Effects of cathode materials and arc current on optimal bias of a cathodic arc through a magnetic duct

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A negatively biased collecting plate was used to collect the ion current of the cathodic arc plasma transported through a curved magnetic duct. The optimal duct bias at which the duct has the maximum efficiency for plasma transport was measured for C, Ti, Mo, and W plasmas as a function of the arc current and guiding magnetic field. The optimal bias decreased with the magnetic field and was almost steady when the field was above 400 G. The optimal bias at 400 G and above increased with the arc current for C plasma but the opposite relationship was observed for Ti, Mo, and W plasmas. The effects of the plasma density, ion mass, ion kinetic energy, and magnetic field on the optimal bias are discussed. © 2002 American Institute of Physics. [DOI: 10.1063/1.1481235]

Plasma deposition systems are used in many industrial applications for the surface modification of materials and fabrication of coatings and thin films. Filtered cathodic arc plasma deposition is an increasingly important method of producing good quality dense coatings. 1–3 The guiding magnetic field and duct bias have been the subject of intense research, and the effects of the guiding magnetic field and the duct bias on the plasma transport have been investigated. 4–6 Almost all the experiments described in the literature have used titanium cathodes, and the arc current is fixed at 100 A so that cross comparisons among different research groups are meaningful. Under these conditions, the optimal duct bias is about 20 V and independent of the guiding magnetic field when the guiding magnetic field is above 300–400 G. This optimal bias enhances the plasma output by a factor of about four. The plasma output of the duct has been observed to increase monotonically with the guiding magnetic field. 4 However, many different cathodic arc materials are used in industry, and the optimal arc current is not always 100 A for different materials. Little is in fact known about the effects of the arc current and cathode materials on the optimal bias. We have determined the optimal duct bias for C, Ti, Mo, and W cathodic arc plasma transports at 50, 100, and 150 A arc current, and have investigated the relationships between these parameters.

The experimental apparatus used in this study included a magnetic duct and cathodic arc plasma source as shown in Fig. 1. The cathodic arc plasma source consisted of a negatively biased electrode 1 cm in diameter and an anode with an aperture 56 mm in diameter. The cathodic arc discharge was operated in a pulsed mode at a frequency of 1 Hz and powered by a 0.3 ms pulse-forming network. The cathodes used in the experiments were C, Ti, Mo, and W. A curved magnetic duct was inserted between the plasma source and main chamber to remove macro-particles produced in the cathodic arc plasma. 5 The curved magnetic filter consisted of a 90° stainless steel pipe with a minor radius r of 40 mm, and major radius R of 100 mm. It was insulated from the anode and vacuum chamber so that it could be positively or negatively biased. A coil wrapped around the duct produced a guiding magnetic field when a dc current was applied. As the distance between the end of the cathodic arc discharge and entrance to the coil was only 20 mm, the coil also produced a focusing (convergent) magnetic field near the cathodic arc. The duct was biased via a capacitor bank of 22 mF. The large capacitance was needed to provide the high duct current needed during the arc pulse, otherwise the duct potential could change significantly when the plasma plume streamed through the duct. A plane collecting plate 26 cm in diameter was positioned in the vacuum chamber about 50 cm from the duct exit to monitor the ion flux transported through the duct. The plate normally faced the duct exit and was negatively biased to −150 V so as to collect the ion current.

FIG. 1. Schematic diagram of the apparatus.

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This voltage was chosen by varying the bias voltage to confirm that it was comfortably within the ion saturation current regime. The vacuum chamber pressure was about 5 \times 10^{-3} \text{ Pa}. In our experiments, the collecting plate current (transported plasma ion current) was monitored as a function of the duct voltage at different duct magnetic field strengths (100–600 G) and arc currents (50, 100, and 150 A). These magnetic field and arc current ranges were chosen based on practical considerations. The cathodic arc and ion currents given here are their peak pulse values, and each value represents the mean of at least five measurements.

The relationship between the optimal duct bias and the magnetic field and the arc current for the four cathode materials is shown in Fig. 2. The optimal bias at 100 G guiding magnetic field increases monotonically with the duct bias within the experimental range of 0 to 90 V for Ti, Mo, and W. The plasma output increases with magnetic field under the optimal bias for all cathode materials. The trend is similar to that of Ti reported earlier.\textsuperscript{4,5,7} Hence, a high guiding magnetic field enhances the plasma transport efficiency as long as the heat generated by the coil is under control. The optimal bias decreases with magnetic field for all the cathodic arc plasmas and arc currents in the 100–300 G regime, and tends to be steady when the magnetic field exceeds 400 G (Fig. 2). This suggests that the relationship between the guiding magnetic field and optimal bias is mainly determined by the electron diffusion in the plasma but not that of the ions.

The ion Larmor radius is larger than the duct minor radius while the electron Larmor radius is much smaller under certain magnetic field. The fact that electrons are bound to the magnetic field lines and the requirement of plasma quasineutrality force the ions to follow the electrons and move along the magnetic field lines (ambipolar drift). Thus, the ions are guided through the duct and the electrons play an important role in the plasma transport. Hence, as many electrons as possible should be kept in the duct to attain a high transport efficiency. This implies that the flux of the electrons lost to the duct wall should be kept to a minimum, and this is particularly true when a positive bias is applied to the duct wall. A proper positive bias can enhance the transport efficiency while simultaneously drawing an extra electron flux to the wall.\textsuperscript{5,8} There is, however, a limit on the positive bias considering the optimal transport efficiency. On one hand, the plasma has its inherent capacity to offer electron flux across the magnetic field, that is, the thermal diffusion flux \( \Gamma_0 = v_e d \), where \( v_e \) is the electron collision frequency and \( d \) is the average free distance of the electrons across the magnetic field. On the other hand, the outer electric field extracts an electron flux \( \Gamma \) from the plasma. The transport efficiency of the filter increases with positive bias initially because the positive bias reduces the ion flux to the wall and does not draw an excessively high electron flux from the plasma. These factors help guide the ions through the duct and increase the plasma transport efficiency of the duct. However, when the positive bias is so high that the electron flux extracted from the plasma by the electric field surpasses the thermal diffusion electron flux the plasma can supply, electron loss in the filter is excessive. This results in an increased ion loss flux to the wall, and the plasma transport efficiency of the duct begins to decrease. Thus the optimal duct bias should be a compromise that makes \( \Gamma_0 = \Gamma \). The optimal bias is determined mainly by the electron transfer rate perpendicular to the magnetic field along the electric field and the inherent ability of the electrons to diffuse. It is therefore influenced by the electron temperature, ion velocity, plasma density, ion mass, and ion charge state.\textsuperscript{9} For the same arc current and guiding magnetic field, the optimal bias variation, from high to low, is \( W > Mo > Ti > C \) in most cases (Fig. 2), correlating with the ion mass. The ion kinetic energies (note we mean ion drift energy, not ion temperature) in the cathodic arc plasma at 100 A arc current are 54, 122, 116, and 106 eV, respectively.\textsuperscript{10} There is not an obvious dependence of the optimal bias on the ion kinetic energy, so the optimal bias is not directly related to the ion kinetic energy.

The optimal bias at 400 G guiding magnetic field (the steady-state optimal bias) increases with arc current for C but decreases with arc current for Ti, Mo, and W, as shown in Fig. 3. This indicates that the relationship between the arc current and optimal bias is determined by both the electrons and ions in the plasma in addition to other parameters. The ion charge state and ion velocity in a nonequilibrium cathodic arc plasma are almost independent of the arc current in the presence of a weak magnetic field, and also they hardly change when the magnetic field changes from zero to hundreds of gauss.\textsuperscript{11–14} The arc current changes the plasma density and affects both the electron transfer rate due to the electric field and the electron thermal diffusion. The magnetic field must be taken into account when one considers the effects of the plasma density on electron diffusion across the magnetic field. Under “collisionless” conditions, where, electron cyclotron frequency \( \omega_{e,c} \) electron–ion collision...
frequency $\nu_{ei}$, the mean free path $d$ for electrons across magnetic field lines is the electron Larmor radius $r$, and is independent of the plasma density. When the plasma density becomes so high as to reach “collisional” conditions, where $\omega_{ce} < \nu_{ei}$, $d$ is no longer equal to $r$. Therefore, the influence of both the plasma density and the magnetic field on the optimal bias is different when the plasma changes from collisionless to collisional. The complex behavior illustrated in Fig. 3 reflects the composite effects of all the aforementioned parameters.

In summary, the electron flux across magnetic field lines in the duct can be visualized in two ways. On the one hand, the plasma has an inherent electron diffusion flux—the electron thermal diffusion flux—that can be considered as the capacity of the plasma to provide electrons. This electron flux is affected by the plasma parameters and magnetic field, but is not related to the electric field. On the other hand, the electric field in the wall sheath produced by the positive bias extracts electrons from the plasma, resulting in an electron flux towards the wall. This electron flux is related not only to the magnetic field, but also to the electric field. The optimal bias is mainly determined by these two electron fluxes. Our experiments show that the optimal bias decreases with the guiding magnetic field and achieves an equilibrium value when the guiding magnetic field is above 400 G. The optimal bias at 400 G increases with arc current for C, but decreases for Ti, Mo, and W. When different cathode materials and arc current are used, a 20 V bias on the duct may not always yield the maximum plasma transport efficiency. The duct bias must thus be carefully selected for different ion species.

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