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Plasma diffusion and transport in a magnetic duct filter*

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A cathodic arc plasma source equipped with a curved magnetic duct to filter macro-particles was used to study plasma diffusion and transport in the duct. We determine the optimal duct bias, at which the magnetic duct produces the maximum plasma output, for titanium cathodic arc plasma at 50, 100 and 150 A arc current, and we investigate the parametric effects of the arc current and guiding magnetic field on the optimal duct bias. The optimal bias decreases as the guiding magnetic field increases from 0.01 to 0.04T and is almost independent of the guiding magnetic field when the magnetic field strength ranges from 0.04 to 0.06T, the upper limit for our equipment. The optimal duct bias at 0.04T guiding magnetic field decreases with increasing arc current.

Keywords: cathodic arc plasma source, plasma, magnetic filter
PACC: 5275, 5230, 2925

1. Introduction

The large ion flux and high degree of ionization are two important characteristics of metal plasmas produced by a cathodic arc plasma source. Cathodic arc plasmas suffer from macro-particle contamination, and a number of techniques have been proposed to mitigate or eliminate the undesirable effects.[1,2] The most common method to remove macro-particles is to insert a curved magnetic filter between the source and the samples. The two most important parameters in designing magnetic filters are the duct bias voltage and the magnetic field. The magnetic field is necessary to efficiently transport the plasma through the filter, and a proper bias on the filter wall increases the plasma output by an additional factor of 3 to 5.[3,4] This is because the magnetic field limits electron motion in the radial direction and the positive bias deters ions from colliding with the filter wall. The effects of the guiding magnetic field and the duct bias on the plasma transport have been investigated.[5−10] Almost all the experiments described in the literature have been conducted at a fixed arc current of 100A, in order to be able to compare the results from different groups. However, a practical arc current for various applications might be different from 100 A, and little is known about the effects of the arc current on the optimal bias. In the present work, we determine the optimal duct bias for titanium cathodic arc plasma at 50, 100 and 150 A arc current and investigate the impact of the arc current and guiding magnetic field on the optimal duct bias. The mechanism of the enhancement on the plasma output by the duct bias is also discussed.

2. Experimental set-up and measurement

The experimental apparatus used in this study includes a magnetic duct and a 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 a grounded anode with an aperture 56mm 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. A curved magnetic duct was inserted between the plasma source

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and vacuum chamber to remove macro-particles produced in the cathodic arc plasma. The curved magnetic filter consisted of a 90° stainless-steel pipe with a minor radius of 40 mm and major radius of 100 mm. There was an insulator between 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 the 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. A large capacitance is needed to provide the high duct current required during the arc pulse, otherwise the duct potential could change significantly when the plasma plume streams through the duct. A planar collector 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 faces the duct exit and is negatively biased to −150 V in order to collect the ion current. The vacuum chamber pressure is about 5×10^{-3} Pa. In our experiments, the collector plate current (transported plasma ion current) was monitored as a function of the duct bias voltage at different duct or guiding magnetic field strengths. The cathodic arc current and ion current given here are peak pulse values and each value represents the mean of at least five measurements.

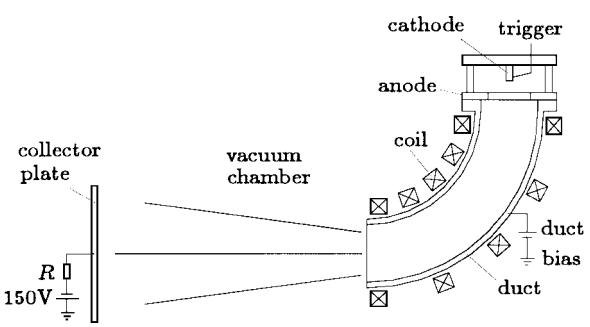


Fig.1. Schematic diagram of the apparatus.

3. Results and discussion

Figure 2 shows the relationship between the plasma output (ion current $I_{\rm out}$) of the duct and the positive duct bias with the magnetic field and arc current as parameters for titanium plasma. The plasma output of the duct at 0.01T magnetic field increases monotonically with the duct bias within the experimental range of 0 to 70 V duct bias for titanium plasma. The ratio of the maximum to minimum plasma output is about 2:1 from 0 to 70 V for 0.04–0.06T guiding magnetic field and 100–150 A arc current. For 0.04–0.06T guiding magnetic field, the plasma output at 0 V duct bias is higher than that at 70 V duct bias at all arc currents. The optimal duct bias decreases as the guiding magnetic field increases from 0.01–0.04T and is almost constant when the guiding magnetic field is between 0.04 and 0.06T for titanium plasma transport at 50, 100 and 150 A arc current (Fig.3).

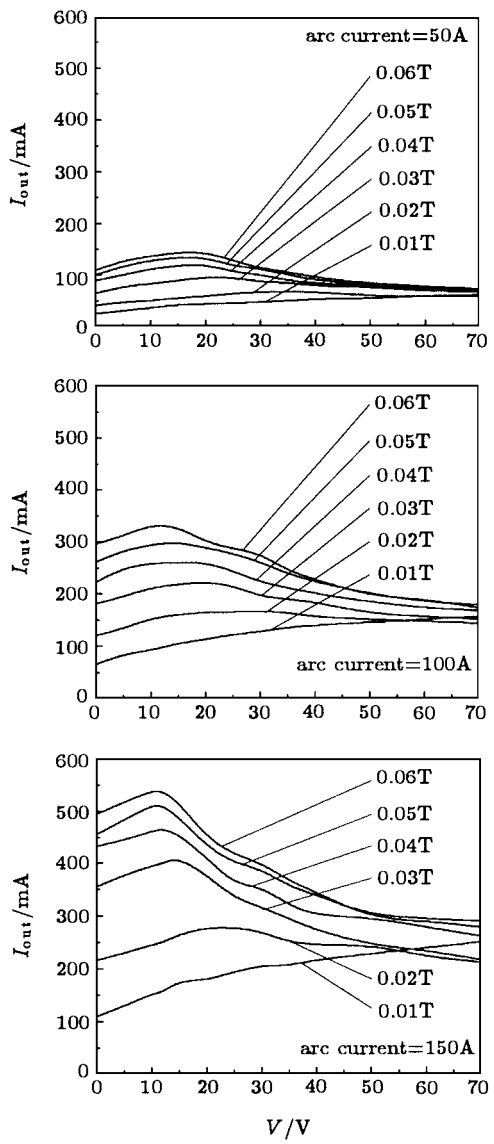


Fig.2. Plasma output $I_{\rm out}$ of the duct versus positive duct bias V with guiding magnetic field and arc current as parameters for titanium plasma transported through the duct. The arc currents are 50, 100 and 150 A, respectively.

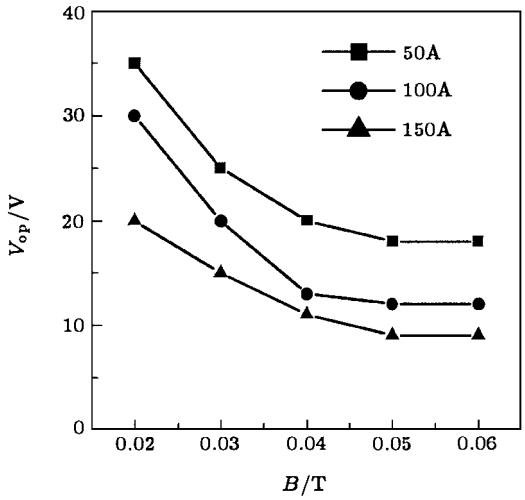


Fig.3. Optimal duct bias V_{op} as a function of guiding magnetic field B with arc current as a parameter for Ti plasma transported through the duct.

It is obvious that a proper positive duct bias increases plasma transport efficiency. The enhancement factor, i.e. the ratio of the plasma output at the optimal duct bias to the plasma output at 0 V duct bias, is below 2 and less than the values of 3 to 5 reported in other papers.[3,4] In our previous experiments using a 45° magnetic duct and 0 to 70 V duct bias, it was found that the maximum enhancement factor reached 4 and the plasma output exhibited a minimum at 0 V duct bias.[6] All the results reported in the literature show that the optimal bias is steady at a high guiding magnetic field and is 10–20 V at an arc current of 100 A, although the exact trend (duct bias versus plasma output curve) varies slightly among different research groups.

At the optimal duct bias, the plasma output of the magnetic duct increases as the guiding magnetic field increases. Hence, a high guiding magnetic field enhances the plasma transport efficiency as long as the heat generated by the coil is under control. We can take the optimal duct bias at 0.04T plus guiding magnetic field to be the steady optimal duct bias. The steady optimal duct bias decreases with the cathodic arc current for titanium plasma (Fig.4). Varying the arc current changes the characteristics of the plasma, such as the electron temperature, ion velocity, ion charge state and plasma density. The ion charge state and ion velocity in a 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 hundredths of Tesla.[11–14] The variable that undergoes the largest change when the arc current varies is the plasma density. Another variable that should be considered is the electron temperature because it also affects the plasma diffusion, and hence substantially affects the optimal duct bias.

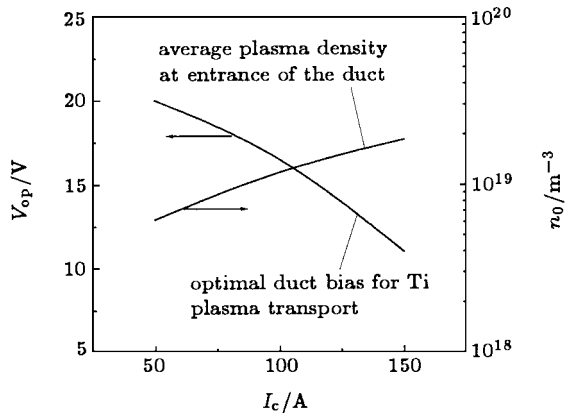


Fig.4. Optimal duct bias V_{op} versus cathodic arc current I_c at 0.04T guiding magnetic field. The calculated average plasma density n_0 at the duct entrance versus cathodic arc current I_c is also shown.

It is believed that the enhancement of the plasma transport efficiency by the duct bias results from the reflection of ions in the plasma.[1,5] A positive duct bias produces a sheath at the duct wall when the duct is filled with plasma. The electric field in the sheath reflects ions through the sheath back to the quasi-neutral plasma and thus a positive duct bias helps to increase the plasma output of the duct. The role of the positive duct bias to focus the plasma flux into the duct should not be confused with that to reflect the ions in the plasma, since both of the roles of the duct bias help to boost the plasma output of the duct under certain conditions. The fact that the optimal duct bias remains steady for high guiding magnetic field cannot be adequately explained by the former role of the positive duct bias. The anode is isolated from the duct and there is an open gap between the cathode and duct in our experiments. When the arc is on and the plasma plume streams through the duct, both the anode and duct will draw electron current. When the positive duct bias increases, the current received by the duct increases while the current received by the anode decreases. If the positive duct bias is high enough and the current to the duct is close to the arc current, then the current to the anode, which is at ground potential, is very small. The plasma plume can be transported through the duct only if the plasma plume enters the duct entrance. The fact that the anode current decreases with positive duct bias implies that the plasma

flux entering the duct increases with higher positive duct bias. The entire plasma flux thus enters the duct if the anode current is near zero. Hence, it appears that a positive duct bias mainly acts as an auxiliary anode to enhance the arc current and to guide the plasma flux into the duct. In this way, the optimal bias helps to increase the transport efficiency. However, similar to a positive duct bias, a strong guiding magnetic field focuses the plasma plume into the duct. We have noticed that the positive duct bias in this experimental regime hardly influences the anode current when there is a strong guiding magnetic field, and so the positive duct bias contributes very little to focusing the plasma plume into the duct in the presence of a strong guiding magnetic field. However, the optimal duct bias is still nonzero in this case. The optimal bias is a substantial positive value in the presence of a strong guiding magnetic field. It can thus be inferred that the role of the duct bias in focusing the plasma plume is independent of the role of the duct bias in reflecting ions near the duct wall.

4. Conclusion

A proper duct bias can improve the plasma output from the magnetic duct of a cathodic arc source, and both the arc current and guiding magnetic field can influence the optimal duct bias. The enhancement of the plasma transport efficiency in the presence of a positive duct bias has two mechanisms. On the one hand, the positive duct bias focuses the plasma flux into the duct entrance, thereby resulting in an increased plasma output. On the other hand, the positive duct bias reflects plasma ions streaming through the duct and deters the ions from impinging on the duct wall. This effect also helps to increase the plasma output. When the guiding magnetic field is not strong enough to focus the plasma flux, a positive duct bias can make up for this inadequacy and the enhancement of the plasma output can be attributed to both the focusing and reflecting mechanisms. When the guiding magnetic field is strong enough to adequately focus the plasma flux into the duct, the focusing role of the positive duct bias is not important and the enhancement of the plasma output is mainly due to the reflecting mechanism. Nonetheless, regardless of whether the guiding magnetic field is strong or weak, the reflection of the ions in the plasma by the positive duct bias is an essential mechanism for the enhancement of the plasma transport through the duct. Our experimental results show that the optimal bias decreases as the guiding magnetic field increases from 0.01 to 0.04T and is almost independent of the guiding magnetic field when the magnetic field is 0.04–0.06T. The optimal duct bias at 0.04T guiding magnetic field decreases with the arc current. Therefore, it appears that the optimal duct bias must be closely related to the plasma parameters and ion reflection by the positive bias.

References

[1] Aksenov I I, Vakula S I and Padalka V G 1980 *Sov. Phys. Technol.* **25** 1164

[2] Anders A 1997 *Surf. Coat. Technol.* **93** 158

[3] Anders A, Anders S and Brown I G 1994 *J. Appl. Phys.* **75** 4900

[4] Zhang T, Zeng Z M, Tian X B, Tang B Y, Chu P K, Brown I G and Zhang H X 1999 *J. Vac. Sci. Technol.* A **17** 3074

[5] Anders A, Anders S and Brown I G 1995 *Plasma Sources Sci. Technol.* **4** 1

[6] Zhang T, Tang B Y, Chen Q C, Zeng Z M, Chu P K, Bilek M M M and Brown I G 1999 *Rev. Sci. Instrum.* **70** 3329

[7] Bilek M M M and Anders A 1999 *Plasma Sources Sci. Technol.* **8** 488

[8] Zhang T, Hou J D, Tang B Y, Chu P K and Brown I G 2001 *Chin. Phys.* **10** 424

[9] Zhang T, Kowk T K, Chu P K and Brown I G 2001 *Chin. Phys.* **10** 320

[10] Liu C G and Qian S J 1998 *Acta Phys. Sin.* (*Overseas Edition*) **7** 22

[11] Brown I G 1994 *Rev. Sci. Instrum.* **65** 3061

[12] Paoloni F J and Brown I G 1995 *Rev. Sci. Instrum.* **66** 3855

[13] Anders A, Yushkov G, Oks E, Nikolaev A and Brown I G 1998 *Rev. Sci. Instrum.* **69** 1332

[14] Oks E M, Anders A, Brown I G, Dickinson M R and MacGill R A 1996 *IEEE Trans. Plasma Sci.* **24** 1174