COMPARATIVE OBSERVATION OF DC ARC PLASMA JETS AND THEIR ARC ROOT BEHAVIORS AT REDUCED PRESSURE

Wenxia Pan[1], Xian Meng[1], Teng Li[1], Xi Chen[2], Chengkang Wu[1]

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

ABSTRACT

Experimentally observed results are presented for the DC arc plasma jets and their arc-root behaviors generated at reduced gas pressure and without or with an applied magnetic field. Pure argon, argon -hydrogen or argon-nitrogen mixture is used as the plasma-forming gas. A specially designed copper mirror is constructed and used for better observing the arc-root behavior on the anode surface of the DC non-transferred arc plasma torch. It is shown that for the cases without applied magnetic field, the laminar plasma jets are stable and approximately axisymmetrical. The arc-root attachment on the anode surface is completely diffusive when argon is used as the plasma-forming gas, while the arc-root attachment often becomes constrictive when hydrogen or nitrogen is added into the argon. When an external magnetic field is applied, the arc root tends to rotate along the anode surface of the non-transferred arc plasma torch.

1. INTRODUCTION

Numerous studies have been performed in recent decades concerning the characteristics of DC arc plasma jets, due to their widespread applications in industries and in labs. Although a wealth of experimental and modeling results have been accumulated in the literature [1-4], our understanding on DC non-transferred arc plasma characteristics is still incomplete, especially on the relationship between the plasma jet characteristics and the behavior of the arc root at the torch anode surface.

In this paper, DC non-transferred arc plasma jets are generated at reduced gas pressure using pure argon, argon-hydrogen or argon-nitrogen mixture as the plasma-forming gas. The generated plasma jets are observed when they are flowing out from the plasma torch as the free jets or as the jets impinging upon a substrate. An external magnetic field is applied if its effect on the arc-root behavior and on plasma jet characteristics is to be studied. The plasma jets are observed using an ordinary camera and an ICCD camera. Arc-root behaviors on the anode surface of the plasma torch are observed using a specially designed copper mirror [5] in coordination with the ICCD camera.

2. EXPERIMENTAL DETAILS

Pure argon, argon-hydrogen (with volumetric percentage 0-18% of H_2) or argon-nitrogen (with volumetric percentage 0-22% of N_2) mixture has been used in the plasma generation, respectively. The total volumetric flow rate of the working gas is changed in the range of 40-470 STP cm^3/s. As in Ref. [6], the working gas is admitted axially and tangentially into the plasma torch. The vacuum -chamber pressure is changed in the range of $(0.05\text{-}3.0)\times10^4$ Pa. Arc current is 80-130 A, whereas the input electric power is 5.5-18 kW, depending on the gas type and vacuum-chamber pressure and on whether an external magnetic field (0.01-0.045 T) is applied. The plasma jet is issuing freely into the vacuum chamber or impinging normally upon a substrate (electrically floating).

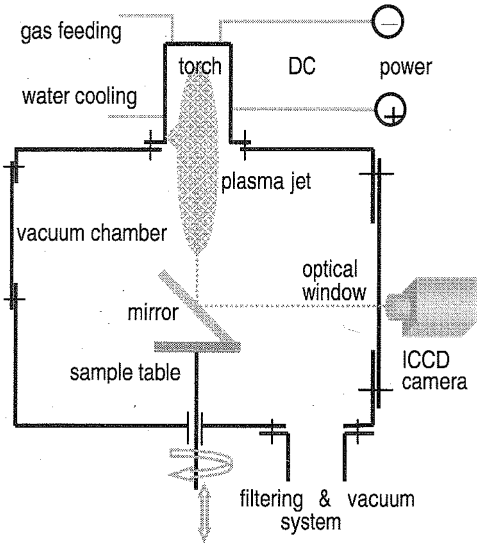

Figure 1. Schematic diagram of the plasma generating and arc-root observing system.

The plasma jets are observed by use of two different imaging techniques. Namely, direct photography of the plasma jet is taken using an ordinary digital camera to show the jet appearance, and an ICCD camera with accurate exposure time capable as short as 5 ns is used to obtain the instantaneous plasma jet images in the visible range. The schematic diagram of the apparatus for the arc-root observation is shown in Fig. 1. A copper mirror with good thermal conductance is installed on the water-cooled sample table under the torch nozzle exit, and the mirror surface is set to be 45° inclination with respect to the torch axis. Thus the mirror can reflect the end-on image of the plasma torch (with certain depth of field) into the ICCD camera, which is located outside the vacuum chamber with its axis perpendicular to the torch axis and with the same height as the mirror center. A boron nitride film is coated at the central region on the copper-mirror surface [5]. With this novel experimental design, the arc root behaviors have been successfully observed in the generation processes of Ar, Ar-H_2 and Ar-N_2 plasma jets.

3. RESULTS AND DISCUSSION

3.1. *Plasma jet appearance*

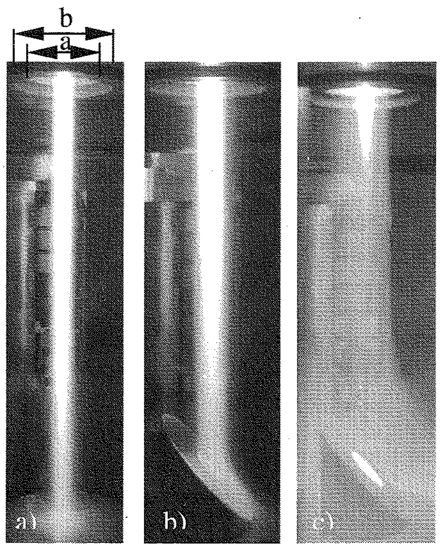

Figure 2. *Photographs showing the appearances of the laminar argon (a), Ar-H_2 (b) and Ar-N_2 (c) plasma jets. Sizes "a" of 60 mm is the inner diameter and "b" of 76 mm is the outer diameter of torch anode flange. Pressure: (a) 3.2×10^3 Pa, (b) 1.6×10^3 Pa, (c) 9×10^3 Pa.*

Figures 2(a)-(c) are the photographs of Ar, Ar-H_2 and Ar-N_2 plasma jets in the laminar flow regime. These photographs are taken by the ordinary digital camera to show the appearances of the plasma jets. Visual observation and the photographs shown in Fig. 2 demonstrate that the laminar Ar, Ar-H_2 and Ar-N_2 plasma jets are steady and with longer high-temperature regions. The laminar plasma argon jet is well axisymmetrical, and the laminar Ar-H_2 and Ar-N_2 plasma jet are also approximately axisymmetrical. The laminar Ar-H_2 and Ar-N_2 plasma jets shown in Figs. 2(b) and 2(c), respectively, are impinging upon the specially designed copper mirror [5] with a 45° inclination with respect to the jet axis, and thus the heated boron-nitride coating in the mirror center can be seen in the photographs of Figs. 2(b) and 2(c).

Figure 3 shows the appearances of the laminar argon plasma jets impinging normally upon the water -cooled substrate, where Figs. 3(a) and 3(b) are taken by the ordinary digital camera, while Figs. 3(c) and 3(d) are taken by the ICCD camera. Figure 3(a) is the case without an external magnetic field, whereas Figs. 3(b), (c) and (d) are with an externally applied magnetic field. It is seen that the laminar argon plasma jets are well axisymmetrical for the case without the external magnetic field. The high-temperature region of the plasma jet under the action of external magnetic field is no longer axi-symmetrical and is not steady, as seen from Fig. 3(b). Figure 3(c) shows the non-axisymmetrical luminous region taken by use of the ICCD camera (exposure time 10 ms). An approximately axisymmetrical picture, reflecting that the high-temperature region of the argon plasma jet rotates around the torch axis due to the action of external magnetic field, can still be obtained provided that the exposure time of the ICCD camera is long enough, as seen in Fig. 3(d) (exposure time 200 ms), which shows that the argon plasma jet can cover up the whole substrate surface with 60-mm diameter due to the rotation of jet high-temperature region. This situation is favorable for some applications since it gives more uniform heating of the substrate even with a relatively large surface area.

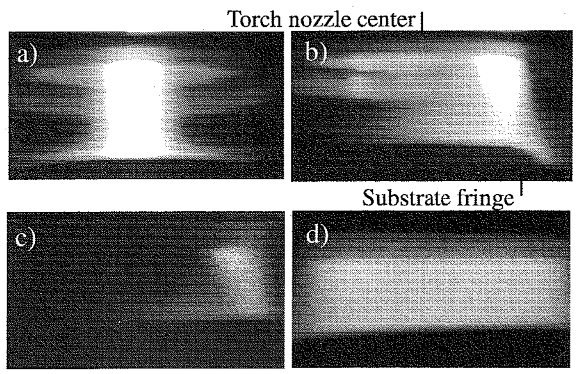

Figure 3. *Appearances of pure argon plasma. b)-d) are with applied external magnetic field.*

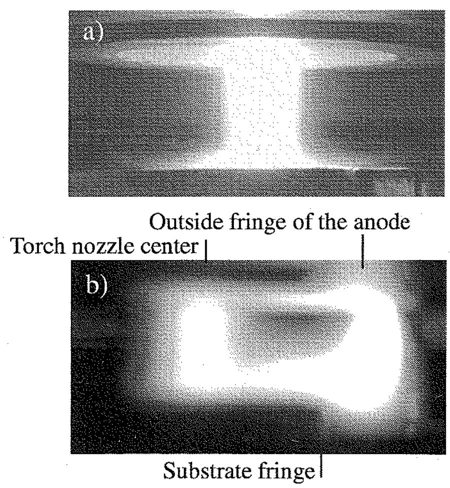

Figure 4. *Appearances of Ar-H_2 plasma jets. a) 4% H_2; b) 15% H_2.*

Figure 4 are two photographs taken by the ordinary camera for the argon-hydrogen plasma jets with different hydrogen contents and for the case without the external magnetic field effects. It is found that the hydrogen content in the Ar-H_2 mixture significantly affects the Ar-H_2 plasma jet characteristics. When the hydrogen content in the Ar-H_2 mixture is relatively low (about 4%), Fig. 4(a) shows a similar impinging jet characteristics as for the pure argon case. However, it is found that Ar-H_2 arc column can be blown out from the torch-nozzle exit for certain parameter combinations. For example, when the hydrogen content is increased to 15%, Fig. 4(b) shows that a straight arc column goes down along the torch axis until it reaches the region near the water-cooled substrate surface and then bends up to the anode-nozzle exit section with a constricted arc-root attachment at the outer fringe of the anode-nozzle. Such a non-axisymmetrical Ar-H_2 arc and local arc-root attachment occurred even for the present case without an external magnetic field.

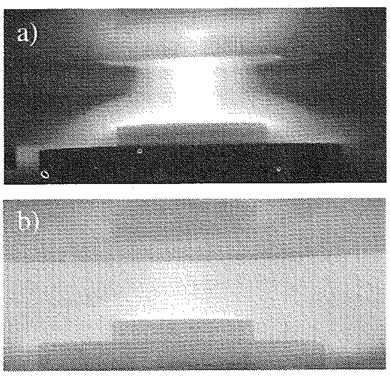

Figure 5. *Appearances of Ar-N_2 plasma. a) 7% N_2 ; b) 13%N_2.*

Figure 5 are two photographs of Ar-N_2 plasma jets impinging normally upon the substrate, where Fig. 5(a) is the impinging plasma jets generated with 7%N_2, and Fig. 5(b) shows the case with nitrogen content of 13% and a higher chamber pressure than Fig. 5(a). Figure 5(a) shows clearly bright core-regions, and it is interesting to notice that with the increase of nitrogen content and chamber pressure, the intensity of the bright core-region in the jet center is weakened and the sharp intensity-contrast between the bright core-region and outer luminous region tends to disappear (see Fig. 5(b)).

3.2. Arc root attachment

Although the laminar argon plasma jet assumes axisymmetrical appearance and the laminar Ar-H_2 or Ar-N_2 plasma jet appearance is also approximately axisymmetrical in Fig. 1, it is difficult to identify their arc-root behaviors only based on their observed appearances. Figures 6-8 present some additional observation results concerning the arc root attachment with the help of the specially designed copper mirror (with a boron nitride coating in the central region of the mirror surface [5]) and the ICCD camera.

Figures 6(a) and 6(b) are the images of the arc root in the argon arc plasma generation. Black central circular regions appearing in the pictures demonstrate that the highly bright arc column in the inter-electrode insert channel can no longer be seen by the ICCD camera, since the strong light emitted from the arc column has been absorbed by the boron nitride film at the central region of the copper mirror. The high-quality arc-root images as shown in Figs. 6(a) and 6(b) cannot be obtained if one employs an ordinary copper mirror (without central coating to absorb the strong arc-column emission) or other directly-photographic methods such as used in Refs. [7, 8]. From Fig. 6(a), we only see an annular low-intensity luminous-region with almost circumferentially uniform intensity distribution on the anode surface, and cannot see any sign of a constricted arc-root formation in the pure argon plasma-jet generation. This arc root behavior does not show any obvious change (Fig. 6(b)) when the chamber pressure is increased. It is found that when pure argon is used as the plasma-forming gas, almost completely diffused attachment of the arc root always appears at the anode surface. Such a diffuse arc-root attachment is obviously favorable for reducing the anode erosion and prolonging the service period of the torch anode.

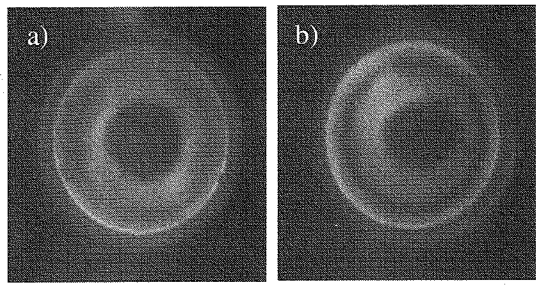

Figure 6. *Images of the pure argon arc roots.*

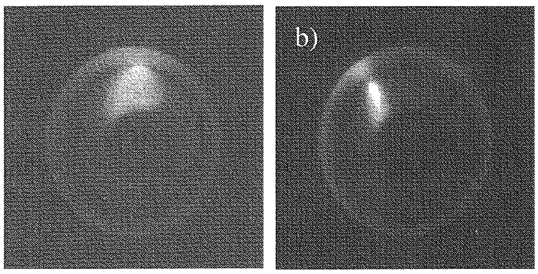

Figure 7. *Images of the Ar-H_2 arc roots. a) 5.5% H_2; b) 9% H_2.*

Figure 7(a) is the upward-view image of the Ar-5.5%H_2 arc root, whereas Fig. 7(b) is the image for 9% H_2 content and higher chamber pressure than Fig. 7(a). It is clearly seen from Fig. 7(a) that an obviously constricted arc root attachment occurs when hydrogen is added into argon for generating the plasma jet, although the content of hydrogen in the Ar-H_2 mixture is as small as 5.5%. The arc root attachment even becomes more sharply concentrated, as shown in Fig. 7(b), when the hydrogen content and the chamber pressure are increased. The arc root generally attaches at the anode wall with a particular angular-direction and shows no apparent movement within the observation time of a few minutes if the jet-generating conditions remain unchanged. Such a special feature of Ar-H_2 arc plasma (with stationary and constricted arc root) would lead to relatively serious anode erosion.

When a small amount of nitrogen instead of hydrogen is added into argon as the plasma-forming gas, it is found that the arc root may show a combined attachment mode, i.e., the arc root attachment on the anode surface is partially diffusive but with a tendency to become constrictive. Figure 8(a) shows such an observed result where the N_2 content is 2.2%. With the increase of the N_2 content, the arc root attachment continuously evolves with increasing constrictive degree. When the N_2 content in Ar-N_2 mixture is higher than 10%, the arc root attachment assumes a sharply constrictive form (see Fig. 8(b), where the upward-view image of the Ar -22%N_2 plasma jet is given). Figure 8(c) shows the image of the arc root attachment in the Ar-14.3%N_2 plasma jet generation with an applied magnetic field. It is found that double arc roots may occur at lower gas pressure and lower nitrogen content (Fig. 8(d)).

The present observation results on the arc root behaviors suggest that the attachment mode on the anode surface of the plasma torch, i.e. as a diffused- or constricted-type arc-root, is mainly determined by the working gas type. The axial position of arc root and its movement are essentially controlled by the balance between the gas flow action and the magnetic field driving the arc.

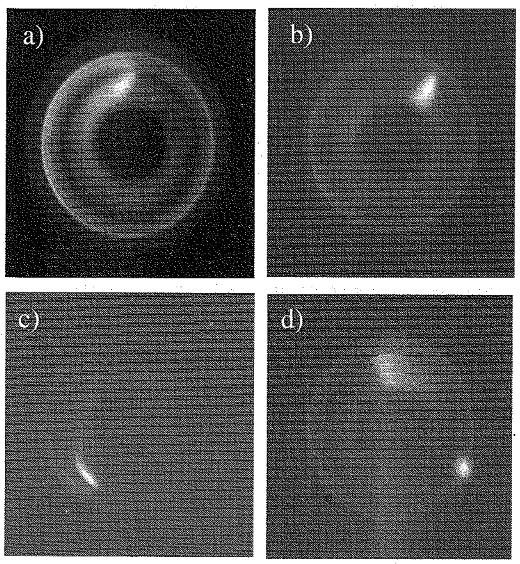

Figure 8. *Images of the Ar-N_2 arc roots. a) 2.2% N_2; b) 22% N_2; c) 14.3% N_2 with an applied magnetic field; d) showing double arc-roots observed at lower pressure and lower nitrogen content.*

4. CONCLUSIONS

The present observation results show that for the case without an applied magnetic field, the laminar argon, argon-hydrogen or argon-nitrogen plasma jet is stable and axisymmetrical or nearly axisymmetrical. When the argon-hydrogen mixture is used as the plasma-forming gas, the arc column may be blown out from the torch anode-nozzle exit until it reaches the region near the water-cooled substrate surface and then bends up to attach at the outer fringe of the anode-nozzle. Arc root attachment on the anode surface is almost completely diffusive when pure argon is used as the plasma-forming gas, while the arc root attachment becomes sharply concentrated when hydrogen is added into argon even only a small amount of hydrogen is added. When argon-nitrogen mixture is used, there may exist a transitional region between the completely diffusive and sharply constrictive arc-root attachments for a changing range of nitrogen contents and/or chamber pressure. A combined mode of diffusive and weakly constrictive attachments and double-arc-root attachment could occur in the transitional region.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (Nos. 10575127 and 50336010).

REFERENCES

[1] E. Pfender, "Thermal plasma technology: where do we stand and where are we going? ", Plasma Chemistry and Plasma Processing, 19(1), pp. 1-31, 1999.

[2] P. Fauchais, "Understanding plasma spraying", Journal of Physics D: Applied Physics, 37(9), pp. R86-R108, 2004.

[3] E. Pfender, "Plasma jet behavior and modeling associated with the plasma spray process", Thin Solid Films, 238, pp. 228-241, 1994.

[4] W. X. Pan, G. Li, X. Meng, W. Ma, C. K. Wu, "Laminar plasma jets: generation, characterization, and applications for materials surface processing", Pure and Applied Chemistry, 77(2), pp. 373-378, 2005.

[5] W. X. Pan, T. Li, X. Meng, Xi Chen, C. K. Wu, "Arc root attachment on the anode surface of arc plasma torch observed with a novel method", Chinese Physics Letters, 22(11), pp. 2895-2898, 2005.

[6] W. X. Pan, W. Hua Zhang, W. Hong Zhang, C. K. Wu, "Generation of long, laminar plasma jets at atmospheric pressure and effects of flow turbulence", Plasma Chemistry and Plasma Processing, 21(1), pp. 23-35, 2001.

[7] L. Lin, Z. Sun, B. Y. Wang, C. K. Wu, "The effects of magnetic field on arc roots behavior and arc characteristics", In: Proceedings of the 3rd Asia -Pacific Conference on Plasma Science and Technology (Tokyo, July 15-17, 1996), Vol. 2, pp. 391-396.

[8] H. Li, Q. Ma, L. C. Li, W. D. Xia, "Imaging of behavior of multiarc roots of cathode in a dc arc discharge", IEEE Transactions on Plasma Science, 33, pp. 404-405, 2005.