Comparison of Figs. 4 and 8 shows that the calculated erosion rates for short-duration stationary and moving arcs have similar values and behave in a similar manner with variation in oxide thickness, (excluding the value for the quite different non-stripping mode on a cathode with the 44 nm oxide film). This close similarity seems rather surprising at first, but Fig. 9 shows that for stationary arcing the radius of the damage area (such as that shown in Fig. 2) for a 100 nm oxide film initially increases at very high speeds and that even at arc durations of 1 μsec this speed has only been reduced to about 15 msec^{-1}. Thus, in effect, the stationary arc can be considered to be a moving arc on a microscopic scale in which the emitting sites are moving radially outwards for some time. The

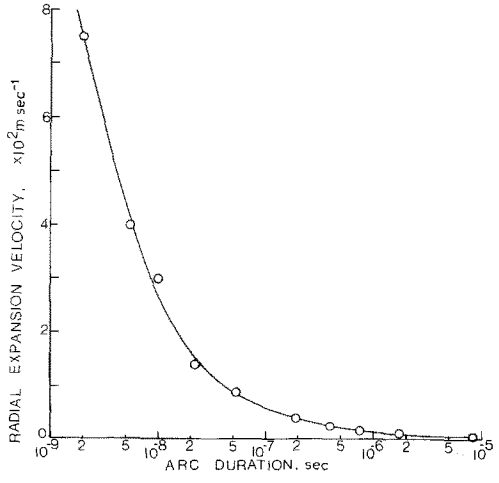

Figure 9 Instantaneous radial expansion velocity of the boundary of a stripped area on a 100 nm oxide film on copper for a 4.5 A stationary arc.

damage caused by a stationary arc is then likely to be similar to that obtained for a magnetically moved arc until, the static arc duration becomes sufficiently long and the damage region so large that all fresh emission has to occur from inside the stripped region. Eventually gross melting of the surface will ensue, but this is unlikely to occur on copper at 4.5 A until durations far in excess of 1 μsec are reached. Similar graphs to Fig. 9 would be obtained for the other oxide thicknesses for which stripping occurred in stationary arcing experiments.

3.2. Comparison of erosion rates for single traverse (or short duration stationary) and multiple rotation arcs

The complete range of erosion rates calculated here for single-traverse and short-duration 45 A arcs has extended from approximately 3×10^{-7} kg sec^{-1} to 3×10^{-5} kg sec^{-1}, whereas those measured [3] at 45 A for arcs of several minutes duration lay in the range 1.5×10^{-8} to 4×10^{-7} kg sec^{-1}. Several factors could contribute in this difference of between one and two orders of magnitude. These are:

(i) re-use of old emission sites in the long-duration tests as the arc exhausts its supply of fresh emission areas as the cathode root rotates many thousands of times,

(ii) the use of water-cooling in the long-duration tests,

(iii) the possibility that in the long-duration tests, material crosses from cathode to anode but subsequently returns to the cathode by the action of the arc,

(iv) the possibility that, because of the curvature of the cathodes in the long duration tests, material can pass across from one part of the cathode to another,

(v) oxidation of the cathodes in the long-duration tests as they are cooling down after arcing from running temperature, and re-oxidation near the end of the arcing period of some of the stripped areas which subsequently remain undamaged. The cooling period was generally much smaller than the arcing period.

After a little consideration, factors (ii), (iv) and (v) can be discounted. Factor (ii) is not important because in the short-duration tests there is insufficient time for an appreciable temperature rise in the cathode bulk so that the same erosion would occur for short-duration arcing even if there were water-cooling. Factor (iv) suggests that in the long-duration tests for 45 A arcing [1–3] the erosion rates for the outer cathode situation should always be lower than for the inner cathode. This was true only for erosion rates near the maximum values and there it was probably due [3] to the poorer water-cooling and heat transfer conditions for the inner cathode case. The gain in weight due to oxidation (factor v) can be shown to be negligible when compared with the calculated erosion losses, as follows.

After many of the long-duration arcing tests, examination of the cathode surfaces showed interference colours which indicated that their oxide films were often thinner than 120 nm [16]. Even if the oxide films were as thick as 500 nm, which was possible over part of the surface in a few of the tests, the weight gain of the cathodes due to oxidation would be only a maximum of about 10^{-6} kg, and even when this gain is averaged over the whole of a typical arcing-plus-cooling period of about 7 min, it represents a rate of gain only about 2×10^{-9} kg sec^{-1}, which is less than 1% of the smallest erosion rate calculated here. Estimates, using oxidation data for copper [17] together with background cathode surface temperatures measured previously by thermocouples [6], confirm that oxide films thicker than about 100 nm would be unlikely to form over the whole surface, even in the full arcing-plus-cooling time. Formation of localized thicker films probabaly results from transient local increases in temperature in the vicinity of the arc cathode root.

Factor (i) is of considerable importance. It has been found that when second and subsequent arc passages occur over the same cathode, the track does not tend to become appreciably wider, at least for the first ten arcs, and the rate of oxide stripping is then very low because most of the oxide within the track width has been removed. Thus fresh emission mainly occurs on successive arc passages from regions already stripped and filled with craters. When a number of arcs are moved a few times over the same linear path with a time interval between them, there is little temperature rise and thus no appreciable fresh oxide growth, and emission occurs around old craters, thus increasing their diameter and possibly their depth. Evidence from stationary arcing indicates that mean crater diameter increases only relatively slowly, e.g. from 0.1 μm after 4 nsec to about 0.15 μm after 3.5 μsec. Thus the mass of material

eroded from already stripped areas by successive arcs is far below that indicated by the mass lost in one arc multiplied by the number of arc passages.

Factor (iii) has now been investigated by passing ten single-traverse 45 A arcs at a velocity of about 100 msec^{-1} along a copper cathode with a 44 nm oxide film. At this current and velocity it has been shown that both the stripping mode and the non-stripping mode can operate on this oxide film thickness [15], but here the stripping mode predominated. A stainless steel anode was used with this cathode, and this anode was then used with an aluminium cathode for a further ten arcs of similar current and velocity. Using electron probe microanalysis it was found that copper from the first cathode remained on the stainless steel anode, and then in the second series of 10 arcs about 30% of this copper re-crossed the gap and landed on the aluminium cathode. This implies that during the first ten arcs between copper cathode and steel anode, some 25% of the copper which had transferred to the anode moved back again to that cathode. Although the concentrations of copper were rather low on the steel anode and aluminium cathode ($\sim 0.1\%$), it appeared that the total transfer of copper from the copper cathode to the stainless steel anode in the first ten arcs occurred at a rate of about 10^{-6} kg sec^{-1}.

This transfer rate cannot be combined directly with the erosion rate shown at 44 nm by the curve in Fig. 8 because the latter is for a single arc traverse and factor (i) needs to be considered. It has been estimated that factor (i) could cause the erosion rate for 44 nm given by the curve in Fig. 8, to be reduced from 8.7×10^{-6} to about 1.5×10^{-6} kg sec^{-1} for 10 successive arc passages. Thus if about 0.5×10^{-6} kg sec^{-1} of cathode material can be returned to the cathode after temporarily being on the anode, as has been estimated, then the net erosion rate for 10 arcs might be of the order of 10^{-6} kg sec.

This phenomenon of transfer of material from one electrode to the other has been reported [19] for stationary arcs between parted copper contacts over a wide range of currents. The electron probe microanalysis evidence given here shows that significant quantities of material, originating from the cathode and landing on the anode, can re-cross the gap when successive 45 A arcs each of duration ~ 1 msec are driven along the electrodes by a magnetic field. It seems likely that this phenomenon occurs to a much greater extent in long-duration rotating arcs. However, it is not thought possible to make a quantitative measurement of this, because there would be a constant transfer of cathode material to the anode and re-transfer of this material and also of parent-anode material back to the cathode, so that electron probe measurements would never distinguish accurately the amount of copper transferred because the thickness of the copper layer could exceed the depth of penetration of the electron probe, and because of its being over-laid by steel from the steel anode.

If instead of ten successive arc passages, one considers the thousands of arc passages occurring in the long-duration rotating arcs [1–3], then factor (i) could reduce the erosion rate to well below 10^{-6} kg sec^{-1}, which is approaching agreement with the range of erosion rates of 1.5×10^{-8} to 4×10^{-7} kg sec^{-1} measured by weight loss [3]. It must be remembered, however, that when a few successive separate arcs run along a cathode surface with appreciable time between them, the mean cathode temperature hardly rises above ambient. On the other hand, when an arc rotates many times over periods of minutes, then the mean surface temperature which can reach at least 260° C [6] causes fresh oxide growth.

3.3. Effect of oxide layer growth on long-duration erosion rates

The situation in long duration arcing is very complex. Because the background cathode surface temperatures rise to as much as 260° C [6], it would appear at first sight that the mean oxide thickness all over the cathode surface should be increasing with time, but with most oxide thicknesses and velocities used in long duration tests, oxide stripping occurs wherever the cathode roots pass. It is unlikely that the initial oxide film of thickness ~ 2.5 nm will be maintained for more than a few seconds [17], because the background temperature builds up to about 200° C within this time [6]. Thus, although the erosion rate may start off at very low values, as indicated by Figs. 4 and 8, it will soon reach the higher values corresponding to stripping oxide thicknesses of tens or perhaps hundreds of nm. A further complication is that for velocities of 80 msec^{-1} or more at an oxide thickness of 44 nm (and probably at a range of thicknesses above and below this) the non-stripping mode may occur [15], so that for a time, perhaps of considerable duration, when the

oxidation rate is low, the erosion rate may be extremely low as suggested by the circle in Fig. 8. In addition, there is the possibility that the oxide thickness varies considerably over the cathode surface at any instant, and the arc is likely to prefer to run in places where electron emission is easiest [18]. Because the oxide conditions on the surface can change appreciably with stripping and re-oxidation, there will be lateral fluctuations in the position of the arc superimposed on its magnetically-directed motion.

Because of the complexity of the process involved in long-duration arcing, no more than a semi-quantitative discussion can be given of the variations in the measured erosion rates with varying arc velocity [4], arcing duration [5] and cooling-water flow-rate [6]. At each current used in the range 45 to 800 A, where the cathode was the outer electrode, the erosion rate was found [4] to vary through a range of 5:1 or even more when the arc velocity was varied. Figs. 4 and 8 show that this type of variation can be explained by changes in the oxide film thickness as the velocity is varied. In particular, at 45 A [3] additional information is available for two cathodes, designated A and B, exhibiting high and low erosion rates respectively. Cathode A was initially estimated [3] to have a mean oxide thickness of the order of 600 nm after arcing, but further consideration using cathode surface temperatures measured at 100 A [6] suggests that the mean oxide thickness was probably as low as 300 nm. Cathode B was estimated [3] to have a mean oxide thickness of about 45 nm. In the apparatus used [2] the cathodes are believed to have cooled to room temperature in a maximum period of about one minute. Data on the oxidation of copper [17] used together with accurately measured cathode surface temperatures [6] suggest that for cathode A it was likely that about 100 nm of oxide grew during cooling, while for cathode B at most 15 nm. For cathode A the maximum oxide thickness during arcing would then be approximately 200 nm and for cathode B it would be 30 nm. Thus cathode B would arc at the very low thicknesses well to the left of the peak in Figs. 4 and 8, where the erosion rate stays at the lowest values, while cathode A would almost certainly spend a large proportion of its time arcing at thicknesses in the range 30 to 200 nm where erosion rates are appreciably higher than any encountered by cathode B. Based upon these results, Fig. 4 indicates a ratio of about 5:1 and Fig. 8 indicates a ratio of 3:1 in the two erosion rates, and these help to explain the 8.4:1 ratio of the erosion rates actually measured for cathodes A and B. This measure of agreement has been achieved even before considering the effect of factors (i) and (iii), discussed in Section 3.2.

When the cooling-water flow-rate was varied at each of two velocities for 100 A arcs, a similar approximate magnitude of overall variation of up to about 4:1 in the erosion rate was obtained [6] as was found for arc-velocity variation. Further, it was found that high erosion rates often corresponded to high cathode surface temperatures [6] and partial blackening of the cathode surface, which indicates that the oxide films were thicker in places than the range of interference colour thicknesses (40 to 130 nm). On the other hand, low erosion rates generally corresponded to oxide films in the interference colour thickness range and low cathode surface temperatures [6]. None of the mean thicknesses exceeded 100 to 200 nm so that the erosion of these cathodes agrees with the behaviour predicted by Figs. 4 and 8. These also suggest that if the mean oxide thickness increases with increasing arc duration, then the erosion rate should also increase with time, provided the oxide film thickness does not exceed some few hundreds of nm. When the oxide film thickness increase above about 80 nm, however, it seems that it may be possible for the instantaneous erosion rate, and hence the overall average rate, to decrease with time. The cathode mass loss, M, at fixed arc current, arc velocity and water flow-rate has been found [5] to be given by $M = kt^n$, t being the arcing duration and k and n are constants. If the surface being eroded did not have an oxide film of varying thickness, then it would be expected that $n = 1$. Normally $n > 1$ but in one test at 100 A n did fall below 1 after about six minutes of arcing, possibly indicating that the oxide film had exceeded a thickness of 100 nm. Confirmation that this was probably so was also provided by the failure of this cathode to support stable arcing on its surface for as long as another electrode at 100 A which had $n > 1$ throughout its arcing life [5], thus suggesting that the oxide film on the former did build up more rapidly.

3.4 The earlier model of erosion [3]

The previous model of erosion proposed by Guile [3] for cathodes with oxide films thicker than ~ 10 nm, does not now seem to be applicable for

the stripping mode. In this model the eroded material was thought to come only from craters which had originally contained current-carrying filaments formed through the oxide. These filaments were supposed to become molten as a result of joule heating [7] and the molten material was explosively ejected from the cathode. This is still thought to be true. Filamentary currents were calculated to be in the range 10 to 80 mA and the lifetimes of these filaments were estimated to be about 1 μsec [3]. It now seems likely that for these relatively thick films emission site currents are about 10 mA and that the site lifetimes are in the range 1 to 100 nsec [14]. Large quantities of the oxide film are also stripped from the cathode, as well as the crater material ejected from former emitting sites. It is possible, however, that the erosion model of Guile [3] does apply to the non-stripping mode. Site lifetimes of about 1 μsec calculated using the model are similar to those obtained in the non-stripping mode, but there is a difference of more than an order of magnitude between the calculated site currents [3] and the non-stripping mode site currents [15].

4. Conclusions

It has been shown that erosion rates estimated for short duration stationary arcs are similar to those estimated for single-traverse moving arcs on the same oxide films, when reasonable allowance is made for the different arc currents. These calculated erosion rates may be reconciled with measured erosion rates for long-duration arcing by taking into account; (a) modifications which occur to the emission and erosion processes as the duration is increased and stripping and re-oxidation both occur, and (b) the large proportion of cathode material transferred back to the cathode after first being deposited on the anode. A semi-quantitative discussion has been given of the variations which occurred in measured long duration arcing erosion rates when arc velocity, arcing duration and cathode cooling-water flow-rate are varied and it appears that the lowest attainable erosion rates should occur if the oxide film thickness can be maintained as near as possible to about 2.5 nm throughout the arcing duration. An earlier model of erosion of copper cathodes with relatively thick films ($\geqslant$ 10 nm) is now thought to have only limited applicability.

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