Transactions of the Materials Research Society of Japan 32[2] 535-538 (2007)

A Unified Numerical Model of Oxygen Plasma Jet at Atmospheric Pressure

Manabu Tanaka, Shinichi Tashiro, Masakazu Shibahara*, Kazushi Tanaka**, Yoshimi Sano*** and Naoyoshi Akiyoshi****

Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaraki, Osaka 567-0047, Japan
Fax: 81-6-687-8689, e-mail: tanaka@jwri.osaka-u.ac.jp, tashiro@jwri.osaka-u.ac.jp
*Department of Marine System Engineering, Osaka Prefecture University, 1-1 Gakuen-cho, Sakai, Osaka 599-8531, Japan
Fax: 81-72-254-9914, e-mail: shibahara@marine.osakafu-u.ac.jp
**Chubu Electric Power Co. Inc., 20-1 Kitasekiyama, Ohdaka-cho, Midori-ku, Nagoya 459-8522, Japan
Fax: 81-52-624-9234, e-mail: tanaka.kazushi@chuden.co.jp
***Nissan Tanaka Co., 11 Chikumazawa, Miyoshi-machi, Irumagun, Saitama 354-8585, Japan
Fax: 81-49-258-5790, e-mail: yoshimi_sano@tanaka.sanso.co.jp
****Toho Kinzoku Co. Ltd., 6-17, 2-Chome, Kitahama, Chuo-ku, Osaka 541-0041, Japan
Fax: 81-6-6202-1390, e-mail: akiyoshi@tohokinzoku.co.jp

In order to understand the plasma cutting process for improving the reliability for stable cutting with a prolonged lifetime, the whole region of oxygen plasma jet, namely, a hafnium electrode as a cathode buried in the water-cooled copper sheath, an arc plasma and a copper nozzle as an anode is treated in a unified numerical model. Calculations are made for the two-dimensional distributions of temperature and fluid flow velocity in the whole region of the oxygen plasma jet for a 400 A in arc current. The current density distribution and also the whole energy balance at the tip of cathode and water-cooled copper sheath are predicted. It is shown that the nozzle diameter strongly affects the plasma jet properties and also the nozzle lifetime but weakly affects the hafnium cathode lifetime.

Key words: Plasma jet, Oxygen, Cutting, Hafnium, Numerical model

1. INTRODUCTION

Electric arcs have been applied in the industrial processing of materials, for example in melting, welding, cutting, thermal spraying, etc. Specially, oxygen plasma cutting is one of the important applications of electric arcs to manufacturing industries, because the cutting process dominates the quality and the precision in assembly of component parts for productions. The oxygen plasma cutting enables to realize high-speed and heavy-gauge cutting up to 50 mm thick steel plates. For the understanding and also the control of this process, it is important to develop a modeling capability, preferably to be able to predict properties of the total arc processing system. For example, in plasma cutting, one of the most important required functions is the reliability for stable cutting with a prolonged lifetime.

The present paper presents a methodology for predicting the temperature distributions inside the torch where the arc and its electrodes are treated as a unified system. Previous modeling of a plasma jet for the cutting process has treated only the arc plasma outside the torch [1]. In the present paper, the basic model and procedure by Tanaka et al [2] for the arc welding process are extended to a plasma jet for the cutting process at the atmospheric pressure, with inclusion of a hafnium electrode as a cathode buried in the water-cooled copper sheath and a copper nozzle as an anode. We also give predictions of the two-dimensional distributions of temperature and velocity inside the torch with plasma jet.

2. A UNIFIED ARC-ELECTRODE MODEL

The hafnium cathode with copper sheath, arc plasma and nozzle anode are described relative to a cylindrical coordinate, assuming rotational symmetry around the arc axis. The calculated domain is shown in Fig. 1. The domain of computation is divided into 95 nodes axially and 70 nodes radially, using a non-uniform grid. The flow is assumed to be laminar, the arc plasma is assumed to be in the local thermodynamic equilibrium (LTE). Furthermore, the cathode surface is assumed to be flat and unperturbed by the arc pressure even if its temperature is higher than the melting point of hafnium. The diameter of the hafnium cathode is 2.0 mm with a 1.75 mm length. The metal vapor from the cathode is neglected in this model. The nozzle anode is assumed to be copper cooled by water. The working gas of plasma cutting process is assumed to be pure oxygen.

The governing equations, boundary conditions and numerical method were explained in details in our previous papers [2, 3], and then only the most pertinent points are explained here.

The mass continuity equation is

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r)+\frac{\partial}{\partial r}(\rho v_z)=0, \qquad (1)$$

the radial momentum conservation equation is

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r^2)+\frac{\partial}{\partial z}(\rho v_z v_r)=-\frac{\partial P}{\partial r}-j_z B_\theta$$
$$+\frac{1}{r}\frac{\partial}{\partial r}(2r\eta\frac{\partial v_r}{\partial r})+\frac{\partial}{\partial z}(\eta\frac{\partial v_r}{\partial z}+\eta\frac{\partial v_z}{\partial r})-2\eta\frac{v_r}{r^2} \quad , \qquad (2)$$

the axial momentum conservation equation is

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_z)+\frac{\partial}{\partial z}(\rho v_z^2)=-\frac{\partial P}{\partial z}+j_r B_\theta$$
$$+\frac{\partial}{\partial z}(2\eta\frac{\partial v_z}{\partial z})+\frac{1}{r}\frac{\partial}{\partial r}(r\eta\frac{\partial v_r}{\partial z}+r\eta\frac{\partial v_z}{\partial r})+\rho g \quad , \tag{3}$$

the energy conservation equation is

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r h)+\frac{\partial}{\partial z}(\rho v_z h)=\frac{1}{r}\frac{\partial}{\partial r}(\frac{r\kappa}{c_p}\frac{\partial h}{\partial r})$$
$$+\frac{\partial}{\partial z}(\frac{\kappa}{c_p}\frac{\partial h}{\partial z})+j_r E_r+j_z E_z-U \quad , \tag{4}$$

the current continuity equation is

$$\frac{1}{r}\frac{\partial}{\partial r}(rj_r)+\frac{\partial}{\partial z}(j_z)=0 \quad , \tag{5}$$

the Ohm's low is

$$j_r=-\sigma E_r,\quad j_z=-\sigma E_z \quad , \tag{6}$$

and Maxwell's equation is

$$\frac{1}{r}\frac{\partial}{\partial r}(rB_\theta)=\mu_0 j_z \quad . \tag{7}$$

Each physical symbol in the above equations indicates the same meaning as general use.

Calculations at points on both electrode surfaces will need to include the special process occurring at the surfaces. Thus, additional energy flux terms need to be included in equation (4) at each electrode surface for thermionic heating and cooling from the electrons, ion heating, and radiation cooling. The additional energy flux for the cathode H_K and for the anode H_A are

$$\text{Cathode} \quad H_K=-\varepsilon\alpha T^4-|j_e|\phi_K+|j_i|V_i \tag{8}$$

and

$$\text{Anode} \quad H_A=-\varepsilon\alpha T^4+|j|\phi_A \tag{9}$$

respectively. Here ε is the surface emissivity, α is the Stefan-Boltzmann constant, ϕ_K is the work function of the hafnium cathode, ϕ_A is the work function of the copper anode, V_i is the ionization potential of oxygen atom, j_e is the electron current density, and j_i is the ion current density. We calculate the electron saturation current density at the cathode surface by thermionic emission of electrons j_R from the Richardson-Dushman equation. The ion current density j_i is then assumed to be $|j|-|j_R|$ if $|j|$ is greater than $|j_R|$; where $|j|=|j_e|+|j_i|$ is the total current density at the cathode surface obtained from equation (5).

The detailed boundary conditions and numerical method are detailedly given in our previous paper [2, 3]. Within both solid electrodes, we set $v_r=v_z=0$. The temperatures at boundaries AB, BC, CD, DE, EF, FG, GH, HI, IJ, JN and MN in Fig. 1 are taken to be the same room temperature, namely, 300 K. The electric potential is set to zero at the bottom of the anode nozzle,

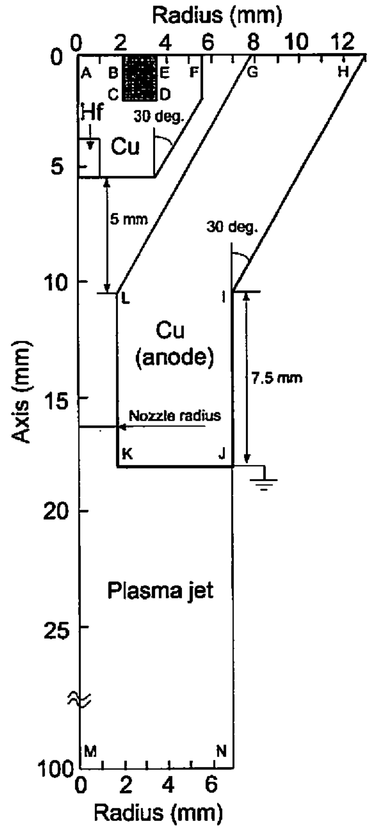

Fig. 1 Schematic illustration of calculated domain.

Table I Major physical properties of metals used in this model.

Hf

T (K)	κ (W/cm/K)	Cp (J/g/K)	σ (A/V/cm)	Work F (eV)	A (A/cm²/K²)	M (g/cm³)
300	0.235	0.146	25446			
1000	0.210	0.146	7981			
2000	0.275	0.146	5917	3.5	14	11.1
3000	0.275	0.146	5917			
4000	0.275	0.146	5917			

Cu

T (K)	κ (W/cm/K)	Cp (J/g/K)	σ (A/V/cm)	M (g/cm³)
300	3.94	0.385	590319	
1000	2.44	0.473	123456	8.9
2000	1.80	0.495	39525	
3000	1.80	0.495	39525	

JK, in Fig. 1. The arc current is uniformly given at the top of copper sheath, ABEF, and also the working gas is applied from the inlet, FG, in Fig. 1. The gas flow rate of the working gas is 50 L/min.

The differential equations (1) to (7) are solved iteratively by the SIMPLEC numerical procedure [4] for the whole region of the plasma jet for cutting process as shown in Fig. 1. Physical properties used in this model are given from the literatures for oxygen [5] and metals [6, 7] which are mainly listed in Table I.

3. RESULTS AND DISCUSSION

Figure 2 represents the two-dimensional distributions of temperature and of fluid flow velocity in the whole

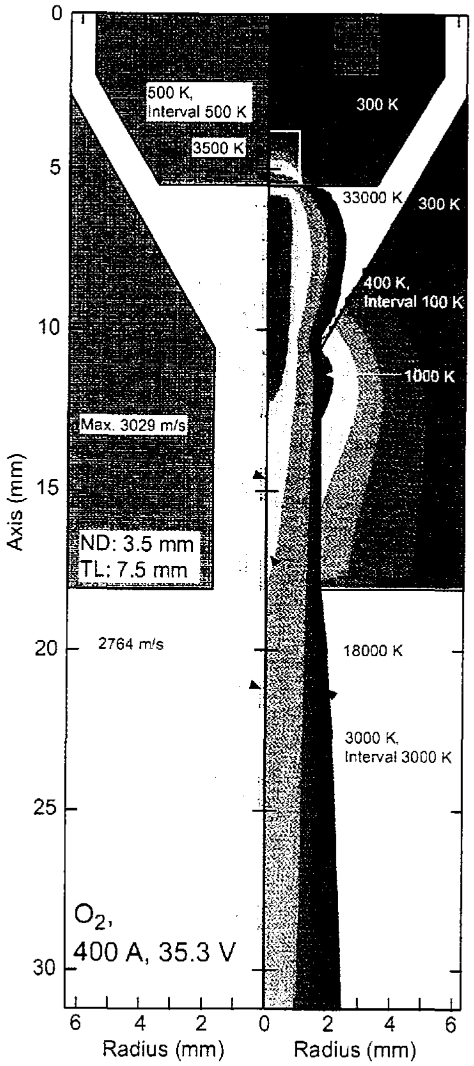

Fig. 2 Two-dimensional distributions of temperature and fluid flow velocity in the whole region of oxygen plasma jet for 400 A in arc current with 3.5 mm in nozzle diameter.

region of the oxygen plasma jet for a 400 A in arc current with 3.5 mm in the nozzle diameter. The arc voltage, namely, electric potential difference between ABEF and JK in Fig. 1 is 35.3 V. The maximum temperatures of hafnium cathode buried in the water-cooled copper sheath and arc plasma are 3500 K at the tip of the cathode and 33000 K on the arc axis close to the cathode tip and also the inlet of the nozzle anode where the maximum surface temperature of the nozzle inside is 1000 K. This calculation indicates that the tip of hafnium cathode is in a liquid state but the nozzle anode is still in a solid state because both melting points of hafnium and copper are 2503 K and 1356 K, respectively [7]. The maximum calculated velocity of the plasma jet reaches 3029 m/s inside the nozzle. The temperature and velocity of the plasma jet close to the nozzle outlet are 18000 K and 2764 m/s, respectively, and then these temperatures and velocities fall off with

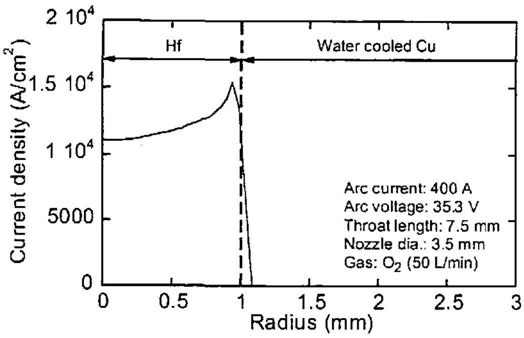

Fig. 3 Current density distribution at the tip of cathode and water-cooled copper sheath.

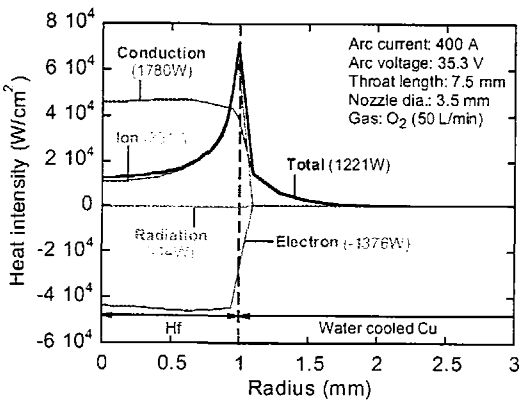

Fig. 4 The whole energy balance at the tip of cathode and water-cooled copper sheath.

distance from the nozzle outlet.

Figure 3 shows current density distribution at the tip of cathode and water-cooled copper sheath in the same conditions with Fig. 2. The peak of current density reaches 15000 A/cm^2 and appears at the off-axis. The arc current poorly flows inside the hafnium because its electrical conductivity is much smaller than that of copper [6].

Figure 4 shows the whole energy balance at the tip of cathode and water-cooled copper sheath in the same conditions with Figs. 2 and 3. The heat flux densities consist of thermal conduction from the arc plasma, ion heating, thermionic cooling due to electron emission and radiation cooling, which are concerned with equations (4) and (8). The total in Fig. 4 is the net heat flux density to the cathode and water-cooled copper sheath. The values between round brackets in Fig. 4 represent the integral heat fluxes for each heat flux density. A ratio indicating ion heating (831 W) among the whole heat input (1780 W + 831 W) reaches about 32 %. The distribution of total is mainly represented by the distribution of this ion heating.

Figure 5 represents the same distributions with Fig. 2 but the nozzle diameter is assumed to be 4.0 mm in this case. The arc voltage is 31.4 V and this value is clearly smaller than that in Fig. 2. The maximum temperature of hafnium cathode is the same with that in Fig. 2 but the

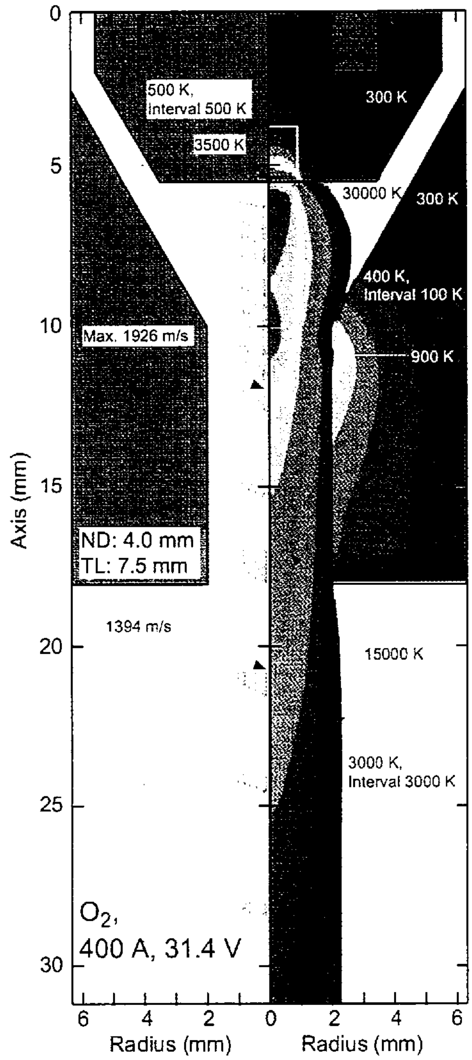

Fig. 5 Two-dimensional distributions of temperature and fluid flow velocity in the whole region of oxygen plasma jet for 400 A in arc current with 4.0 mm in nozzle diameter.

maximum temperature of arc plasma decreases to 30000 K. Both maximum values for the surface temperature of the nozzle inside and the calculated velocity of the plasma jet clearly decrease to 900 K and 1926 m/s, respectively.

From the above results, it is suggested that the nozzle diameter strongly affects the temperature and velocity of plasma jet and also the lifetime of the nozzle. However, the lifetime of hafnium cathode will be weakly affected by the nozzle diameter due to the same temperature but would be strongly affected by the configurations of cathode including the water-cooled copper sheath.

4. CONCLUSIONS

1) The whole region of oxygen plasma jet for cutting process, namely, a hafnium electrode as a cathode buried in the water-cooled copper sheath, an arc plasma and a copper nozzle as an anode has been treated in a unified numerical model.
2) The two-dimensional distributions of temperature and fluid flow velocity in the whole region of the oxygen plasma jet for a 400 A in arc current were predicted.
3) The current density distribution and also the whole energy balance at the tip of cathode and water-cooled copper sheath were predicted.
4) It was shown that the nozzle diameter strongly affected the plasma jet properties and also the nozzle lifetime but weakly affected the hafnium cathode lifetime which would be strongly affected by the configurations of cathode including the water-cooled copper sheath.

References

[1] K. Nishiguchi and K. Matsuyama, Quarterly J. Japan Welding Soc., 11, 353-59 (1993).
[2] M. Tanaka, H. Terasaki, M. Ushio and J.J. Lowke, Metall. & Mater. Trans. A, 33A, 2043-52 (2002).
[3] S. Tashiro, M. Tanaka, M. Nakatani, K. Tani and M. Furubayashi, Trans. MRS Japan, 31, 483-86 (2006).
[4] S.V. Patanker, Numerical heat transfer and fluid flow, Hemisphere Publishing Co., Washington (1980).
[5] M.I. Boulos, P. Fauchais and E. Pfender, Thermal plasmas, Plenum Press, New York (1994), pp.408-12.
[6] V.Y. Zinovyev, Kinetic properties of metals in high temperature, Moscow Metallurgy, Moscow (1984).
[7] Japan Institute of Metals (Ed.), Data book of metals, Maruzen, Tokyo (1993).

(Received December 9, 2006;Accepted February 28, 2007)