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Generation of Long, Laminar Plasma Jets at Atmospheric Pressure and Effects of Flow Turbulence

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Long, laminar plasma jets at atmospheric pressure of pure argon and a mixture of argon and nitrogen with jet length up to 45 times its diameter could be generated with a DC arc torch by restricting the movement of arc root in the torch channel. Effects of torch structure, gas feeding, and characteristics of power supply on the length of plasma jets were experimentally examined. Plasma jets of considerable length and excellent stability could be obtained by regulating the generating parameters, including arc channel geometry, gas flow rate, and feeding methods, etc. Influence of flow turbulence at the torch nozzle exit on the temperature distribution of plasma jets was numerically simulated. The analysis indicated that laminar flow plasma with very low initial turbulent kinetic energy will produce a long jet with low axial temperature gradient. This kind of long laminar plasma jet could greatly improve the controllability for materials processing, compared with a short turbulent arc jet.

KEY WORDS: Laminar plasma jet; flow turbulence; arc jet length.

1. INTRODUCTION

Atmospheric dc arc jet is widely used in materials processing. Its high temperature and high-energy intensity of the gas flow makes it possible to heat materials to temperatures impossible with ordinary heating sources. At the same time, its particularly high activity could bring about rapid reaction rates and process speeds.(1–3) To improve the process control, continued research on the generation, diagnostics, and modeling of the plasma jet has been carried out(4–6) for a better understanding of the plasma state. Most of the nontransferred dc plasma jets generated at atmospheric pressure are in a turbulent state of flow. Plasma jets fluctuate continuously in length, diameter, and position, because of the irregular jumping of the arc root in torch channel, caused by the effects of gas feeding, gas expansion, and magnetic forces in the generating procedure.(1,7) The arc fluctuation will lead to a

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rapid mixing of the jet flow with the surrounding atmosphere after it leaves the torch nozzle, bringing about a short arc jet, low efficiency for materials heating, and difficulties in process control. For example, it is found that the fluctuation of an arc jet could cause problems on the control of particle heating in plasma spraying.(8,9) Unstable properties of turbulent-flow plasma jet limit its usage to an area of low-precision materials technology. Recently, there was research on restricting the fluctuation by limiting the arc root movement(10) or improving the gas flow conditions.(11,12) Systematic studies are necessary to investigate the effects of gas feeding and flow control, geometry of arc channel, and property of power supply on the stability and flow character of a plasma jet. This is really important to the improvement of process controllability for materials technology.

In this work, long arc plasma jet of good stability was generated. Effects of torch geometry, gas-flow control and character of power supply on the length and stability of plasma jets were experimentally examined and influence of the flow turbulence at the exit of torch nozzle on the temperature distribution of the plasma jet was studied by numerical simulation.

2. GENERATION OF LONG, LAMINAR ARC JET

2.1. Experiment

A new, nontransferred dc arc torch was designed to generate long plasma jets. The schematic drawing of its structure is shown in Fig. 1. The torch was built mainly with a cathode, interelectrode inserts, and an anode. This structure provides an arc channel in which the arc root could be confined to a certain circular range on the anode wall, according to the gas feeding and input power conditions. Anode nozzles with inside diameters of 4 to 10 mm were used. The main gas inlet can be tangential to the channel wall or along the axial direction of the torch, and the auxiliary gas was tangential to the wall. Argon and mixtures of argon with 30–70% nitrogen were used as the plasma working gases at a flow rate of 200 to 500 cm^3/s. Fluctuation of gas flow rate was limited to a range lower than ± 3% of its given value by using mass-flow controllers. Plasma jets were generated at atmospheric pressure with an input power of 3 to 12 kW and arc current of 80 to 300 A, using direct-current power supplies with capacity of 30 and 15 kW output. Another plasma torch with a normal structure without interelectrode inserts and auxiliary gas was also made and tested under about the same working conditions, to confirm the effects of interelectrode inserts on the arc length and flow stability of a plasma jet. The power supplies have good arc ignition and relatively stable output characteristics. The stability of plasma jet was determined by measuring the voltage and current fluctuations and by observing its appearance.

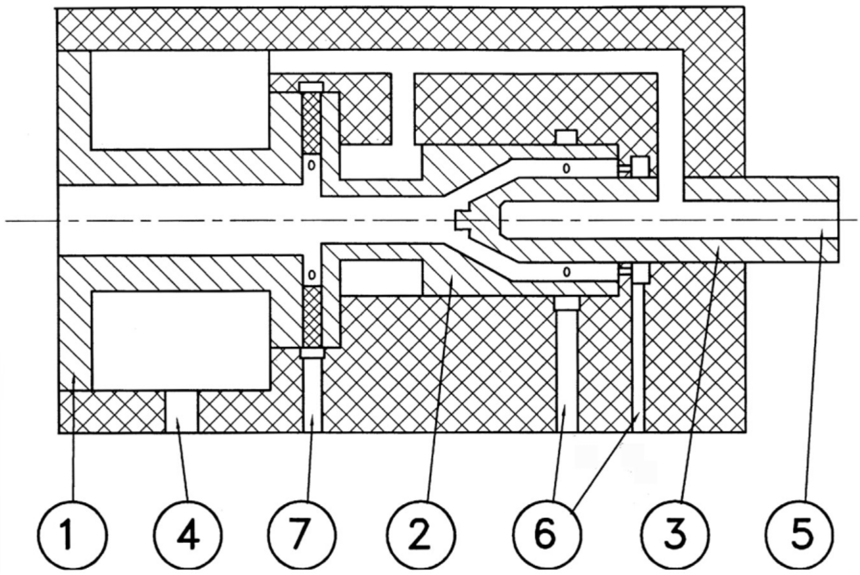

Fig. 1. Schematic drawing of the new torch. (1) Anode; (2) interelectrode insert; (3) cathode; (4) water in; (5) water out; (6) main gas inlet; (7) auxiliary gas inlet.

2.2. Results

2.2.1. Torch Structure

A relatively long arc jet with very low noise could be generated with the normal-type dc plasma torch, by regulating the gas feeding method, gas flow rate, and arc current. In this case, the ratio of arc length to its diameter of plasma jets was generally lower than 10. The stability of jet flow was easily disturbed by a small fluctuation of inlet gas flow and input power or by a slight anode erosion.

A long plasma jet of a length-to-diameter ratio up to 45 or even more could be generated, by using the torch, including an interelectrode insert. Figure 2 shows an example of the long plasma jet, with $Ar:N_2 = 80:140\,cm^3/s$, arc current of 160 A, and a nozzle diameter of 8 mm. Plasma jets of different length could be obtained with quite favorable stability, by regulating the size and shape of the interelectrode insert and anode nozzle. A long plasma jet seems to be more easily obtained by using a torch with a long interelectrode insert channel. Multipiece metal components insulated from each other could be used to form an insert to avoid double arcing from cathode to insert and then from insert to anode, when a long insert channel is needed. The anode nozzle could be shaped with a uniform inside

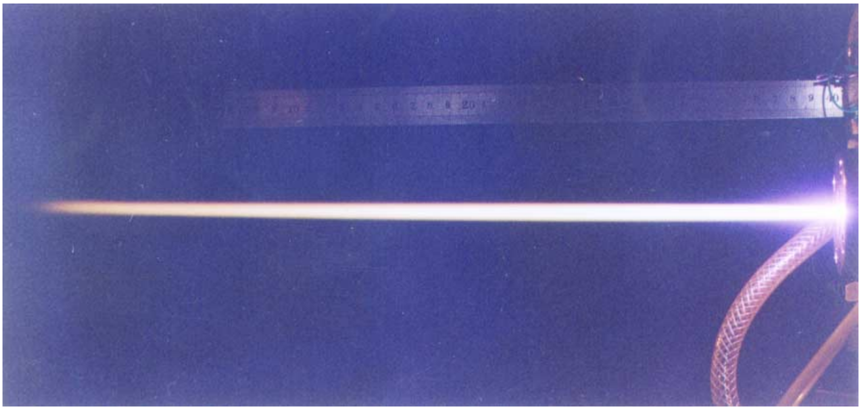

Fig. 2. Long plasma jet with argon and nitrogen as the working gas.

diameter or having a step with a larger diameter at the exit side. That is, the interelectrode insert could be a single- or multipiece component and the shape and size of anode nozzle could be changed in a relatively wide range, to regulate the state of plasma jets.

Thus, effects of gas feeding method, flow rate and gas type, input power, and characteristics of power supply on the jet conditions were examined with the torch containing an interelectrode insert.

2.2.2. Working Gas

Figure 3 shows argon plasma jets generated with the same torch with an 8-mm nozzle diameter. The input power was the same, at about 6 kW, with arc current of 160 A, and power supply of 30 kW. Gas flow rate of the jet in Fig. 3a was 450 cm^3/s, that of (b) and (c) was 220 cm^3/s. Figure 3a has a typical appearance of turbulent plasma jet. The jet was quite short and was accompanied by a very high noise. The noise decreased and the arc length increased, as the gas flow rate decreased. In the generation of the jets shown in Figs. 3b and c, jet noises were lower than that from the power supply. The apparent difference in arc length of the two jets was caused by the different inlet methods of the plasma working gas. The gas was fed along the torch axis for the jet (b) and tangentially with the channel wall for the jet (c). The results indicated that revolving the inlet gas on the arc channel wall could be favorable for lengthening the plasma jet. This could be caused by two reasons. The first is that the gas revolving could stabilize the arc column to decrease its fluctuation. The second is that revolving could be favorable in causing the arc root to move circumferentially on the anode

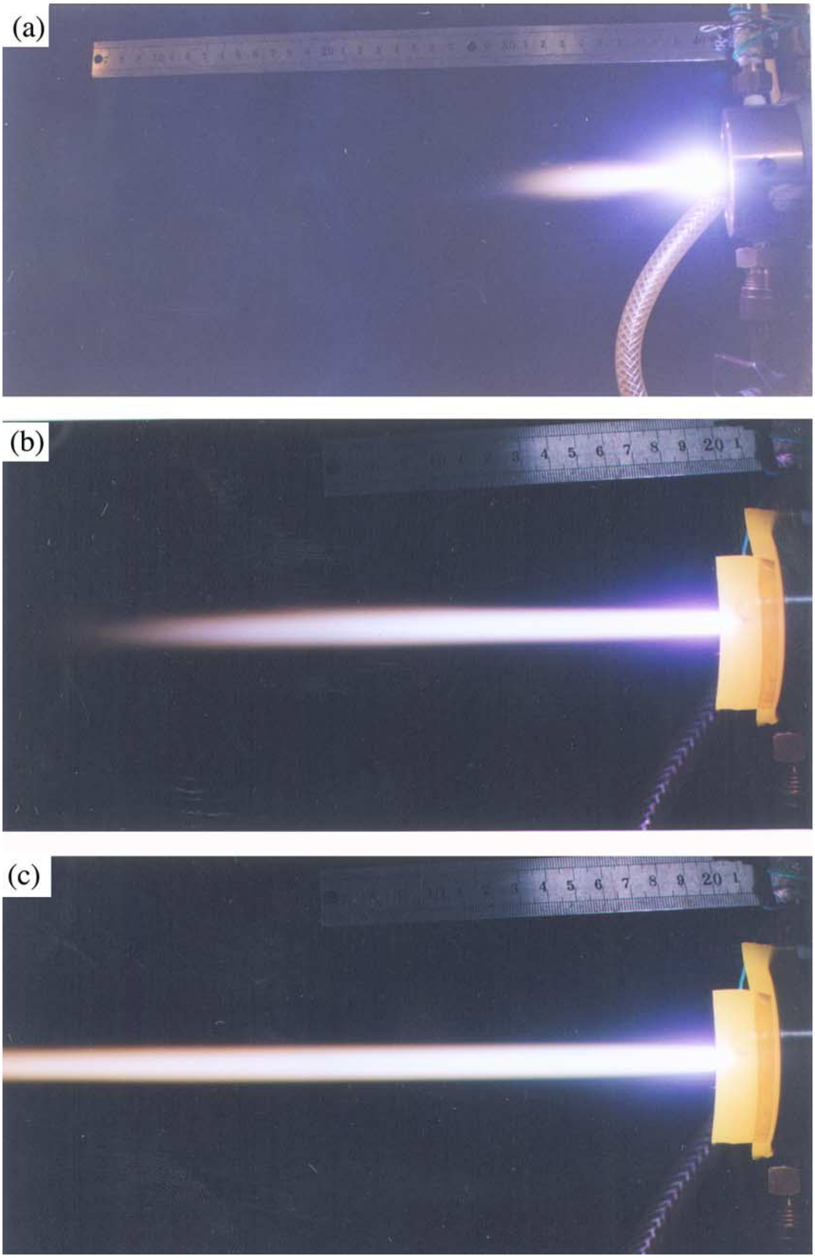

Fig. 3. Argon plasma jets generated at gas flow rate of (a) 450 cm^3/s and (b) and (c) 220 cm^3/s. The gas was fed along the torch axis for the jet (b) and tangentially for the jet (c).

wall with a reduction of its motion in the up- and downstream directions, thus reducing the flow fluctuation.

Plasma jets shown in Figs. 2 and 3c were generated at the same gas flow rate and feeding condition, but different gas component. The jet in Fig. 2 was a mixture of $Ar:N_2 = 80:140\,cm^3/s$; the one in Fig. 3c was with pure argon gas. Mixing argon with the nitrogen of the plasma gas increased the jet length, because it is easier to increase the input power and to give the plasma jet a higher enthalpy than in the case of pure argon.

Auxiliary gases could play a role in the further regulation of plasma conditions and for the addition of reactive gas species to the plasma, according to the needs of special-materials processing. The addition of reactive gases from the auxiliary inlet could greatly reduce cathode erosion and channel contamination, which would be caused by the excited and/or decomposed gas components.

2.2.3. Characteristics of Power Supply

Power supplies of 15 and 30 kW used in this work not only have different power ranges, but also different characteristics. The 30-kW supply is designed for thermal plasma CVD process at reduced pressure; the 15 kW one is for plasma cutting. Figure 4 shows the voltage features of the two supplies to generate plasma jets with input power of 3.5 kW and arc current of 100 A at the same argon gas flow rate of $200\,cm^3/s$ and feeding conditions. Voltages of the 15-kW power supply fluctuated irregularly on a relatively large scale, which apparently differs from that of the 30-kW power supply. The stability of plasma jets seemed to be correlated to the characteristics of the power supply. The 30-kW power supply could generate a plasma of stable long jet, but the 15-kW one could only produce a relatively short and unstable plasma jet, even under the same gas feeding conditions and torch structure.

Figure 5 indicates the fluctuation characteristics of the working current of the 30-kW supply. Measurement was conducted by using a torch of a nozzle diameter of 8 mm with argon gas of $200\,cm^3/s$. In the low current region, the ratio of $(I_{max} - I_{min})/I$ is higher than 22%; in the high current region, it is lower than 9%. That is, the fluctuation decreased as the working current increased. At the same time, it was confirmed by experimental observation that flow stability and arc length of plasma jets increased as working current increased in the range shown in Fig. 5.

Accordingly, to generate a long and stable plasma jet, it is desirable to choose a power supply with a low output fluctuation and to use it in the favorable working range.

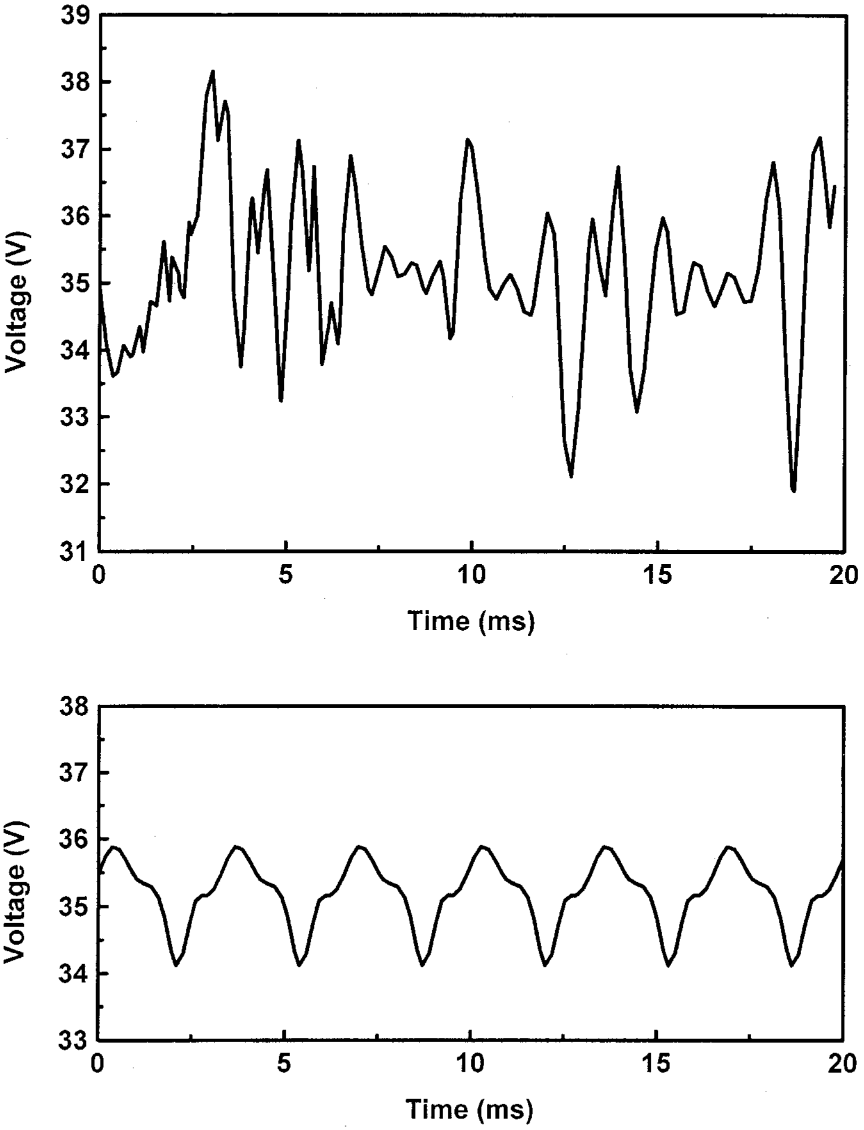

Fig. 4. Voltage features of two power supplies working at an output power of 3.5 kW. The upper curve is the 15-kW power supply and the lower is for 30-kW power supply.

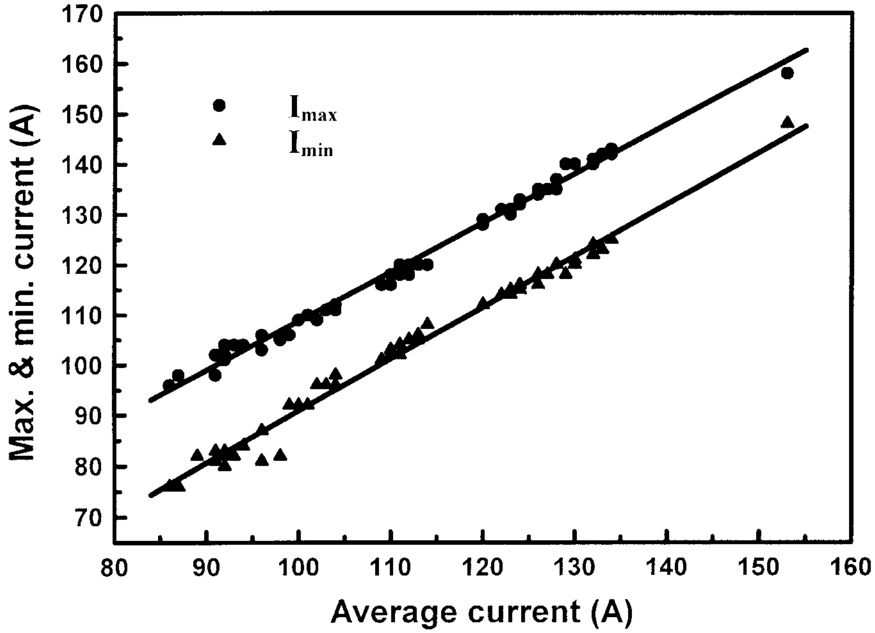

Fig. 5. Current fluctuations compared with its average value for 30-kW power supply.

3. ANALYSIS OF INFLUENCE OF FLOW TURBULENCE ON LENGTH OF PLASMA JET

Above experimental results indicated that torch structure, gas feeding and flow rate, and characteristics of power supply will all affect the stability of plasma jets. This suggests the flow character of a plasma jet is mainly determined in the generating process. That is, initial fluctuation of a plasma jet could be represented by flow turbulence at the exit of the torch nozzle. Accordingly, effects of the turbulent kinetic energy at the torch nozzle exit on the temperature distribution of plasma jets, which determines the arc jet length, were studied by numerical simulation. The real turbulent kinetic energy value and distribution at the nozzle exit were not measured and its detailed relation with the arc root fluctuation is not discussed here. Two typical conditions of turbulent and laminar flow jet were simulated.

3.1. Method

Figure 6 shows a sketch of the simulation region. A plasma jet of specified temperature and velocity profiles emerges from the torch nozzle into an

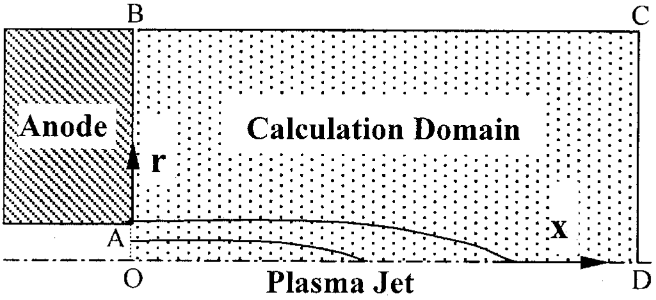

Fig. 6. A sketch of the simulation region.

infinite space. K–ε model was used to simulate the turbulent flow. Transport equations to simulate turbulent plasma jets were formulated based on the following assumptions:(13) (1) The plasma is in local thermodynamic equilibrium at atmospheric pressure; (2) flow conditions are symmetrical about the torch axis; and (3) the arc is optically thin.

3.1.1. Governing Eqations

Based on the assumptions, governing equations for the numerical simulation of a turbulent plasma jet can be written in the general form:(14)

$$\frac{\partial}{\partial x}(\rho \mathrm{u} \phi) + \frac{1}{r}\frac{\partial}{\partial r}(r \rho \mathrm{v} \phi) = \frac{\partial}{\partial x}\left(\Gamma_\phi \frac{\partial \phi}{\partial x}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r \Gamma_\phi \frac{\partial \phi}{\partial r}\right) + S_\phi \tag{1}$$

where ϕ is the general variable, Γ_ϕ the corresponding diffusion coefficient, S_ϕ is the source term; u and v are the axial and radial velocity components, ρ is the mass density, and x and r are the distances in the axial and radial directions. Boulos *et al.*(15) work was referred to for the gas thermodynamic and transport properties.

3.1.2. Boundary Conditions

Boundary conditions of the flow were assumed as follows: exit of torch nozzle, OA; radius of torch nozzle is $R = 4\,\mathrm{mm}$. The radial velocity component $\mathrm{v} = 0$. Two conditions with a different K_{OA} value of $0.005\,\mathrm{u}^2$, $0.5 \times 10^{-30}\mathrm{u}^2$, and $\varepsilon_{OA} = 0.1 K_{OA}^2$ were considered. Temperature and axial velocity were assumed to be:(14)

$$T = T_{\mathrm{w}} + (T_{\max} - T_{\mathrm{w}})\left[1 - \left(\frac{r}{R_0}\right)^2\right]^{1/2} \qquad \mathrm{u} = \mathrm{u}_{\max}\left[1 - \left(\frac{r}{R_0}\right)^2\right]^{3/2}$$

where $T_{\max} = 12{,}000$ K. The gas flow rate was 330 cm^3/s and Reynolds number was estimated to be about 630 under the given conditions.

The wall surface AB:

$$\mathrm{u}_\mathrm{w} = 0, \qquad \nu_\mathrm{w} = 0, \qquad T_\mathrm{w} = 350\,\mathrm{K}$$

The axis of symmetry OD:

$$\nu = 0, \qquad \frac{\partial \mathrm{u}}{\partial r} = 0, \qquad \frac{\partial T}{\partial r} = 0, \qquad \frac{\partial K}{\partial r} = 0, \qquad \frac{\partial \varepsilon}{\partial r} = 0$$

The top-free boundary BC:

$$\frac{\partial(\rho \nu r)}{\partial r} = 0, \qquad \frac{\partial \mathrm{u}}{\partial r} = 0, \qquad \frac{\partial T}{\partial r} = 0, \qquad K = 0, \qquad \varepsilon = 0$$

This boundary is far from the main flow region. The flow velocity here is very low and thus could be treated as a fully laminar flow regime to reduce the calculation time.

The exit boundary CD:

$$\frac{\partial \mathrm{u}}{\partial x} = 0, \qquad \nu = 0, \qquad \frac{\partial T}{\partial x} = 0, \qquad \frac{\partial K}{\partial x} = 0, \qquad \frac{\partial \varepsilon}{\partial x} = 0$$

3.2. Influence of Turbulent Kinetic Energy at Torch Nozzle on Arc Length

The governing differential equations were solved using the SIMPLE algorithm on a 92 × 50 unequal-interval grid. Figure 7 is the simulated isotherm graphs of argon plasma jets of two conditions with $K_{\mathrm{OA}} = 0.005\mathrm{u}^2$ and $0.5 \times 10^{-30}\mathrm{u}^2$ at the exit of the torch nozzle on length of plasma jet. The plasma jet showed a typical turbulent flow character when K_{OA} was $0.005\mathrm{u}^2$. Its temperature along the axial direction decreased rapidly, thus indicating a very short arc length. The plasma jet showed almost a laminar flow character, as shown in Fig. 7, when K_{OA} had a very small value of $0.5 \times 10^{-30}\mathrm{u}^2$. These numerical results suggest that the length of a plasma jet is decisively affected by the flow turbulence at the exit of anode nozzle, i.e., defined by the generating process before it leaves the torch nozzle. Laminar flow plasma of very low turbulent kinetic energy will present a long arc jet.

Figure 8 displays temperature changes along the axis of simulated jets of Fig. 7. The axial temperature gradient of turbulent plasma jet is high and decreased when the flow has a very low initial turbulent kinetic energy.

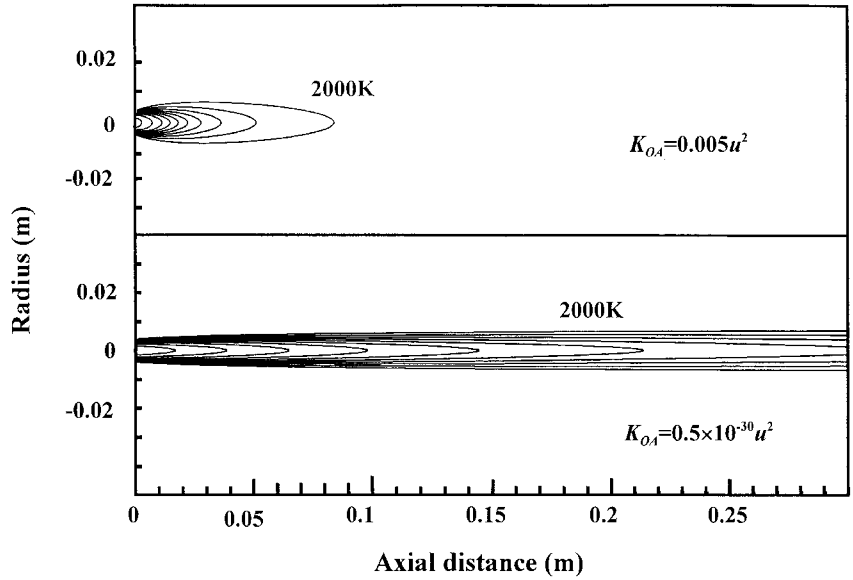

Fig. 7. Simulated isotherms of argon plasma jets of different turbulent kinetic energy at the torch nozzle. Temperature difference between two near lines is 1000 K.

4. DISCUSSION

Experimental results indicated that torch structure, gas feeding, and characteristics of power supply affected the stability and length of plasma jets. These factors affect the flow field inside the arc channel and the movement of arc root on the anode wall, which thus affects the flow condition of plasma jet.(7) Generally, the two important forces acting oppositely on the anode arc root attachment are the gas dynamic drag force and Lorentz force. The forces fluctuate according to the waving of gas feeding and input power and move the arc root attachment up- and downstream, thus causing the surging behavior of arc jet and turbulent flow conditions. Laminar plasma jet could be generated in this work just by restraining the fluctuation of gas feeding and input power and then the arc root movement. However, an unsuitable limiting of the arc root movement will cause anode erosion or plasma breakdown problem. Making the arc root move around a narrow circular region on the anode wall could be a suitable way to produce a stable laminar plasma jet and, at the same time, to prevent the anode from erosion. In brief, an overall balancing of the generating conditions is necessary to obtain a plasma jet with favorable length and stability.

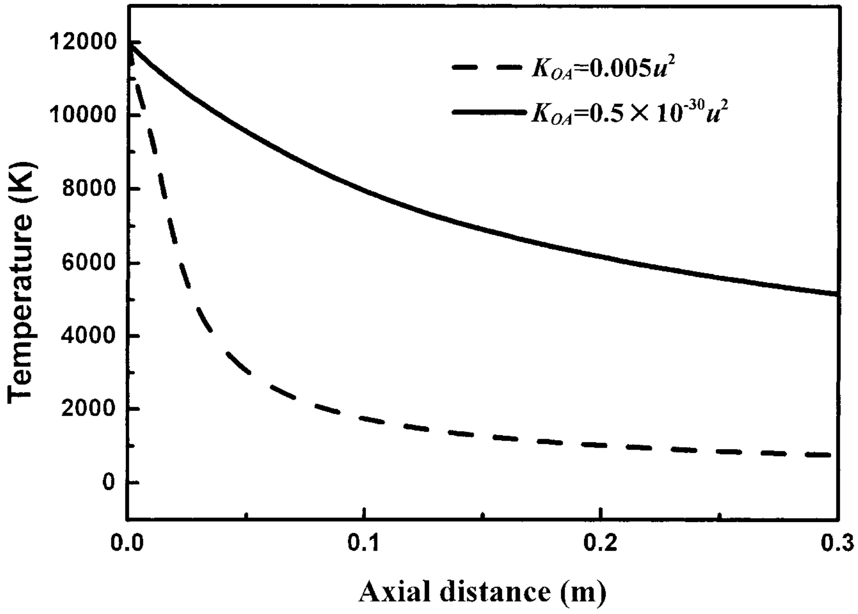

Fig. 8. Temperature changes along the axial direction of the two plasma jets in Fig. 7.

The reduced temperature gradient of a long-arc laminar-flow plasma jet shown in Fig. 8 suggests advantages for the process control of materials technology. For example, when a turbulent plasma jet is used for surface treatment of materials, a small change of specimen position, surface condition, and a slight fluctuation of the generating parameters of plasma jet will greatly affect the temperature for specimen heating. This will influence the results of treatment and bring about a low process controllability. Thus, by the results shown in Fig. 8, it is clear that long arc jet of low flow turbulence with low axial temperature gradient could greatly improve the process control for material surface technology.

5. CONCLUSIONS

Experimental results confirmed that torch structure, gas feeding, and characteristics of power supply are all important factors affecting the plasma jet length and stability of an atmospheric dc arc jet. The flow character of a plasma jet was mainly determined by its generating process and an overall balancing of the generating conditions is necessary to obtain a favorable plasma jet with a certain jet length and flow stability. Long laminar plasma jets of pure argon and mixtures of argon and nitrogen could be obtained. The jet length could reach a value of about 45 times its diameter. Simulation results indicated the flow turbulence at the exit of torch nozzle greatly affects the temperature distribution of a plasma jet. Laminar flow plasma of extremely low turbulent kinetic energy displayed a very long arc jet. The analysis of the temperature distribution of plasma jets indicated that the long plasma jet could greatly increase the controllability for materials processing.

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