Arc Root Motions in an Argon–Hydrogen Direct-Current Plasma Torch at Reduced Pressure *

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Arc root motions in generating dc argon–hydrogen plasma at reduced pressure are optically observed using a high-speed video camera. The time resolved angular position of the arc root attachment point is measured and analysed. The arc root movement is characterized as a chaotic and jumping motion along the circular direction on the anode surface.

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Reduced pressure plasma spraying process has been well established for a broad variety of industrial applications, such as in aeronautics, gas turbines and medical industries for fast deposition of thick layers with relative high quality in a controlled atmosphere.[1−3] Among various plasma sources, dc plasma is still one of the most accessible solutions for reduced pressure plasma spraying. The versatility of this technology enables easier deposition of a wide range of materials. In a typical dc plasma spraying process, metal or ceramic feedstock in the form of powder, wire or liquid drops is injected into the arc jets, being heated, melted, accelerated and finally directed to the target surface of the work piece to form the desired coatings. The quality of deposited coating is thus greatly affected by the thermal history in which the feedstock encountered in the plasma jets. To improve the coating quality, uniform heating and transportation of the injected material is essential. However, non-stability is one of the major limitations in dc plasma spraying process,[4] which hinders further improvements of the reproducibility and controllability of the process. Among all the factors that affect the stability of a dc plasma jet, the fluctuation caused by the intrinsic discharge behaviour between the electrodes is considered to be an important one. The arc attachment at the anode surface is continuously fluctuating in length and position,[5] which accordingly causes the fluctuation of arc length, arc voltage and arc power, and eventually affects the quality of the sprayed coating. For atmospheric plasma spraying (APS), a wealth of experimental and simulation work[6−8] has been carried out to better understand the dynamics of the arc inside the dc plasma torch. On the other hand, experimental results regarding the arc root behaviour at reduced pressures are seldom reported.

Using a specially designed dc plasma torch comprising of a compound inter-electrode insert and a varying diameter anode,[9] relatively stable plasma jet has been generated at reduced pressure between 0.2–30 kPa. How the arc root attaches and moves under such a situation is of great interest. With the aid of a 45° tilted copper-mirror, the attachment behaviour of the arc root on the anode surface was observed with an ICCD camera.[9] However, due to the relative long time of data transfer needed, the motions of the arc root is difficult to be characterized by the ICCD camera. In this Letter, the inside anodic arc root movements of a dc non-transferred Ar–H_2 plasma jet operated at 10 kPa were monitored by a high speed video camera. Preliminary results are reported.

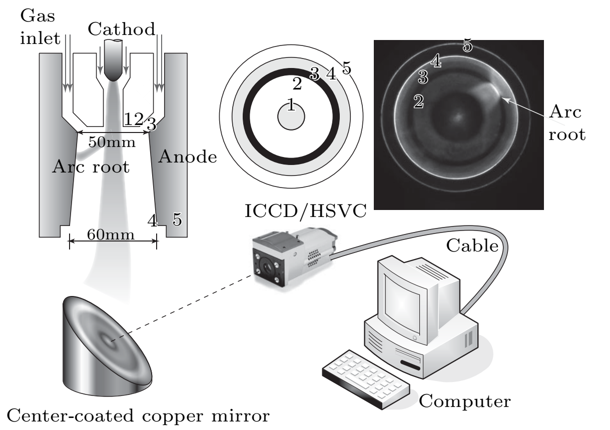

Fig. 1. Experimental setup to capture the inner image/video of the arc root.

Figure 1 shows the schematic illustration of the experimental setup. A central-region-coated copper mirror was used to reflect the real-time inner condition of the plasma torch. The images of the arc root was then recorded by an ICCD camera (iStar®, Andor Tech., USA) or a high speed video camera (HSVC) (MotionBLITZ® Cube3-6C, Germany). The arc current and voltage were simultaneously recorded by an oscilloscope (Tektronix,USA). Because the 45° cop-

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per mirror reflects the upward view of the inner parts of the plasma torch, images attained show concentric circles, which corresponds to the different edges of the torch as marked by numbers 1–5 in the insert of Fig. 1. The anode surface is between circles 3 and 4. Image analysing software named ImageJ (National Institute of Health. USA) with an oval profile plugin was used to identify the angular position of the anodic attachment when the arc root is constricted. Figure 2(a) shows a typical attained ICCD photo of the arc root. Figure 2(b) shows an example of the measured relative intensity along the circle in Fig. 2(a). The polar axis directs to the right and the positive angle is clockwise. The peak in the profile shows the angular position of the attachment (230.8°, or −129.2° in Fig. 2(b)). The HSVC speed was set to be 4270 fps (frames per second) and the exposure time for each frame was set to be 100 µs. The aperture of the lens was kept constant at 2 for all the captures. The plasma was generated at the arc current of 80 A. 10 vol% H_2-Ar with total gas flow rates of 8.6 slm was used as plasma gas. The chamber pressure was kept at 10 kPa for all the experiments.

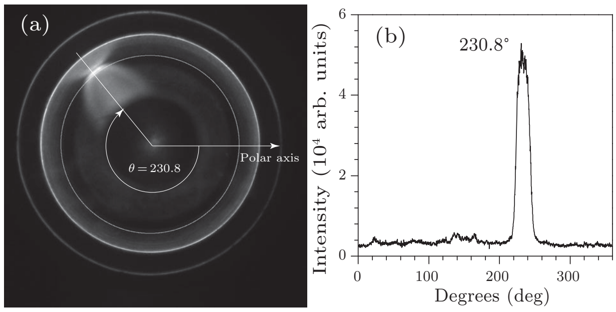

Fig. 2. Image analysing of the attained photo: (a) ICCD photo of typical arc root attachment of an Ar–H_2 plasma, (b) intensity profile along the oval line indicated in (a).

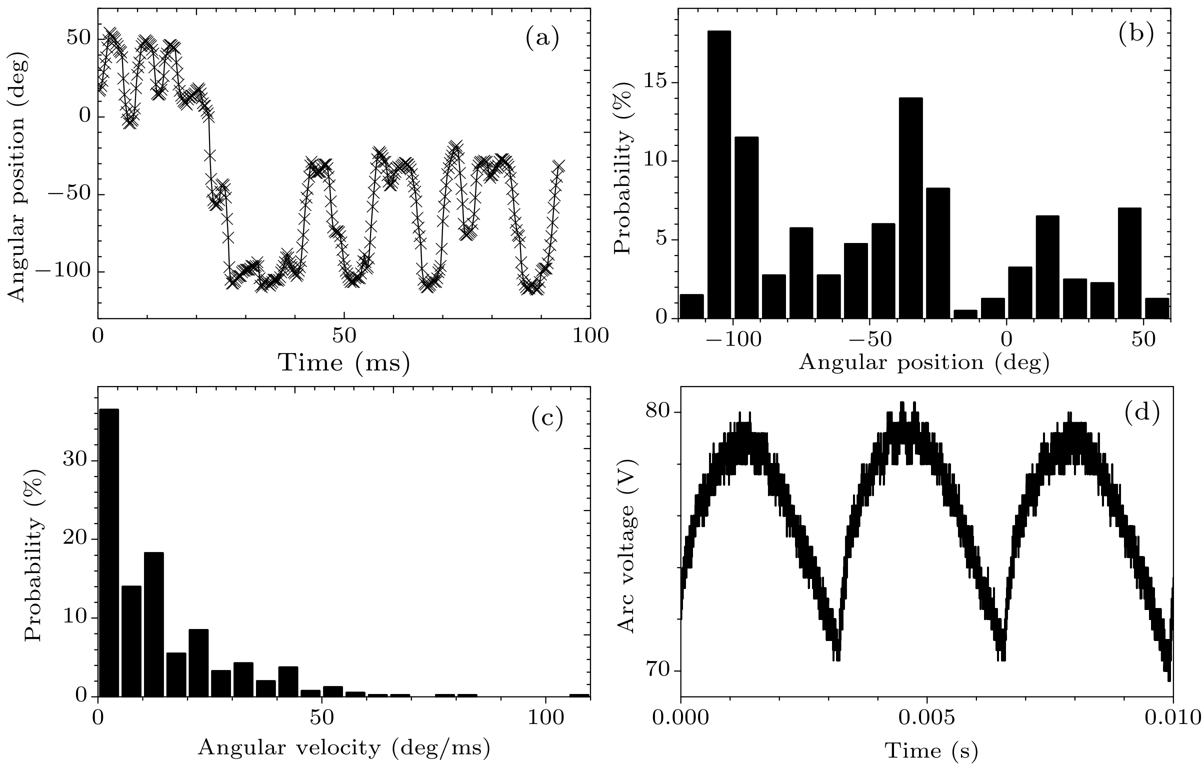

Fig. 3. Circular motion of the arc root recorded by HSVC: (a) evolution of the circular position of the anodic attachment in 0.1 s, (b) probabilities of the anodic attachment at different angular positions, (c) probabilities of the movement velocity of the arc root along the anode surface, (d) time dependence of the arc voltage spectrum.

In the present study, no remarkable changes of the axial position of the arc root attachment were observed. However, for the Ar–H_2 plasma, circular motion of the arc root was clearly seen. Figure 3 shows the characteristics of the circular arc root motions. Figure 3(a) plots the evolution of the angular positions of the attachment points in 400 consequential frames within 94 ms. The chaotic movements of the arc root can be seen: in such a short time scale, the arc root moves randomly in half of the circum from −120° to 60°, though some preferred positions can be identified. Figure 3(b) shows the frequency probabilities over the 400 frames of different angular positions with bins of 10°. In the present study, there are two main probability peaks near −110° and −30°, while small peaks around −80°, 10° and 40° can also be seen. Long residence time of the arc root attaching at a fixed point is not desirable since surface melting might occur because of the high heat flux of the arc root. By measuring the slope of adjacent points in Fig. 3(a), the average velocity of the arc root movement was calculated. Figure 3(c) shows the result. In most cases, the arc root does not move much with the movement velocity smaller than 10 deg/ms, 90% of the movements are within 30°ms^{-1}. However, long distance jumps of the arc root also occur, e.g. velocity larger than 100 deg/ms can be seen in Fig. 3(c). The arc voltage spectrum is shown in Fig. 3(d), which exhibits sinusoidal-like shapes governed by the 300 Hz characteristic frequency of the rectified power supply with negligible high frequency fluctuations.[10] From the spectrum, a rather steady arc root behaviour can be deduced. No correspondence between the circular arc root movements (Fig. 3(a)) and the arc voltage spectrum (Fig. 3(d)) can be identified. As mentioned above, no remarkable axial position changes of the arc root attachment were observed in the present study, indicating that although the arc root moves chaotically on the anode surface in the circular direction, the circular motion itself has unnoticeable effect on the fluctuations of the arc voltage.

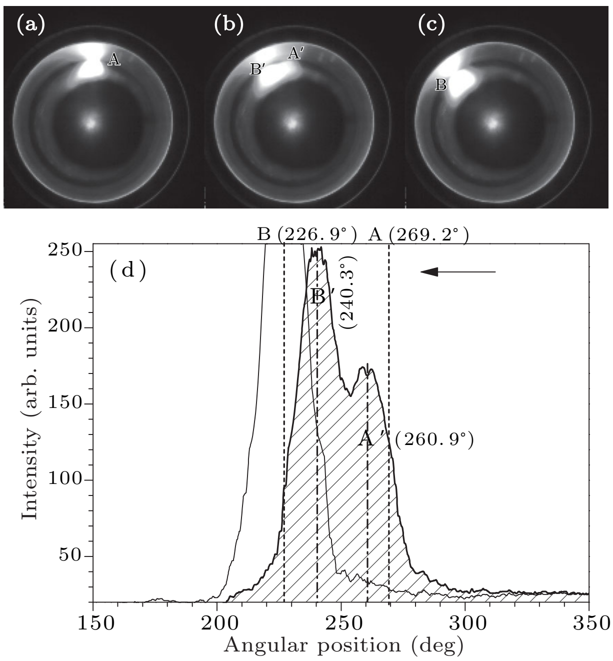

Fig. 4. Sequential HSVC images of a sudden jump of the arc root. Exposure time of each frame is 100 µs and the time step is 234 µs.

The "sudden jump" of the arc root was seldom captured in one frame of the video clip, while Fig. 4(b) shows an example when the arc root moves from spot A to spot B. Figures 4(a) and 4(c) show the adjacent previous and later images to Fig. 4(b) respectively. A much wider attachment can be observed in Fig. 4(b), which means that within the exposure time, the arc root moves over such a wide area. Figure 4(d) shows the oval profiles of the arc roots in the three photos. A split-peak profile of Fig. 4(b) is clearly shown. One peak is at the angular position of 260.9° and the other is at 240.3°. Within the exposure time of 100 µs, the movement velocity is at least 206 deg/ms or 108 m/s. While the average velocities of 35.5 deg/ms and 57.3 deg/ms were identified for the case of A→A' and B'→B, respectively. In such cases, the exposure time of 100 µs for each frame is still not short enough to separate different arc root lives.

In summary, analysis of the circular arc root motion in an Ar–H_2 dc non-transferred plasma torch at reduced pressure of 10 kPa shows that the arc root moves chaotically on the anode surface. Wandering around a stagnant point and rapid jumping are the two main modes of the circular motion of the arc root. The speed of the circular motion is mainly in the order of tens of degrees per millisecond while sudden jumps faster than several hundred degrees per millisecond also occur. Such circular movement of the arc root has little effect on the fluctuations of the arc voltage. Instead of being detrimental to the stability of the plasma jet, the circular arc root motions on the anode surface may help to alleviate electrode erosion and to prolong the life time of the torch. Further study is in progress, aiming to understand the relationship among the plasma generating conditions, the arc root behaviour and the stability of the plasma jet better.

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