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Electric Characteristics of Plasma Arc Produced by Bi-Anode Torch

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In order to improve the voltage control and stability of a plasma arc, a new-type plasma torch was designed and constructed. The torch, called bi-anode torch, has two anodes that were inter-insulated and have different distances from the cathode tip. The position of the arc root can be controlled to attach to either anode surface during operation to obtain a low-voltage and high-fluctuation arc or a high-voltage and low-fluctuation arc. The paper discussed the occurrence of the double-arc phenomenon and its prevention. Experimental work has been carried out to compare voltage-current (U-I) characteristic of the arc when using different plasma gases and anode arc root attaching to different anode surfaces. The results show that the U-I characteristic of the plasma arc is affected by the position of the anode arc root attachment and the composition of the plasma gas, which was explained by a simplified arc model.

Keywords bi-anode, double-arc, gas composition, plasma spraying, U-I characteristics

1. Introduction

Over the past decades, plasma spraying, as a well-established technology in modern surface engineering, has been applied widely to industrial practice in depositing coatings with various functions (Ref 1, 2). In order to obtain high-quality coating, it is necessary to increase the arc power especially when spraying high-temperature materials such as ceramics and superalloy. The common practice to increase the arc power is achieved by increasing the arc current. In practical spraying using a stick-type cathode, the arc power reaches 60 kW, which requires an arc voltage of 60 V and an arc current up to 1000 A (Ref 3). Large arc current not only decreases the thermal efficiency of the torch, but also accelerates electrode wear, especially the wear of the anode nozzle. An alternative way is to increase the arc voltage, but it is difficult to achieve by using conventional torch design.

The arc voltage is not an independent spraying parameter in conventional plasma spraying. It is determined by the process parameters such as arc current, gas flow rate, gas composition, and nozzle diameter (Ref 4). Conventional non-transferred plasma torch consists of a stick-typed cathode and a nozzle-shaped anode. The arc stretches between the cathode tip and the water-cooled anode wall. The working gas is introduced axially around the circumference of the cathode. Due to the entrainment of the cold gas in the arc column, the arc column is expanding with the arc developing downstream until the arc strikes the anode surface to form the anode arc root. Theoretically, the anode arc root position can be determined by the Steenbeck's minimum principle, which postulates that the anode arc root will be in such position that makes the total arc voltage be a minimum for a given current, working gas flow and torch configuration. This principle has been proved useful by the work of Paik and coworkers (Ref 5, 6). Based on this principle and according to the industrial practice, the traditional-designed plasma torch cannot achieve high voltages.

Besides, the anode arc root is unsteady under the general spray conditions. Two forces act on the connecting column that crosses the cold boundary layer and connects the arc column and the anode arc root. They are the drag force from the gas flow and the Lorenz forces due to the self-magnetic field. Generally, because the former is much larger than the latter, the anode arc root is pushed downstream and the arc voltage increases until a short-circuit occurs to lead to a new re-arcing in the upstream direction, which results in the fluctuation of the arc voltage (Ref 7). Bisson and coworkers (Ref 8, 9) studied the effect of the plasma fluctuation on the in-flight particle. The experimental results show that the arc fluctuation results in the unsteady heating and the accelerating of the in-flight particle, and furthermore deteriorates the uniformity of the sprayed coatings.

Some works have been carried out to control the motion of the anode arc root to obtain a clean plasma jet. Choi et al. (Ref 10) designed a stepped nozzle that can enhance the turbulence in the cold boundary layer to

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reduce the motion of the anode arc root. The experimental results show that the entrainment of ambient air into the plasma jet appears to be reduced. Osaki et al. (Ref 11) developed a new-type torch whose two electrodes installed perpendicular to the nozzle axial with the distance between two electrodes is 39 mm. The arc shows a U-shape when igniting. The experimental results show the arc voltage can get up to 140 V under a pure argon flow and the enthalpy of the plasma arc is higher than that of a normal arc.

In order to improve the voltage control and stability of a plasma arc, we designed and constructed a new-type plasma torch. The torch has two inter-insulated anodes connected in serial and with different distance from the cathode tip. The anode arc root can be controlled to attach to either anode surface to produce a low-voltage and high-fluctuation arc or a high-voltage and low-fluctuation arc. The thermal characteristics of the bi-anode torch have been studied in previous work (Ref 12). This paper will concentrate on the electric characteristics of the bi-anode torch.

2. Structure of Bi-Anode Torch and Experimental Procedure

2.1 Structure of Bi-Anode Torch

For a given spray condition, the arc voltage highly depends on the arc length, or the distance between the cathode tip and the anode arc root. A bi-anode plasma torch, as shown in Fig. 1, was specially constructed to lengthen the arc column and increase the arc voltage. It has a similar configuration to the conventional spraying torch except that it has two anode nozzles that are connected in serial and insulated from each other by a ceramic ring. The nozzle close to the cathode is called Anode I and the one far away from the cathode is called Anode II.

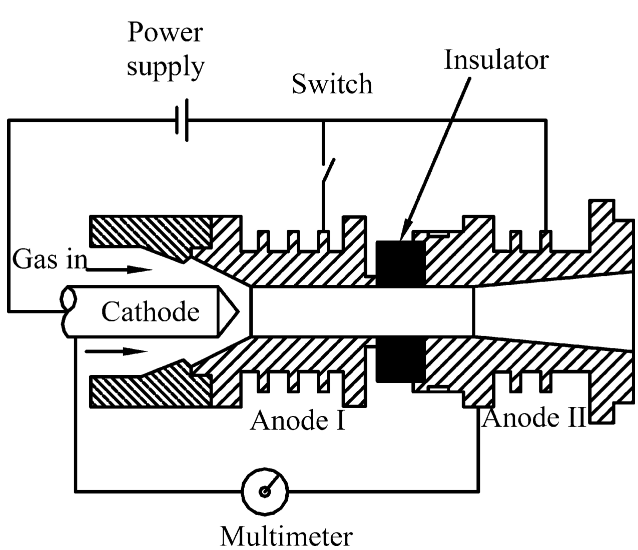

Fig. 1 The structure of the bi-anode plasma torch

The diameter of the nozzle passage is 5 mm. The distance from the cathode tip to the inlet of Anode I is 2 mm. The length of Anode I is 15 mm and the thickness of the insulation ring is 10 mm. Thus, the distance from the cathode tip to the inlet of Anode II is 27 mm. Anode II is always connected to the power supply while Anode I is connected to the power supply with a switch.

During the arc ignition, the switch is closed to make Anode I connected to the DC power supply. The anode arc root will attach to the surface of Anode I at this stage. The torch is operated in the Anode I mode. In the Anode I mode, the plasma arc is same as a traditional one. The anode arc root position and arc voltage can be determined by the Steenbeck's minimum principle. After the arc has been ignited, the switch is opened to make Anode I disconnected from the DC power supply. The anode arc root on Anode I surface will disappear because there is no current flow through Anode I. However, as the ionized plasma gas has a high electric conductivity, the plasma arc will not stop and the anode arc root will surely jump to the surface of Anode II. The torch is operated in the Anode II mode. In the Anode II mode, the arc length is more than 27 mm and the arc voltage can be significantly increased.

2.2 Experimental Procedure

In the experiments, the arc voltage was measured using a digital multimeter (Kaise KU-2608, Japan) with accuracy up to 0.1 V when measuring the voltage (range 0-400 V). The multimeter was directly connected to the cathode stick and anode nozzle to eliminate the measuring error produced by the resistance of the cable in the electrical circuit. Of course, owing to the actual arc voltage is fluctuated in a frequency ranging from 2 to 20 kHz, the arc voltage measured by the multimeter was just an average value.

3. Results and Discussion

3.1 Occurrence and Prevention of Double-Arc Phenomenon

To apply the bi-anode plasma torch, one must consider the occurrence of the ''double-arc'' phenomenon. According to the Steenbeck's minimum principle, the arc voltage will maintain a minimum value under a given spraying condition. Because the conductivity of the anode material (copper) is much lower than that of the plasma gas, if the length/diameter ratio of Anode I nozzle is large enough, two serial arcs will take place of the original arc to maintain a lower arc voltage (as shown in Fig. 2). One arc column is formed between the cathode tip and the surface of Anode I, and the other arc column is formed between the surfaces of Anode I and Anode II, that is, Anode I is not only the anode of the first arc but also the cathode of the second arc. The occurrence of the double-arc not only decreases the arc voltage but also results in the thermal wear of Anode I nozzle. In the design of the bi-anode torch, in order to prevent the occurrence of the double-arc

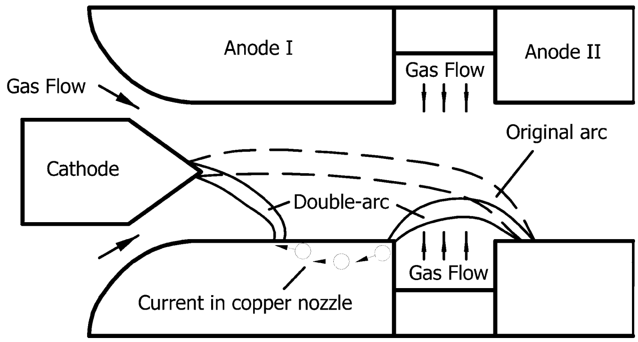

Fig. 2 The occurrence of double-arc phenomenon

phenomenon, four gas inlets are setting at the insulator position between Anode I nozzle and Anode II nozzle. Part of the gas flow (about a quarter of the plasma flow) are injected tangentially into the nozzle through the insulator. This design can effectively prevent the occurrence of double-arc phenomenon. Figures 3 and 4 show the measurement results of the arc voltage in the Anode II mode when applying insulated materials or copper as the materials of the Anode I nozzle. Obviously, the double-arc phenomenon will never happen when applying an insulated Anode I nozzle. However, the insulated anode nozzle is unsuitable for practical use because the low thermal conductivity of the insulator material will cause the thermal wear of the nozzle.

According to the measurement results, in the different arc current, the arc voltage has little difference when applying insulated materials or copper as the material for the Anode I nozzle. However, the difference in the arc voltage becomes large with the increase of the gas flow (shown in Fig. 3), which results from the different roughness between the two sets of anodes. The copper Anode I nozzle has a smooth surface that keeps the working gas being a laminar flow. In a laminar flow, increasing the gas flow will significantly compress the arc column and increase the arc voltage. However, the insulated Anode I, made of alumina material, has a surface rougher than the copper Anode I nozzle, which makes the working gas a turbulent flow, especially in the region close to the nozzle surface. The turbulence flow increases the heat flux to the nozzle wall, counteracts the cold boundary layer to compress the arc column, and prohibits the increase of the arc voltage.

The measurement results indicated the double-arc phenomenon has not occurred when applying a copper Anode I nozzle and it proved the gas flow from the insulator can effectively prevent the occurrence of the double-arc phenomenon. The reason is related to two factors. On the one hand, the gas flow from the insulator can effectively compress the arc column and increase the thickness of the cold boundary layer at the insulator. It can effectively prevent the occurrence of the double-arc phenomenon because larger voltage is required to break down the cold boundary layer to form the second arc of the double-arc. On the other hand, the gas flow from the insulator

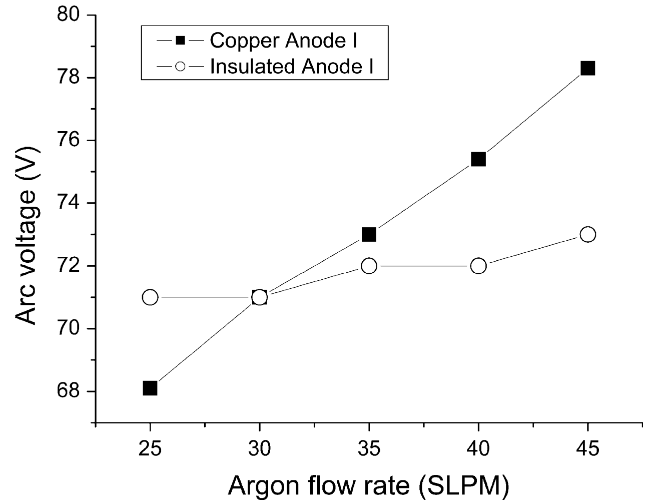

Fig. 3 The arc voltage versus gas flow when using a copper Anode I nozzle and an insulated Anode I

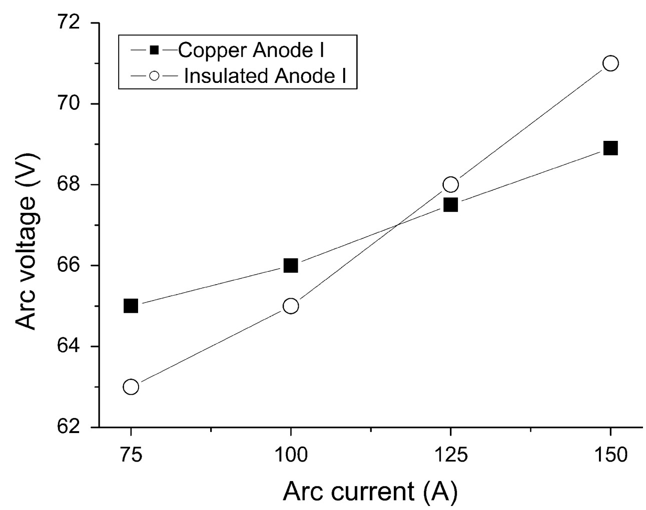

Fig. 4 The arc voltage versus arc current when using a copper Anode I nozzle and an insulated Anode I

also cools down the end of the first anode close to the insulator, where it is prone to be over-heated by the plasma gas to form micromelting area that can be the cathode arc root of the second arc of the double-arc. According to our experience, higher arc current (over 200 A) and lower gas flow rate (<15 slpm) will increase the possibility of the double-arc. Besides, double-arc is more likely to occur in pure argon plasma than in the Ar-H_2 plasma.

Obviously, the injection of the cold gas from the insulator tends to cool the overall plasma, reduce the specify enthalpy of the plasma, and even deteriorate the plasma flow. However, these adverse effects can be reduced to minimum by some measure, such as the introduction of the gas is tangentially but not vertically, and the flux of the introduced gas is much lower than the flux of the plasma flow. Of course, there are some ways other than the introduction of additional gas to prevent the occurrence of the double arc, such as increasing the length of the insulator or inserting additional anode and insulator between Anode I and Anode II. However, the former will bring the problem of the cooling of the insulator, and the latter will increase the complexity of the torch structure. Compared with the above ways, introducing additional gas from the insulator is a robust and simple way to prevent the occurrence of the double-arc.

3.2 U-I Characteristics of Plasma Arc

The experimental conditions for measuring the arc voltage-current characteristics in different gas compositions are given in Table 1. The arc current ranged from 75 to 150 A (175 A for argon) with a step of 25 A. The voltage-current characteristics under different anode modes and different gas compositions were studied respectively and the results are given in Fig. 5-7. In Anode I mode, the arcs show ‘‘dropping’’ voltage-current characteristic regardless of gas compositions. The ‘‘dropping’’ voltage-current characteristic means that the arc voltage decreases with the increase of the arc current, which is consistent with the plasma arc produced by the traditional plasma torch. In Anode II mode, however, the plasma arcs have different voltage-current characteristics for different gas compositions. The argon arc shows a distinct ‘‘rising’’ voltage characteristic, the Ar-N_2 arc shows a ‘‘level’’ voltage-current characteristic, and the Ar-H_2 arc, same as Anode I mode, shows a ‘‘dropping’’ voltage-current characteristic. The reason will be discussed in detail below.

For a DC plasma arc, its voltage-current characteristic depends on the relations between the arc current and electric resistance of the arc column. Higher arc current will widen the cross-section of the arc column and intensify the ionization of plasma gas. As a result, the electric resistance of the arc reduces. If the decrease of the electric resistance is slower than the increase of the arc current, the arc shows a ‘‘rising’’ voltage-current characteristic. Otherwise, the arc will show a ‘‘dropping’’ voltage-current characteristic. For the arc in the nozzle passage, when the arc current is low, the arc column is much thinner than the nozzle passage. So the arc has enough space to expand its column when increasing the arc current. The electric resistance decreases very fast so that the arc shows a ‘‘dropping’’ voltage-current characteristic. The expansion

Table 1 The condition for the measurement of the voltage-current characteristic

Gas	Flow rate
Ar	1.5 m^3/h
Ar-N_2 mixture	1.5 + 0.5 m^3/h
Ar-H_2 mixture	1.5 + 0.3 m^3/h

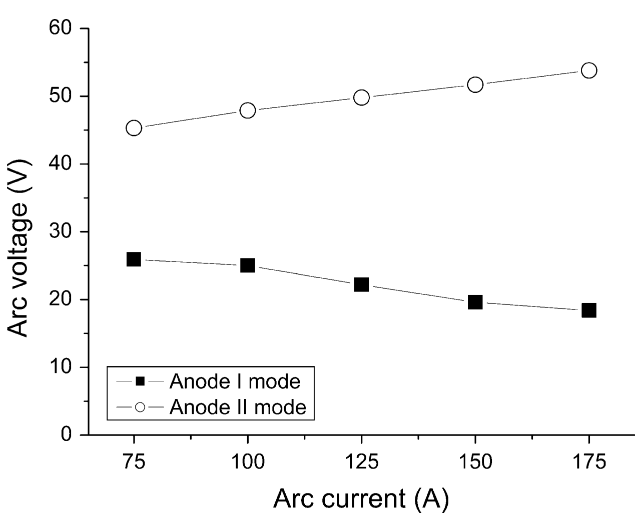

Fig. 5 The voltage-current characteristics of argon plasma arc in different modes

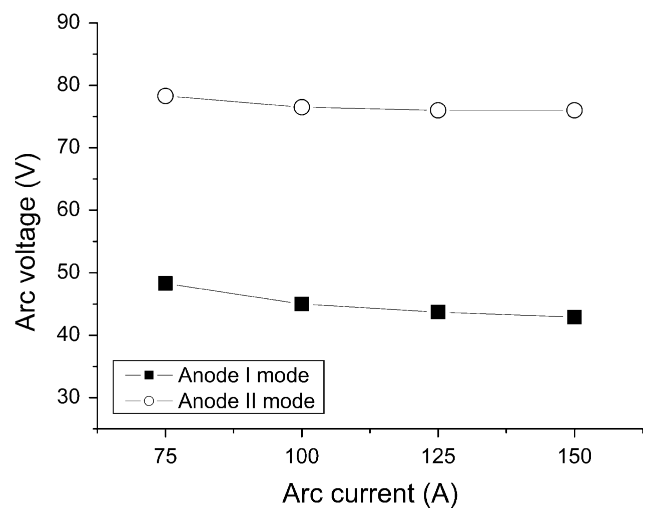

Fig. 6 The voltage-current characteristics of Ar-N_2 arc in different modes

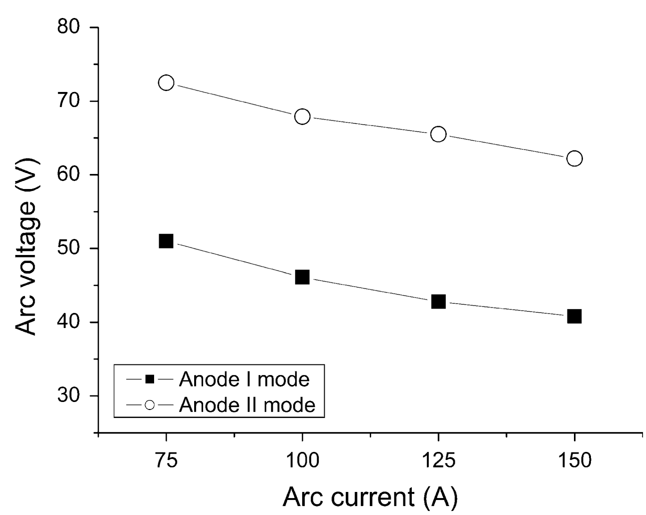

Fig. 7 The voltage-current characteristics of Ar-H_2 arc in different modes

of the arc column, however, will finally be restricted because of the existence of the nozzle wall. When the arc diameter is very close to the nozzle diameter, that is, the arc ''fills up'' the nozzle passage, the arc diameter changes little with the increase of the arc current. Under this condition, the electric resistance drops slowly with the increase of the arc current and the arc shows a ''rising'' voltage-current characteristic.

Generally speaking, for a given arc current, the arc column has a definite radius. However, for a spray arc, its diameter shrinks to be very small in front of the cathode tip due to the cooling effect and increases gradually along the axial distance. In the Anode I mode or for the traditional arc, two factors make the arc show a ''dropping'' voltage-current characteristics. On the one hand, the arc length is short so that the arc column cannot expand adequately along the axial distance, resulting in a smaller arc column than the nozzle passage and the arc cannot fill up the nozzle passage. On the other hand, higher arc current reduces the thickness of the cold layer and makes ''restrike'' occur in the upstream direction close to the cathode, which reduces the average length of the arc and decreases the arc voltage. In the Anode II mode, however, the arc is much longer and can expand adequately along the axial direction to fill the nozzle passage. It explains the occurrence of a ''rising'' voltage-current characteristic of argon arc in the Anode II mode but not in the Anode I mode. The pure argon arc is more likely to get a ''rising'' voltage-current characteristic, but the introduction of hydrogen or nitrogen into the argon arc will change its voltage-current characteristic. It is related to the characteristics of the gas mixture.

The electric characteristics of the arcs relate to their electric and thermal conductivity. The electric conductivities of argon, nitrogen, and hydrogen are not much different under all temperatures. However, the thermal conductivities of nitrogen and hydrogen, as shown in Fig. 8 (Ref 13), are much higher than that of argon. It is because nitrogen and hydrogen are diatom molecules, so the dissociation from a molecule to two atoms significantly increases the reactive thermal conductivities of the plasma gas. Besides, for the Ar-H_2 plasma arc, the recombination effect makes the hydrogen atoms congregate at the fringe of the arc column (Ref 14), which greatly intensifies the heat transmission from the arc to the nozzle wall.

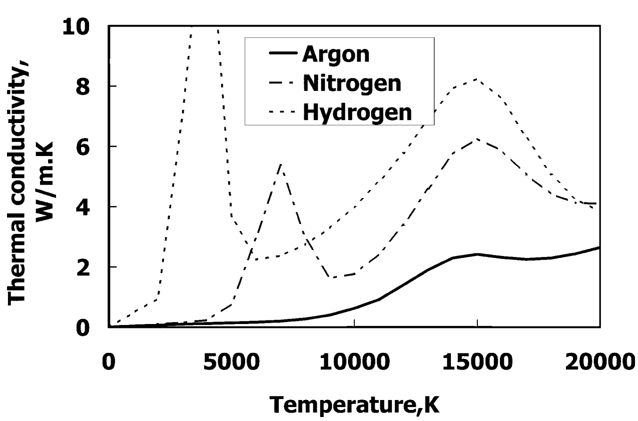

Fig. 8 Thermal conductivities of argon, nitrogen, and hydrogen

In the Anode II mode, because the arc column can expand adequately along the axial distance, the arc can be regarded as a fully developed arc, which can be defined as this: the Joule heat produced by the arc current is equal to the energy loss of the arc by means of convection and radiation. In this situation, the energy conservation equation of the arc can be stated as:

$$\frac{1}{r}\frac{d}{dr}\left(rk\frac{dT}{dr}\right) + jE - U_r = 0 \qquad \text{(Eq 1)}$$

where T is the arc temperature, k is the thermal conductivity of the plasma, r is the radial distance to the nozzle center, j is the arc current density, E is the electric field strength, U_r is the radiant coefficient. The first term of Eq 1 is the heat conduction from the arc to the nozzle, the second term is the energy produced by the arc, and the third term is the energy loss by radiation. The boundary conditions are:

$$\begin{aligned} &r = 0{:}\frac{dT}{dr} = 0 \\ &r = R{:}T = T_w \end{aligned} \qquad \text{(Eq 2)}$$

where R is the nozzle diameter and T_w is the temperature of the nozzle wall and it is 300 K in the calculation. To solve the equation, current conservation equation is required and it can be stated as:

$$I = 2\pi \int_0^R jr\,dr = E\left(2\pi \int_0^R \sigma r\,dr\right) \qquad \text{(Eq 3)}$$

where σ is the electric conductivity of the plasma gas. Given k, σ and U_r as the functions of the plasma temperature, the above-mentioned equations can be solved to determine the arc temperature and the electric field for different arc currents.

Given the nozzle diameter is 5 mm, the voltage-current characteristics of fully developed argon and hydrogen arcs were calculated and the results are shown in Fig. 9. With the increase of the arc current, the electric field strength first drops to a minimum and then continuously increases, that is, the arc has a ''dropping'' voltage-current characteristic in low arc currents but a ''rising'' voltage-current characteristic in high arc currents. However, the current for the hydrogen arc to get a ''rising'' voltage-current characteristic is 230 A, while that for the argon arc is only 25 A. It means that the argon arc gets a ''rising'' voltage-current characteristic in a much lower arc current than the hydrogen arc does. The reason is the fully developed arcs with different gas composition have different temperature distribution and arc diameter. This paper regards 8000 K as the temperature at the edge of the arc column, because above this temperature, the gas will be significantly ionized. The change of the arc diameter with the arc current is shown in Fig. 10. The argon arc has a larger diameter than the hydrogen arc and is more likely to fill the nozzle passage to get ''rising'' voltage-current characteristic in low arc currents.

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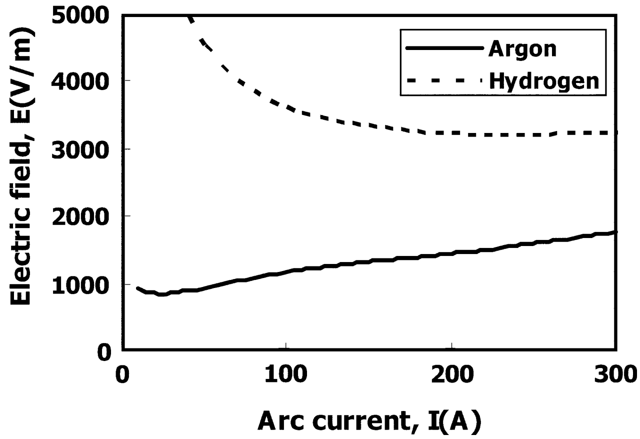

Fig. 9 The electric field versus arc current in argon and hydrogen gas composition

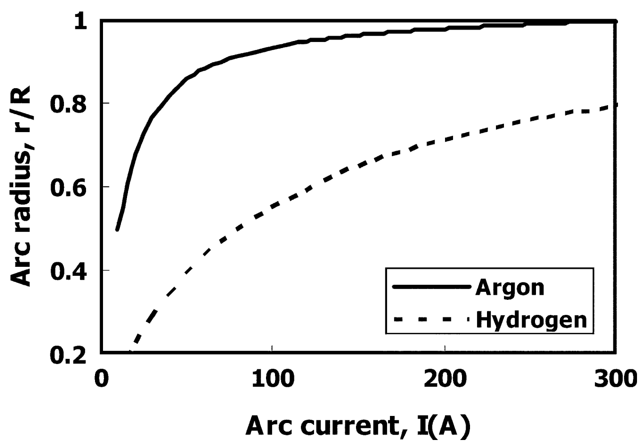

Fig. 10 The arc radius versus arc current in argon and hydrogen gas composition

According to the calculated results, the experimental results in the Anode II mode can be explained as follows. Under the voltage ranging from 75 to 150 A in the experiment, the argon arc of low thermal conductivity gets a ''rising'' voltage-current characteristic, the Ar-H_2 arc at the edge of which the hydrogen atoms recombine to make it just like a hydrogen arc of high thermal conductivity gets a ''dropping'' characteristic, and the Ar-N_2 arc with thermal conductivity between that of the Ar and Ar-H_2 arcs gets a ''level'' voltage-current characteristic.

4. Conclusions

A special bi-anode plasma torch was designed and constructed to improve the performance of the plasma torches. The electric characteristics of the new torch were studied and the conclusions are stated as follows:

1. Changing the anode arc root from Anode I to Anode II increases the arc length and leads to a higher arc voltage.
2. Large length/diameter ratio of the Anode I nozzle increases the possibility of the double arc phenomenon. Some gas flow at the insulator position can effectively prevent the occurrence of the double arc.
3. In the Anode I mode, the arc always shows ''rising'' voltage-current characteristic, which is consistent with a traditional one. In the Anode II mode, the voltage-current characteristic of the arc relates to the thermal conductivity of the plasma gas, pure argon arc of low thermal conductivity shows a ''rising'' voltage-current characteristic while Ar-H_2 arc of high thermal conductivity shows a ''dropping'' voltage-current characteristic.

Acknowledgments

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