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Arc behaviour and plasma chemistry in electrode erosion

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Abstract - This paper deals with the fundamental aspects of cathode erosion for non refractory materials and highlights the importance of the system chemistry for cathode erosion. The experimental work was performed in a test chamber with concentric copper cylinders as electrodes. The arc current varied between 100 - 1 100 A. An external magnetic field, varying from 10 to 1 500 G was used to move the arc. Different plasma gases were used (Ar, He, N_2, air, CO, Cl_2, CH_4 and mixtures of the polyatomic gases with the inert gases) at atmospheric pressure. Heat transfer simulations included both transient two dimensional models and steady three dimensional models. It is shown that the cathode erosion is a physical phenomenon and that it is a function of three main parameters: arc residence time, arc attachment diameter and cathode spot distribution. The system chemistry affects all three parameters and it is of fundamental importance in cathode erosion phenomena.

INTRODUCTION

Electrode erosion still limits the industrial application of thermal plasmas. For non refractory materials, the rate of cathode erosion is greater and therefore has been more studied. The understanding of electrode phenomena is important in any thermal plasma application since the electrodes are partially responsible for the stabilization and behaviour of the electric arc and plasma. Many parameters have been proposed as being important for cathode erosion (B,I, arc velocity, cooling, gas flow rate, arcing duration, type of plasma gas, purity of the electrode materials) by different researchers (ref.1-4).

What follows is a summary of the present knowledge based on our own work and that of others. We make a special effort to highlight importance of the composition of the plasma gas and electrode on arc behaviour and electrode erosion. Whenever possible, we present conceptual models representing the phenomena.

EQUIPMENT AND EXPERIMENTAL PROCEDURES

Many different types of equipment have been used to study electrode erosion. They can be separated into two classes of experiment: transient, in which the electric arc and plasma pass once over the electrodes and the arc is extinguished (rail electrodes is a typical example) and continuous, where the electric arc and plasma move over the electrode surfaces over long periods (concentric cylindrical electrodes is a typical example). We chose continuous experiments with concentric electrodes for our work. The pressure is near atmospheric.

The equipment used in the experimental part of this work has been described in detail elsewhere (ref. 5). A schematic diagram of the equipment used is shown in Fig. 1. It consists of concentric cylindrical copper electrodes. The arc is struck between the electrodes and is rotated by an axial external magnetic field or by a gas vortex, or a combination of the two. The magnetic field strength was varied between 10 and 1 500 G; the arc current between 100 - 1 100 A although most of the results were

obtained between 100 and 200 A. The chemistry of the atmosphere inside the test chamber is well controlled and the pressure is kept at 1.1 atm. The plasma gas was normally injected axially at the top of the chamber; the gas flow rate varied between 0 to 40 standard l/min and for most experiments was fixed at 20 l/min. The erosion was determined by weight difference (before and after the experiment). The electrodes were cleaned with dilute nitric acid before weighing to ensure that the native oxide layer formed before experiments was always the same and that any oxide formed during the experiment was removed before weighing. Different plasma gases were used; Ar, He, Cl_2, H_2S, N_2, NH_3, O_2, H_2, CO, CH_4, air, and mixtures of the polyatomic gases with the inert gases.

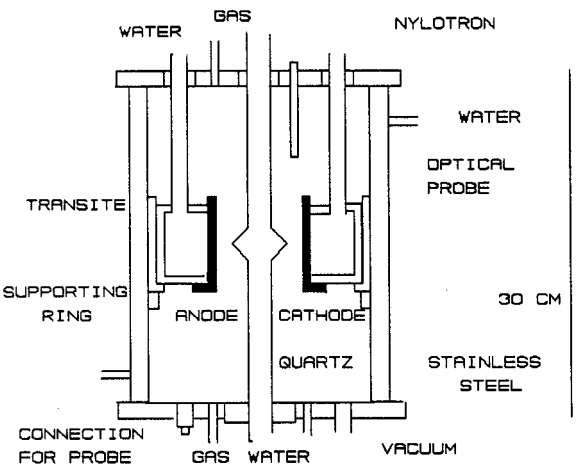

Fig. 1. Schematic drawing of equipment

Several different diagnostic techniques and instruments were used during the experiments: an optical probe (for mean arc velocity measurements), high speed filming, arc voltage fluctuation measurements, an arc foot current density probe, Auger-ESCA-SEM measurements for surface analyses and a Kelvin probe for work function measurements. These techniques and equipments have been described in detail elsewhere (ref. 6-8). The most important experimental and theoretical results and conclusions are presented below.

RESULTS AND DISCUSSION

I. Erosion, a physical phenomenon

In our work even for very reactive atmospheres such as Cl_2 and O_2, we concluded that cathode erosion is a physical phenomenon controlled by heat transfer. Erosion is caused by the application of localized heat which cannot be dissipated either by conduction through the cathode or radiation and convection from the cathode surface. In order to maintain an energy balance, material melts and volatilizes from the cathode surface resulting in erosion of the electrodes. The chemistry of the system is important because it affects the physical parameters important for erosion but not directly as a chemical reaction between the electrode and the plasma. This is further discussed below.

Our experimental results, those of other researchers and the analysis of our heat transfer models lead us to suggest that three parameters are important for erosion on copper cathodes: arc residence time, arc root diameter and cathode spot density (distance between spots). The influence of each of these as well as the influence of chemistry on them is explained below. The various interactions between the parameters influencing copper cathode erosion and electrode erosion in general are shown schematically in Fig. 2.

II. Parameters affecting cathode erosion

A. Arc residence time

Two types of arc velocity are important in determining the arc residence time at a specific spot on the electrode: the mean arc velocity and the instantaneous arc velocity. They are discussed separately below.

a) Mean arc velocity

From a macroscopic point of view, the faster the arc root moves over the electrode surface, the more uniformly is its heat distributed and the lower should be the erosion. To understand the importance of chemistry on the arc velocity, it is first necessary to understand how the electric arc and plasma are affected by the magnetic field, current and other parameters. It has been proposed, for our geometry, that the steady state velocity of an electric arc driven by a magnetic field is determined by a balance

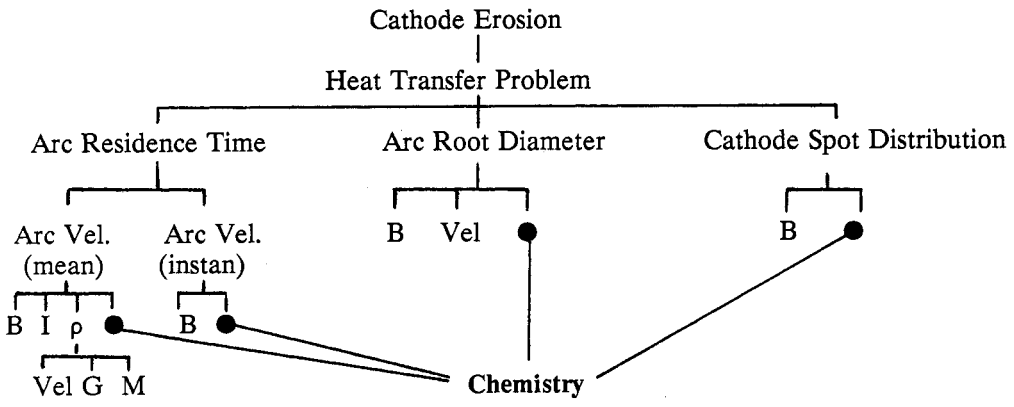

Fig. 2. Interactions between cathode erosion operating characteristics and chemistry

between the Lorentz force and an aerodynamic drag force. The former pulls the arc forward while the latter retards it. This balance of forces predicts that

$$\text{Vel} \propto B^{0.50} I^{0.50} \tag{1}$$

where Vel = arc velocity, B = magnetic field strength, I = arc current

We have shown (ref. 7) that this analysis neglects a very important "surface drag force" acting on the arc root. The correct equation is:

$$B I d + 0.5 C_d d D \rho \text{Vel}^2 + S = 0 \tag{2}$$

where B = magnetic field, I = arc current, C_d = drag coefficient, d = arc length in the direction perpendicular to B, D = arc diameter, ρ = gas density, Vel = arc velocity, S = surface drag force. Further, the arc diameter is a function of the current and velocity, while the density of the gas through which the arc passes is a function of its molecular weight and temperature. In cases where the surface drag force is negligible (see below), the arc velocity should be:

$$\text{Vel} \propto B^{0.60} I^{0.56} \tag{3}$$

As has been verified (ref. 7) for arcs in argon and helium contaminated with low concentrations of polyatomic gases. The importance of the mean arc velocity on cathode erosion can be seen in Fig. 3, where pure N_2 was used as the plasma gas. As the arc velocity increased the cathode erosion rates decreased. This effect is also predicted by our three-dimensional heat transfer model for a uniformly moving arc root on the surface of a copper cathode (ref. 9). Harry (ref. 4) also observed this reduction in cathode erosion rates for faster arcs in air.

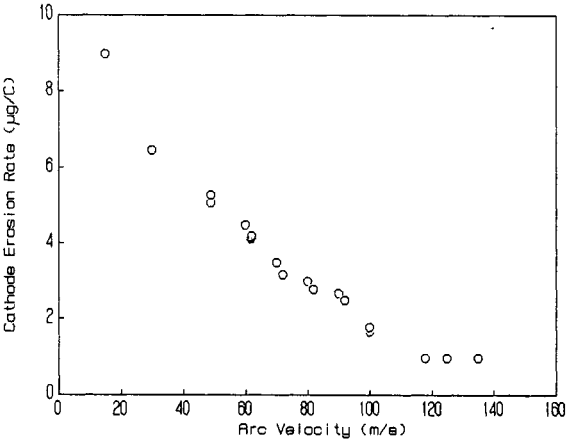

Fig. 3. Erosion rates in nitrogen as function of arc velocity.

b) Instantaneous arc velocity

When the surface drag is important, the arc velocity is not uniform on a short time scale; then the instantaneous arc velocity becomes important. To understand the importance of the surface drag force is first necessary to understand how the arc moves. The arc root moves from one discrete arc attachment to another on the cathode only if the combined voltage drop due to the arc column and electrodes falls are less than those at the present site. Since the column voltage increases as the

arc is stretched by the magnetic field, at some point, the arc is forced to move to a new site. Thus the ease with which a cathode emits electrons affects the speed at which the arc can move; the apparent "surface drag" increases as electron emission becomes increasingly difficult.

We have shown (ref. 8) that the work functions of copper cathodes which had been operated in argon or helium with low concentrations of CO or nitrogen were lower than that of pure copper cathodes. A higher work function was also found for electrodes operated in Ar+10%Cl_2 which had "thick films" (> 10 μm). Mean velocity measurements showed that for clean surfaces or thick contaminant layers, equation (ref. 3) was not followed and that surface drag was important. High speed photography showed that the arc was always held back by the cathode attachment giving a visual confirmation of the existence of surface drag.

Instantaneous arc root velocities measurements were made using a frame-by-frame analysis of high speed movies of the arc shot at 5 000 frames/s. The results were presented as histograms which gave the frequency distribution of the distance moved between frames. As an example, the histograms for five arc rotations for Ar and Ar+0.3%CO are presented in Fig. 4. Although the mean arc velocities were both approximately 4 m/s, the instantaneous arc velocities were quite different. In argon, the arc root remained still or almost still for long times and then suddenly jumped large distances. The arc in Ar+0.3%CO moved uniformly. We were also able to correlate the arc voltage or current fluctuations with time to the arc motion. Thus, an arc in argon showed continuous small variations in current upon which were superimposed about 25 large peaks in current. These peaks occurred at voltage minima, i.e. when the arc jumped to a new location.

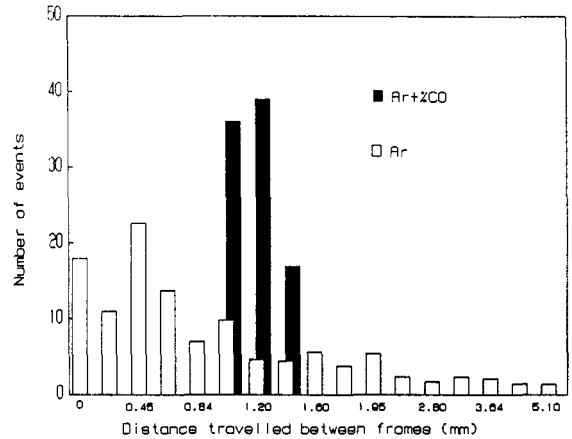

Fig. 4. Histograms of residence time distribution for argon and Ar+0.3%CO.

The importance of instantaneous velocity on erosion rate is shown by an erosion rate of 13.5 μg/C in argon and only 0.4 μg/C in Ar+0.3%CO at the same mean arc velocity of 4 m/s. Similar results were obtained for argon contaminated with nitrogen.

The effect of instantaneous velocity was also examined using a two-dimensional transient model with cylindrical geometry (ref. 9). The model could treat single or multiple cathode spots (see below) with a finite lifetime. As a first approximation, no phase changes were considered, and a volumetric source term was used to simulate Joule heating and ionic bombardment which are the important heat sources for cathode erosion. The only mechanism for heat loss was conduction through the cathode. The input parameters were power input, cathode spot dimensions (radius and depth), cathode spot lifetime and the dimensions of the cathode.

The variation of the cathode maximum temperature (top of the cathode surface at the centre of the cathode spot) with cathode spot lifetime is shown in Fig. 5. The total power input was 1 000 W, the cathode spot diameter 1 mm and the dimensions of the cathode were radius 5 cm and thickness 2.5 mm. It can be seen that the increase in the temperature is extremely fast; less than 100 μs after the heat pulse started, the temperature already was 60 % of its "steady state" value at 100 s. These simulations show the tremendous importance of the instantaneous arc

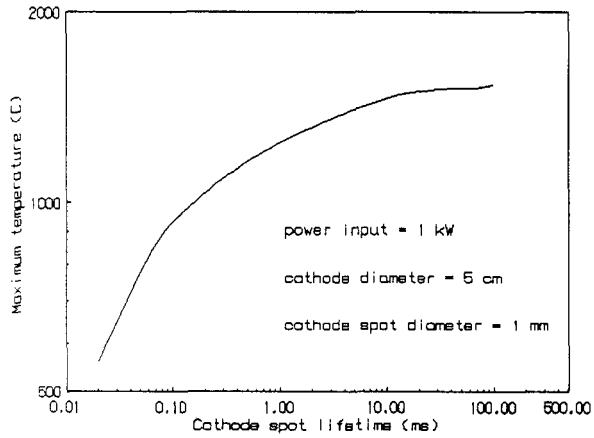

Fig. 5. Variation of maximum cathode temperature with cathode spot lifetime.

velocity. The arc for pure Ar and Ar+0.3%N_2 (with low magnetic fields) remained stationary for more than 100 μs, and at times as long as 1 ms. The simulations can explain the high erosion rates of these experiments. If the arc stays over a spot for 100 μs instead of the 10 μs which are characteristic of a more uniformly moving arc, such as Ar+0.3%CO, the cathode surface temperature would be twice as high and therefore the cathode erosion will increase significatively.

Table I: Current densities and arc root dimensions for different operating conditions

	B (G)	I (A)	Vel (m/s)	J_{max} (kA/m)	D_{max} (mm)	D_{eq} (mm)
Ar	1000	95	8	75	2.5	1.2
He	1000	110	23	33	8.5	2.1
He+0.4%N2	800	110	180	11	27	3.6
He+0.4%CO	30	110	230	12	32	3.4
Ar+0.3%CO	30	140	9	42	10	2.1

B. Arc root diameter

To examine the effect of current density and arc attachement on erosion rate, we developed a new technique to measure the linear current density of the arc attachment at the cathode (ref. 10).The technique uses the signal induced in a coil imbedded below the surface of the electrode and this overcomes many of the problems with previously used methods. It has been shown that the equivalent arc attachment diameter (D_{eq} = [4 I/(J_{max} π)]$^{0.5}$) depends primarily on the surface chemistry and magnetic field strength and slightly on the arc velocity. Some examples of the peak linear current density, the maximum dimension of the arc root and D_{eq}, for different operating conditions are given in Table I.

At the same magnetic field of 1 000 G, argon and helium had erosion rates of 13.5 and 1 μg/C respectively. No direct observation can be made of the effect of arc diameter on erosion rate because the velocities were different. By decreasing the argon flow rate, it was possible to speed up the arc in argon. Extrapolation of erosion rate versus velocity data gave an erosion rate of 3 μg/C for argon which is much higher than the value obtained for pure helium at the same velocity. The data show that erosion rate is approximately inversely proportional to the square of the equivalent arc diameter, or directly proportional to the mean current density. Within experimental error, the same results were obtained for the case of helium contaminated with small amounts of CO and nitrogen.

The importance of arc attachment diameter was also simulated using the 3-D steady state heat transfer model. The surface temperatures obtained using an input power of 1 000 W and a velocity of 2 m/s while varying the attachment diameter from 0.01 to 2 mm are shown in Fig. 6. The surface temperature reaches extremely high values because no melting or volatilization of material is considered. The results show that surface temperature and thus erosion is a strong function of D_{eq}.

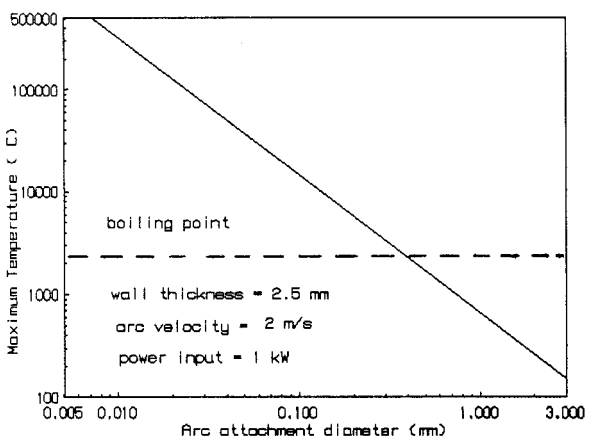

Fig. 6. Effect of variations in arc attachment diamter from 3-D model.

C. Cathode spot distribution

The arc attachment at the cathode is made of individual cathode spots (ref. 11-13). Different researchers claim that that each spot carries currents between 0.5 and 3 A, has a dimension between 0.1 and 1 μm and a lifetime between 0.1 and 1 us. The very existence of these cells has been disputed by other researchers (ref. 14,15). We found an indirect verification of the existence of these cathode spots.

Although our technique for measuring the arc attachment at the electrodes was usually incapable of resolving individual cathode spots, some signals were definitely composed of individual contributions.

This was the case for example for Ar and He contaminated with CO and to a smaller extent for He contaminated with N_2 and pure nitrogen and always at low magnetic field. For argon contaminated with 0.3% CO, 50 individual contributions could be resolved. A possible interpretation of the splitting of the signal is that it represents the individual spots which make up the arc attachment. In view of the limited resolution of the probe, it must then be concluded that the spots observed under low magnetic fields and contaminated surfaces were further apart then was normally the case. This has an important effect on the erosion rate.

Our 2-D, transient heat transfer model simulations indicate that the surface temperatures reached between individual cathode spots is a very strong function of the spot separation. This is shown for example in Fig. 7 where cathode surface temperatures are shown for two different spot diameters at separations of 1.5, 10, and infinite spot diameters. It is clear that not only is the power density for the attachment very important , but so is the geometric distribution of the spots in the arc attachment.

We obtained experimental evidence for this using nitrogen arcs. At a field of 250 G (gas flow rate of 20 l/min) the arc velocity was 50 m/s and the erosion rate 5.6 μg/C. For a field of 130 G (gas flow rate of 0.2 l/min), where the spot separation was expected to increase, the arc velocity was 47 m/s and the erosion rate was 4.0 μg/C. Thus even for a lower arc velocity, the erosion rate was 29 % lower at the lower magnetic field. Similar results were obtained with argon and helium contaminated with nitrogen and CO at low magnetic fields.

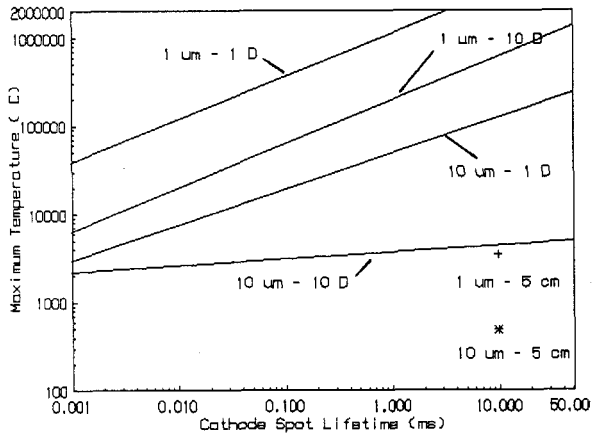

Fig. 7. Effect of cathode spot spacing on cathode temperature from 2-D model.

III. Other aspects of electrode erosion

A. *Minimum erosion rate for isolated spots*

Some researchers (ref. 3) have reported a minimum erosion rate for copper cathodes of the order of 0.3 μg/C using air at atmospheric pressure. We found a minimum erosion rate of around 0.4 μg/C for Ar+0.3%CO, He+0.4%CO at high magnetic fields as well as for Ar+0.3%CO and He+0.4%N_2 at low magnetic fields. Slightly lower values, around 0.3 μg/C, were found for very short time experiments (10 s experiments). Therefore it seems that for the whole range of operating conditions ($0 < B < 1\,500$ G, $80 < I < 1\,000$ A, different plasma gases) there was a minimum value for the erosion rate of the cathode which compares well with the value found by other researchers. In all these cases the minimum value was found for contaminated surfaces, where the spots are further apart.

B. *Cathode erosion rate at high currents*

The maximum arc current used for our experiments was 1 100 A, with Ar+0.3%CO. Up to this level of current, there was no difference in the erosion rate when compared with lower arc currents (up to 200 A). The arc velocity also followed equation 3 up to the maximum current used in this work.

C. *Power input to the cathode*

Although we calorimetrically measured the power input to the cathode for each experiment, we were able to find no correlation between this power input and erosion rate. This is because the main contribution to the power input is due to radiation from the arc and its flux is too dilute to cause erosion.

D. Anode erosion rate

The erosion rate for the anode was measured with helium as the plasma gas. The polarity of the electrodes was inverted in order to have the anode as the test electrode. No weight loss was detected over the maximum operating time (dictated by the severe erosion of the now small cathode) indicating that the erosion rate for the anode was at the most 0.1 μg/C (the precision of the scale used was better than 0.001 g). This low erosion rate was corroborated by the fact that a single anode could be used for at least 50 hours during cathode erosion measurements for different plasma gases. The lower erosion rate for the anode is probably due to the lower current density when compared with the cathode. The current density of the arc at the anode was measured for pure argon arcs and indeed it was much smaller than for the cathode (ref. 6). The anode does also not display anode spots for currents lower than 1 000 A (ref. 16) and therefore the heat is dissipated over the entire arc attachment.

CONCLUSIONS

The erosion of copper cathodes is a physical phenomenon, depending on the temperature of the cathode surface within the arc attachment region. The arc attachment is made of individual contributions, the cathode spots. The cathode spots can be grouped closer together or at greater spacing according to the external magnetic field strength and surface conditions (chemistry of the system). The erosion rate reaches a minimum value when the spots are further apart. The erosion rate is also affected by the residence time of the arc attachment over the same region of the cathode surface.

Acknowledgements

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