Arc Root Attachment on the Anode Surface of Arc Plasma Torch Observed with a Novel Method *

PAN Wen-Xia(潘文霞)[1**], LI Teng(李腾)[1], MENG Xian(孟显)[1], CHEN Xi(陈熙)[2], WU Cheng-Kang(吴承康)[1]

[1]*Institute of Mechanics, Chinese Academy of Sciences, Beijing 100080*
[2]*Department of Engineering Mechanics, Tsinghua University, Beijing 100084*

(Received 8 July 2005)

The arc-root attachment on the anode surface of a dc non-transferred arc plasma torch has been successfully observed using a novel approach. A specially designed copper mirror with a boron nitride film coated on its surface central-region is employed to avoid the effect of intensive light emitted from the arc column upon the observation of weakly luminous arc root. It is found that the arc-root attachment is diffusive on the anode surface of the argon plasma torch, while constricted arc roots often occur when hydrogen or nitrogen is added into argon as the plasma-forming gas.

PACS: 52.80.Mg, 52.70.Kz, 52.50.Nr

The arc root attachment on the anode surface of a dc non-transferred arc plasma torch not only affects the anode erosion and thus influences the service period of the plasma torch, but also affects the characteristics of the plasma jet generated from the plasma torch. Because of the experimental difficulty, so far in the literature there are only a few papers[1–5] devoted to observing the arc root attachment within the arc plasma torch. Direct photography was employed in Refs. [1–4] to observe the arc root at the electrode surface, but the photographs obtained in this way were often not very clear for identifying the arc-root location and size due to the interference upon the arc-root image caused by the intensive light emitted from the high-temperature arc column located at and around the plasma torch axis. As an improved approach, Ref. [5] used a specially designed mask (i.e. a black cylinder of 6-mm diameter and 40-mm length) to intercept the intensive light emitted from the arc column in order to observe better the arc root shape and location in the arc plasma torch. However, we found that it is not convenient to use this approach in the present experiment to observe the arc root attachment at low gas pressure.

In this Letter, the arc-root attachment on the anode surface of the dc non-transferred arc plasma torch is observed by using a new experimental arrangement shown schematically in Fig. 1. That is, a copper mirror with 45° inclination with respect to the plasma torch axis is used to transmit the upward-view image of the arc plasma torch into the ICCD camera, which is located outside the vacuum chamber (not shown in Fig. 1) encircling the plasma torch and the copper mirror, and with its axis perpendicular to the torch axis and having the same height as the mirror centre, as seen in Fig. 1. The outer diameter of the copper rod to make the mirror is 60 mm, and a boron nitride film with diameter of about 20 mm is coated at the central region of the mirror surface. Figures 2(a) and 2(b) show the pictures of the copper mirror surface before and after the boron nitride coating has been prepared.

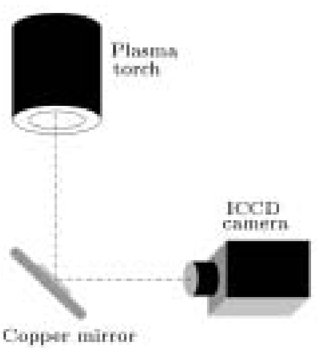

Fig. 1. Schematic diagram of the experimental arrangement for the arc root observation.

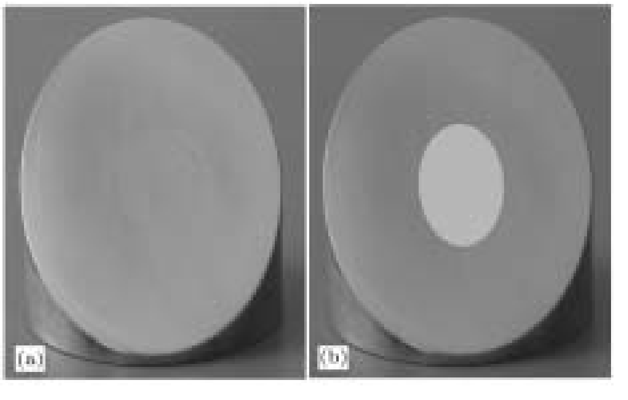

Fig. 2. Photographs of the copper mirror before (a) and after (b) the boron nitrite film coated at the central region of the mirror surface.

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* Supported by the National Natural Science Foundation of China under grants Nos. 50336010 and 10575127.
** Email: wxpan@imech.ac.cn

The copper mirror is set on a water-cooled holder far from the plasma torch exit. Figures 3(a) and 3(b) show the argon plasma jets generated at the same pressure and gas flow rate, but an external magnetic field is applied for Fig. 3(b); whereas Fig. 3(c) is for the Ar–3%H_2 plasma jet. The plasma jets are approximately axisymmetrical for the case without external magnetic field, as seen in Figs. 3(a) and 3(c). While for the case with the effect of external magnetic field, the argon jet is asymmetrical, as seen in Fig. 3(b). The heated boron nitride film on the in-use copper mirror surface can be clearly seen in these photographs.

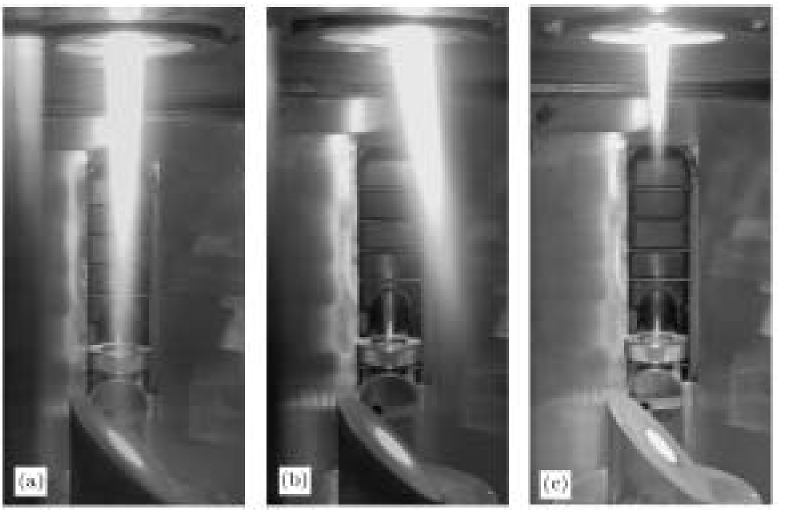

Fig. 3. Photographs of the plasma jet and the in-use copper mirror set on a water-cooled holder in the vacuum chamber. Argon plasma jets at pressure of 3.2×10^3 Pa and gas flow rate of STP 75 cm^3/s (a) in the absence of and (b) in the presence of an applied magnetic field; (c) Ar-3%H_2 plasma jet at 2.5×10^4 Pa and STP 325 cm^3/s in the absence of the applied magnetic field.

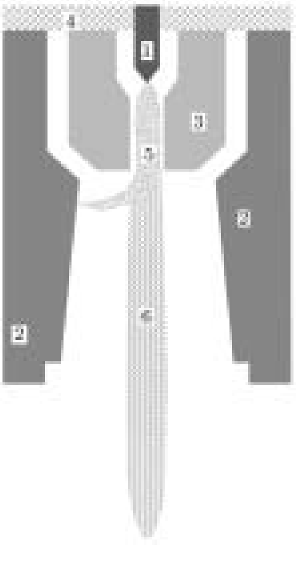

Fig. 4. Schematic diagram of the configuration of the dc transferred arc plasma torch used for the plasma generation. (1) cathode, (2) anode, (3) inter-electrode insert, (4) insulator, (5) arc column, (6) plasma jet.

Figure 4 shows the schematic diagram of the dc non-transferred arc plasma torch used in this study for generating the plasma jets. The plasma torch is installed at the top of a large-volume vacuum chamber (not shown in Figs. 1 and 4), and the inner diameter of torch anode-nozzle exit is 60 mm. Pure argon, argon–hydrogen or argon–nitrogen mixture has been used to generate the plasma. The total volumetric flow rate of the working gas can be adjusted in a wide range (40–470 STP cm^3/s), and thus both laminar and turbulent plasma flow regimes can be achieved in the experiment. The vacuum-chamber pressure can also be regulated in a wide range of 0.05×10^4—3.0×10^4 Pa. Arc current is 80–130 A, whereas the input electric power of the plasma torch is 5.5–18 kW, depending on the gas type, arc current and vacuum-chamber pressure. The plasma jets produced at reduced pressure are issuing freely into the vacuum chamber or impinging upon the electrically-floating copper mirror, as shown in Fig. 3.

In order to show the relative dimensions of the plasma-torch parts, we present two upward-view photographs of the torch configuration taken by an ordinary digital camera and an ICCD camera, as shown in Figs. 5(a) and 5(b) respectively, for the case without plasma generation (i.e. for cold-state case). A ruler is put across the torch exit section to show the sizes, and a lamp is used to illuminate the observed object. The inter-electrode insert channel cannot be seen in Figs. 5(a) and 5(b) since it is just covered up by the ruler. It should be noted that the bright spots seen in Figs. 5(a) and 5(b) are formed only due to the reflection of lamp light at the end wall of the torch anode. The detailed upward-view drawing of the plasma torch configuration shown in Fig. 4 is plotted in Figs. 5(c) for cross reference with Fig. 5(a) and 5(b).

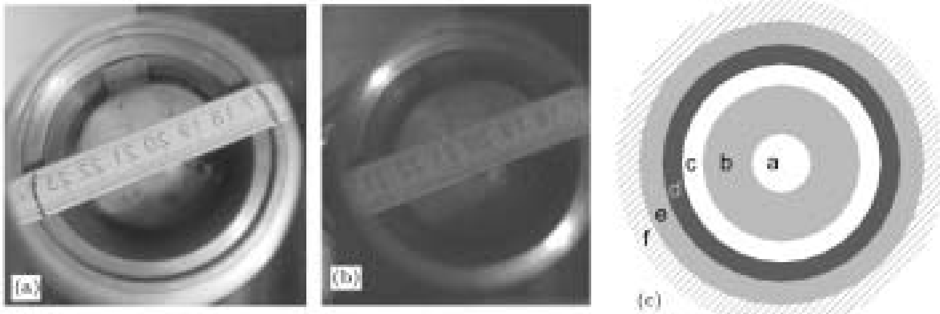

Fig. 5. Upward-view photographs and schematic drawing showing the plasma torch configuration, i.e. photographs taken by the ordinary digital camera (a) and by the ICCD camera (b) with a ruler across the anode exit section. (c) The schematic drawing: (a) central channel-hole of the inter-electrode insert; (b) end wall of the inter-electrode insert; (c) spacing between the inter-electrode insert and anode; (d) tapered inner surface of the anode; (e) step surface near the anode exit; (f) outside flange for fixing the torch.

The dc non-transferred arc plasmas are observed by using the two different imaging techniques. That is, direct photographs of the plasma jets are taken by using the ordinary digital camera to show the jet appearances (as shown in Figs. 3(a)–3(c)), and the ICCD camera with shorter exposure time (e.g. 10 μs) is used to obtain the instantaneous images to observe the arc root attachment. Since the diameter of the boron nitride coating on the copper mirror surface (about 20 mm) is appreciably larger than the diameter of the central channel-hole of the inter-electrode insert or the arc column diameter (shown by 3 and 5 in Fig. 4) but notably less than the inner diameter of the torch anode-nozzle (60 mm at the torch exit), the reflection from the mirror surface of the intensive light emitted from the central arc column in the non-transferred arc plasma torch can be greatly weakened and thus the interference caused by the arc column radiation upon the detailed observation of the arc root attachment at the anode surface can be effectively avoided.

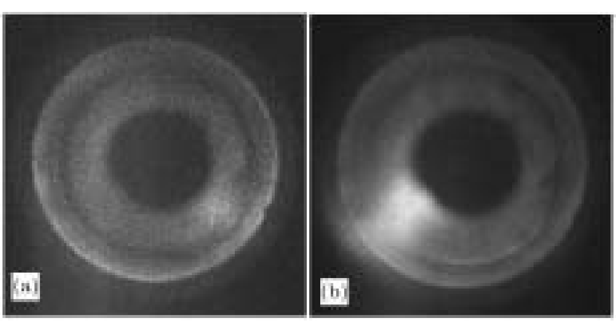

Fig. 6. ICCD images showing the arc root attachment on the anode surface of argon arc plasma torch for cases without (a) and with (b) external magnetic field. The plasma generation conditions are the same as for Figs. 3(a) and 3(b).

The upward-view images taken by using the ICCD camera (with 50-μs exposure time) through the special copper mirror are presented in Figs. 6(a) and 6(b) to show the arc root attachments at the torch anode-nozzle surface with pure argon as the plasma-forming gas, respectively. Black central regions appearing in both the images demonstrate such a fact that the highly bright arc column in the inter-electrode insert channel can no longer be seen by the ICCD camera since the intensive light emitted from the arc column has been effectively absorbed by the boron nitride film on the copper mirror surface. It is found that by using such a special copper mirror design (with the boron nitride coating), the weakly luminous argon arc root shown in Fig. 6(a) can be observed more clearly. Such a high-quality argon arc-root image cannot be obtained if one employs an ordinary mirror (without the boron nitride coating) or other direct photographic methods such as those used in Refs. [1–4].

The arc-root attachment on the anode surface of the dc non-transferred argon arc plasma torch shown in Fig. 6(a) is for the case within the laminar flow regime and at the chamber pressure of 3.2×10^3 Pa. From Fig. 6(a) we only see an annular weakly-luminous region with relatively uniform light-intensity distribution on the anode surface, and cannot see any sign of a constricted arc-root formation. This arc root behaviour does not show any obvious change when the chamber pressure is enhanced to 2.3×10^4 Pa, i.e. almost one order of magnitude higher (not shown here as a separate figure). It is found that almost completely diffused arc-root attachment always appears at the anode surface when pure argon is used as the plasma-forming gas, regardless of whether the plasma jet is in laminar or turbulent flow regime. Such a diffused arc-root attachment is obviously favourable for reducing the anode erosion and prolonging the service period of the torch anode. When an external magnetic field with intensity of about 0.02 T is applied, the argon plasma jet appearance is deflected from axisymmetry, as shown in Fig. 3(b). Figure 6(b) presents the corresponding upward-view ICCD image for this case. A part of the deflected argon plasma jet is seen in Fig. 6(b), leading to the result that the weakly luminous arc root can no longer be clearly seen. Such a fact indicates that if a stronger light (e.g. from the arc column or the high-temperature region of the deflected plasma jet) is not excluded effectively from the view field of the ICCD camera, the diffused arc root attachment with weaker luminosity as in Fig. 6(a) can hardly be observed.

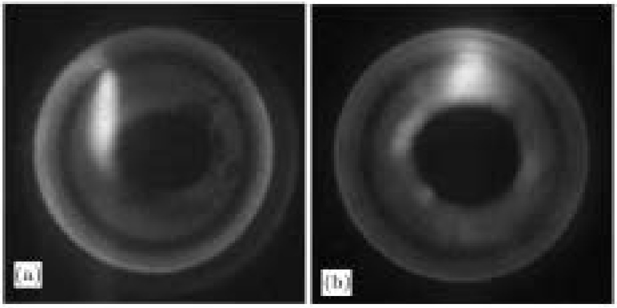

Fig. 7. ICCD images showing the arc root attachment on the anode surface of Ar-3%H_2 (a) and Ar-12%N_2 (b) arc plasma torches. The gas pressure and total flow rate are 2.5×10^4 Pa and STP 325 cm^3/s for (a), while 5.0×10^3 Pa and STP 85 cm^3/s for (b).

It is found that adding H_2 into Ar as the plasma-forming gas even with small hydrogen content will lead to the formation of a constricted arc root on the anode surface. Figure 7(a) presents a typical upward-view image for the Ar-3%H_2 arc plasma torch to show the arc root attachment on the torch anode surface. From Fig. 7(a), one can clearly see an extremely bright, sharp, constricted Ar-H_2 arc root, which is somewhat twisted by the swirling gas flow. It is found that adding N_2 into Ar as the plasma-forming gas can also lead to the formation of the constricted arc root, as shown in Fig. 7(b), while a slightly larger amount of nitrogen is required. Comparison of Figs. 7(a) and 7(b) reveals that the sharpness of the arc-root constriction of the Ar-12%N_2 arc is appreciably less than that of the Ar-3%H_2 arc, although the percentage content of nitrogen in the former is much larger than that of hydrogen in the latter.

In summary, the arc root attachments on the anode surface of non-transferred arc plasma torch have been successfully observed from the images taken by ICCD camera through a 45° inclined copper mirror with a boron nitrite coating on the centre of the mirror surface. The arc-root attachment is diffusive for the argon arc plasma generation, while a constricted arc root often occurs when hydrogen or nitrogen is added into argon to generate the plasma jet at reduced pressure.

References

[1] Lin L, Sun Z, Wang B Y and Wu C K 1996 *Proceedings of the 3rd Asia-Pacific Conf. Plasma Sci. Tech.* (Tokyo, June 15–17) **2** 391

[2] Duan Z, Wittmann K, Coudert F, Heberlein J and Fauchais P 1999 *Proc. 14th Int. Symp. Plasma Chem.* (Prague, August 2–6, 1999) p 233

[3] Li H, Ma Q, Li L C and Xia W D 2005 *IEEE Trans. Plasma Sci.* **33** 404

[4] Chazelas C, Coudert J F and Fauchais P 2005 *IEEE Trans. Plasma Sci.* **33** 416

[5] Dorier J L, Gindrat M, Hollenstein C, Salito A, Loch M and Barbezat G 2001 *IEEE Trans. Plasma Sci.* **29** 494