THE EFFECT OF CATHODE SURFACE TEMPERATURE ON EROSION RATE IN A SCHOENHERR TYPE ARC HEATER OPERATED ON OXYGEN

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ABSTRACT

It has been suggested in unpublished work on copper alloy electrodes, and also documented by Guile\(^1\) working with OFHC copper electrodes, that cathode erosion rate obeys an Arrhenius type relationship with the average surface temperature of the arcing area \(T_i\) in K. In order to test this hypothesis the erosion rate of copper alloy cathodes\(^2\) was determined at constant arc current in a Schoenherr type arc heater operated in oxygen over a range of \(T_i\). The range of \(T_i\) investigated was limited due to a tendency for the heat flux to adjust so that variations in \(T_i\) were minimised, and while cathode erosion rate is shown to be markedly dependent upon \(T_i\), the results do not give detailed support to the hypothesis.

1. INTRODUCTION

The use of direct current arc heaters, as a source of high temperature oxygen, has been successfully applied to titanium dioxide production by Tioxide over a period of approximately 20 years. To obtain maximum plant efficiency the frequency of process interruptions necessary for replacement of worn electrodes must be minimised. In the Tioxide application with copper or copper alloy electrodes, cathode lives of up to 1,000 hours are regularly achieved, with anode lives in excess of 2,000 hours. Thus the useful life of the units is determined by the rate of wear of the cathode.

Erosion of the cathode is controlled by (a) choice of electrode material, (b) efficient cooling of the electrode, and (c) imparting a high speed circular motion to the arc root by means of vortex injection of the working fluid and application of an axial magnetic field. The effect of cooling and arc linear velocity upon cathode erosion rate has been investigated extensively by Professor Guile of Leeds University\(^2\)\(^-\)\(^11\). Part of this work showed that cathode erosion rate was not necessarily a simple function of arc or coolant velocity for magnetically rotated arcs, but a series of maxima and minima was observed at critical values of magnetic field strength and cathode cooling water flowrate.\(^7\)\(^-\)\(^11\). It was postulated in Ref. 11 that minima in erosion rate occurred when the thickness of the surface oxide film was a few tens of nm, with maxima occurring when the oxide film thickness is some hundreds of nm. This postulate was in accord with Tioxide experience, in that erosion rate was found to increase with operational lifetime and increasing oxide film thickness. A closer examination and comparison of erosion and oxidation rates of copper and copper alloys indicated a probable correlation between the two and hence between erosion and cathode surface temperature, in that erosion rate might be expected to exhibit an Arrhenius type relationship with...
surface temperature. As a first step the results from three different scales of operation were analysed and a correlation between the erosion rate and the estimated electrode surface temperature \( (T_i) \) was developed. The results of this analysis are shown in Figure 1. The resultant relationship was of the Arrhenius type but included a pre-exponential term involving erosion band width \( (W) \), gas flow rate \( (m) \) and cathode internal diameter \( (d) \),

\[
i.e. \quad \frac{dm}{dt} = A \left( \frac{W^a m^b}{d^c} \right) \exp \left( \frac{-G_e}{RT_i} \right)
\]

Surprisingly, no effect of arc current was found. The effective activation energy, 0.20 ev, is in close agreement with Guille's value of 0.17 ev\(^1\), who found a simple Arrhenius relationship for arcs running on copper electrodes in a 2 mm annular gap. For the Schoenherr type arc heater it is also necessary to include a pre-exponential term representative of the scale of operation, the significance of which is not yet understood.

Whilst useful for predictive work when changing operating parameters or scale, it was decided that the utility of this approach for optimisation of a particular unit size warranted investigation. In the work described the average inner wall temperature of the cathode erosion zone was varied by change in coolant flowrate and cathode wall thickness.

2. \textbf{EXPERIMENTAL}

The arc heater used in this study, was developed by Tioxide from a Linde N250 unit, and has a normal operating range of 50 to 250 kW. The proprietary tubular copper alloy cathode electrode, 27.5 mm O.D. x 184 mm long, is water cooled with coolant supplied on a closed loop system by a multi-stage, high pressure pump. A solenoid fitted to the rear electrode (cathode) provides an axial magnetic field which rotates and controls the axial location of the arc root. The peak magnetic field strength is normally 0.09 Tesla. Oxygen was supplied from a high pressure pipeline and injected tangentially through critical orifices into the inter-electrode gap. Arc initiation was carried out by applying a suitable open circuit voltage across the electrodes and injecting helium into the electrode gap\(^1\). All tests were carried out at a constant arc current of 100 A.

Heat loss to the cathode was calculated from coolant flowrate and inlet and outlet water temperatures, monitored by thermocouples. Cathode weight loss rates were determined over a total period of approximately 20 hours by weighing the clean electrode every 4 hours. For a given set of operating conditions individual results were found to be reproducible to with \( \pm 5\% \) of the mean value.

Two series of tests were carried out. In the first, \( T_i \) was varied by changing coolant velocity at three different conditions of arc heater operation. In the second series the cathode wall thickness was varied and the coolant flowrate adjusted in order to change \( T_i \) in a predetermined manner, on the assumption that the heat flux would be constant for a given set of arc operating conditions. In practice, the heat flux was found to exhibit a fairly strong dependence upon coolant flowrate, making controlled variation of \( T_i \) impossible.

3. \textbf{RESULTS AND DISCUSSION}

The results are given in Table 1, where \( T_i \) is calculated from the heat flux and conventional heat conduction and convection equations, assuming that all of the heat is lost to the coolant through the erosion band when steady state conditions exist. For conduction through the cathode wall, the difference between the inner and outer cathode surface temperatures is given by

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\[ T_1 - T_w = \frac{Q}{2\pi K W} \ln \frac{r_o}{r_i} \]  

where \( K \) is the thermal conductivity of the cathode material, \( W \) the effective width of the heat path, taken as equivalent to the width of the erosion band, obtained by measurement upon completion of each test, \( r_o \) and \( r_i \) the outer and inner radius of the cathode.

For convective cooling of the outer wall

\[ T_w - T_b = \frac{Q}{h_{nb} \pi d W} \]  

where \( h_{nb} \) is the convective heat transfer coefficient, \( T_b \) the bulk temperature of the coolant and \( d \) the outer diameter of the cathode.

A detailed examination of the results shows that the erosion rate is strongly dependent upon coolant velocity, as shown in Figure 2. There is little evidence of a cyclic variation as observed by Guile, erosion rate approaching a minimum level with increasing coolant velocity. Erosion rate plotted as a function of heat transfer coefficient, \( h_{nb} \) and \( \ln \frac{r_o}{r_i} \), shown in Figure 3, clearly establishes that the rate is a function of \( \frac{T_1}{r_i} \), when reference is made to the heat transfer equations.

A comparison of the measured erosion rates with those predicted by Equation (1) is shown in Figure 4. There is considerable scatter in the results, with a tendency for under prediction. It is apparent that while useful on a global scale Equation (1) cannot be used for detailed prediction of erosion rate without further refinement. The effective activation energy of 0.20 ev provided by Equation was suggested by Guile to be indicative of fusion of the electrode material as the dominant arc erosion process. This explanation is favoured by the author as a result of observations made over a considerable period of time. It is noticeable that with new electrodes there is an initial period, which can extend to tens of hours, during which time the arcing area attains a polished finish, prior to formation of islands of oxide which ultimately spread to totally cover the area traversed by the arc root. The difference in erosion rate for the two surfaces is minimal e.g. the electrode from runs 1 and 2 (Table 1) had an oxidised erosion band while those from runs 3 and 4 had a polished band. The relatively minor differences in erosion rate suggest a common erosion controlling mechanism. Notable differences in rate only occur when the oxide layer is sufficiently thick for spalling of the oxide to occur, with a resultant increase in erosion rate.

4. CONCLUSIONS

The dependence of erosion rate of copper alloy cathodes operating in an oxygen atmosphere upon average surface temperature, can be broadly described by an Arrhenius type relationship with an apparent activation energy of 0.20 ev. This relationship allows a reasonable estimate to be made of erosion rate when changes in operating conditions and/or scale are required but further refinement of the relationship is required before detailed prediction of cathode erosion rate can be made. In particular, the validity of the assumptions made in the estimation of average surface temperature needs to be checked. Further work involving an investigation of the radial and axial temperature gradients within the electrode wall is therefore required.
ACKNOWLEDGEMENTS

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REFERENCES

12. B.P., 1,112,444.
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<th>Heat Loss to Cathode (Watts)</th>
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\[ X = \text{SCALE 1} \]
\[ \Delta = \text{SCALE 2} \]
\[ \bigcirc = \text{SCALE 3} \]

\[ x_{\text{WALL}} = 5.89\,\text{mm} \]
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\[ \bigcirc \text{ WALL} = 3.89\,\text{mm} \]
\[ \Delta \text{ WALL} = 1.89\,\text{mm} \]

**FIGURE 1**

**FIGURE 2**

**FIGURE 3**

**FIGURE 4**