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Investigation of the behaviours of cathode spot current density on plasma parameters in low-current vacuum arc

***Abstract**. In order to investigate current density affecting plasma parameters, the cathode spot model is performed. The cathode spot model assumes that the collisionless ion sheath and the singly ionized collisional plasmas are directly connected. It was found that current density increases with decreasing arc current. The dependent variables, cathode temperature, electron current fraction, plasma temperature, sheath voltage, plasma density and cathode electric field increased in accordance with the increase in current. Alternatively, the cathode spot radius is inversely dependent on current density. These plasma parameters are related to T-F emission and thermionic emission process. This cathode spot model of the present analysis which is used to investigate the cathode spot parameter in low-current vacuum arc may be valid for volatile materials.*

***Streszczenie.** W celu zbadania wpływu gęstości prądu na parametry plazmy wykonano model plamki katodowej. Model plamki katodowej zakłada, że bezkolizyjna powłoka jonowa i pojedynczo zjonizowana plazma kolizyjna są bezpośrednio połączone. Stwierdzono, że gęstość prądu wzrasta wraz ze spadkiem prądu łuku. Zmienne zależne, temperatura katody, udział prądu elektronowego, temperatura plazmy, napięcie powłoki, gęstość plazmy i pole elektryczne katody rosły zgodnie ze wzrostem prądu. Alternatywnie promień plamki katody jest odwrotnie zależny od gęstości prądu. Te parametry plazmy są związane z emisją T-F i procesem emisji termojonowej. Ten model plamki katodowej z niniejszej analizy, który jest stosowany do badania parametru plamki katodowej w niskoprądowym łuku próżniowym, może mieć zastosowanie w przypadku materiałów lotnych. (**Badanie zachowań gęstości prądu punktowego katody na parametry plazmy w łuku próżniowym o niskim natężeniu prądu**)*

Keywords: Current density, plasma parameters, cathode spot model, copper cathode.
Słowa kluczowe: Gęstość prądu, parametry plazmy, model plamki katodowej, katoda miedziana.

Introduction

Vacuum arcs play a dominant role in numerous industrial applications, e.g. for vacuum interrupters, thin film technologies. The cathode region is considered as the most active region in vacuum arcs. The cathode spots provide not only current continuity but also supply the medium for the discharge, namely the metal vapour [1-3].

During arc, the current density of cathode spot is very important parameter for arc cathode. The cathode current density has a direct effect on T-F emission and thermionic emission on cathode surface[4-6]. Accordingly, extensive research works have been conducted on modeling of vacuum arcs[5,6]. The model is used in presenting the current density in relation with plasma parameters in different views as shown in the original model.

In order to investigate the behavior of the current density which affects plasma parameters, cathode spot model as shown in Fig. 1 is performed for an analysis of the phenomena of current density in low current vacuum arc. The cathode spot region is considered as the collisionless space charge sheath connected by singly ionized collisional plasmas. In this paper, this model is used in analyzing phenomena of the relation between the current density and other plasma parameters.

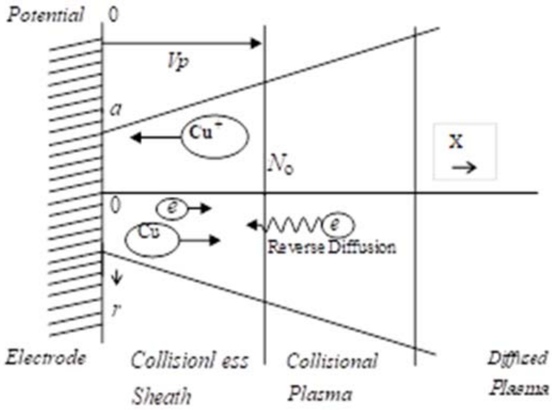

Fig.1. Cathode Spot Model

System of Equations

The cathode spot model assumes that the collisionless sheath and the collisional plasma are directly connected. Eight equations are required in order to determine the eight dependent variables. Due to the lack of a simple exact formula which could determine the sheath voltage V_p, some other means are required. The experimental data of effective heating voltage for cathode input $V_{eff}(I)$ and some parts of ion current fraction $\delta(I)$ flowing toward the anode are applied to obtain the eight dependent variables (Most ion currents are in the direction of the cathode). As mentioned above, the seven dependent variables and independent variable are plotted with current density in a new approach.

Equation of electric field

The equation of the electric field of the cathode surface is given by the Mackeown equation, including the effect of the space charge of the electrons returning from the collisional plasma to the sheath.

$$(1)\ F_0^2 = \frac{4}{\varepsilon_0}\left\{\left[\sqrt{\frac{M}{2q}}(1-S)J - \sqrt{\frac{m}{2q}}SJ\right]\sqrt{V_p} - \frac{2kT_eN_o}{\varepsilon_o}\left[1-\exp\left[\frac{-qV_p}{kT_e}\right]\right]\right\}$$

Equation of electron emission current

The electron emission current from the cathode is determined primarily via the thermionic mechanism, together with the Shottky effect.

$$(2)\qquad SJ = AT^2\exp\frac{-q\left(\Phi_o - \sqrt{\dfrac{qF_o}{4\pi\varepsilon_o}}\right)}{kT}$$

Equation of energy balance

Equation (3) is the solution of heat of conduction $\nabla(K\nabla T)=0$ at the boundary condition, which is as follows:

$$-K\frac{\partial T}{\partial X} = JV_{eff}\ ,\ r \le a.$$

(3) $$K_o(0.45T + 348) = \frac{8a}{3\pi} JV_{eff}$$

The dependence of thermal conductivity of copper on temperature is also considered. [7-9]. The heat loss due to thermal conduction into the cathode is as follows:

(4) $$JV_{eff} = (1-S)J\big(V_p + V_i - \Phi_o + H_o(T)\big) - SJ\Phi(F_0,T) - P_{ev}(T)$$

The first term of the right-hand side of equation (4) is the input due to the ion bombardment, the second term is the power dissipated by the electron emission, and the third term is the power dissipated by vaporization[10].

Equation of current

(5) $$I = \pi a^2 J$$

Equation of mass flow

(6) $$\Gamma_{ev}(T) - N_0 M\left(\frac{kT_e}{2\pi M}\right)^{\frac{1}{2}} = \frac{\delta J}{q} M$$

The first term of the left-hand side of equation (6) is the atom flux due to evaporation from cathode, and the second term is the return flux of ions from the plasma to cathode. The right hand-side of equation (6) is the mass flow to the anode provided by the ion current

Equation of ion current

The ion current density (1-*S*) *J* in the pace charge sheath is assumed to be equal to the ion saturation current density of collisional plasma. Thus, equation (7) is concluded as

(7) $$(1-S)J = qN_o\left(\frac{kT_e}{2\pi M}\right)^{\frac{1}{2}}$$

Equation of the plasma region

Particle conservation

The equation of particle conservation is the same as equation (6).

Energy conservation of the collisional plasma.

(8) $$\frac{kT_e}{q} J(2 + 2\delta - S) + qV_i\frac{\Gamma ev}{M} = 0.851 a\eta J^2$$

The first term of the left hand–side of equation (8) is the energy flow into the cathode and the anode, and the second term is the power required by ionization. The right-hand side is the input power to the plasma by joule heating [11], where η is the plasma resistance expressed by Spitzer formula.

The experimental data

The experimental data for effective cathode heating voltage $V_{eff}(I)$ are obtained using the calorimetric method [4], as shown in Fig. 2. The ion current fraction $\delta(I)$ is set to 0.1 [11,12].

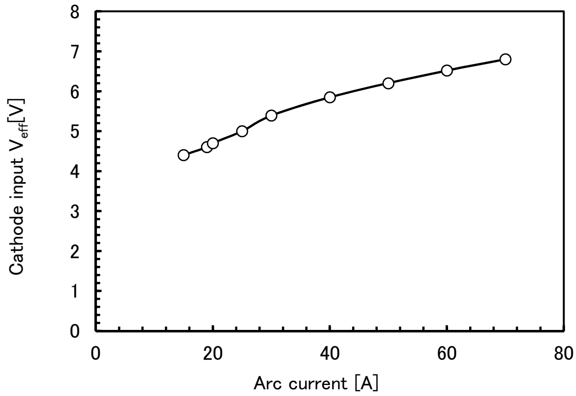

Fig.2. Effective cathode heating voltage

Numerical results and conclusions

The simultaneous algebraic equations (1~8) are solved numerically using a bisection method. The eight dependent variables are obtained for independent variable of arc currents ranging 19 ~ 70 A, as shown in Fig. 3~7.

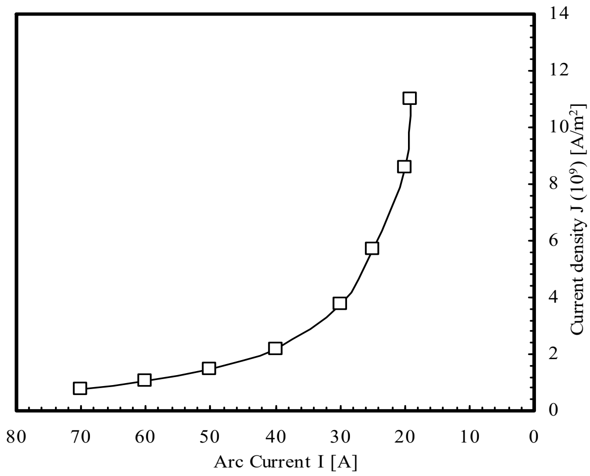

Fig.3. Current density va Arc current.

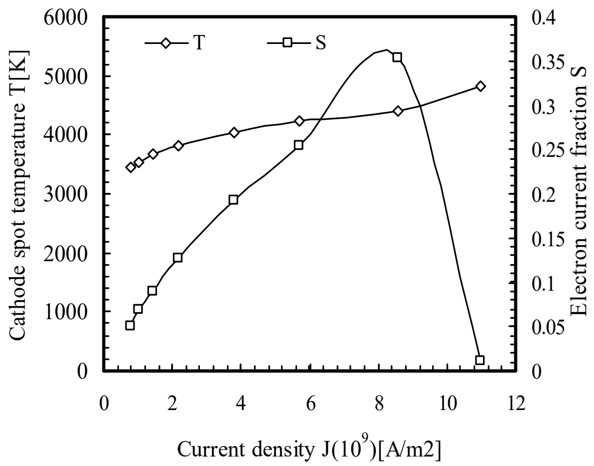

Fig.4. Cathode spot temperature and Electron current fraction vs Current density

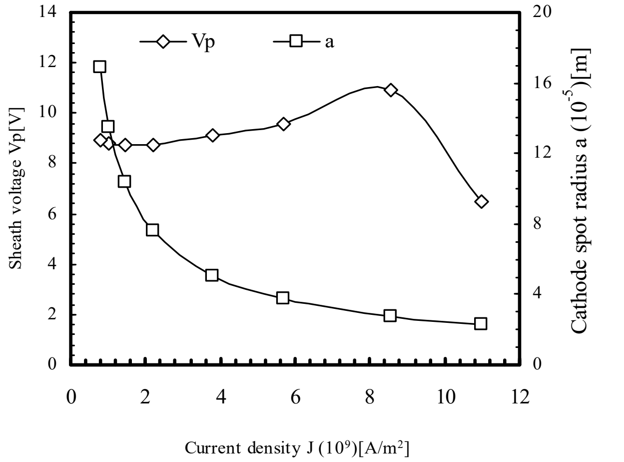

Fig. 5. Sheath voltage and Cathode spot radius vs Current density

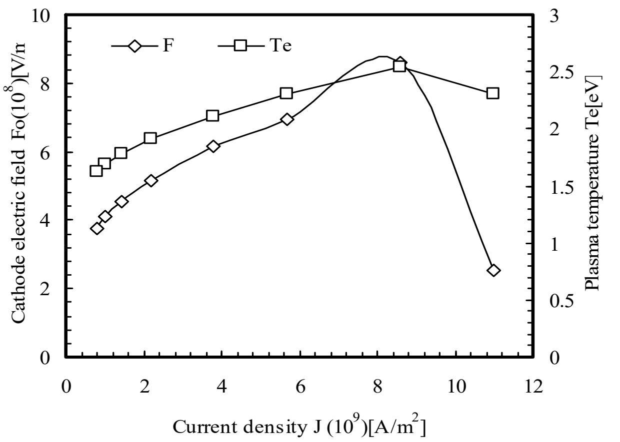

Fig.6. Cathode electric field and Plasma temperature vs Current density

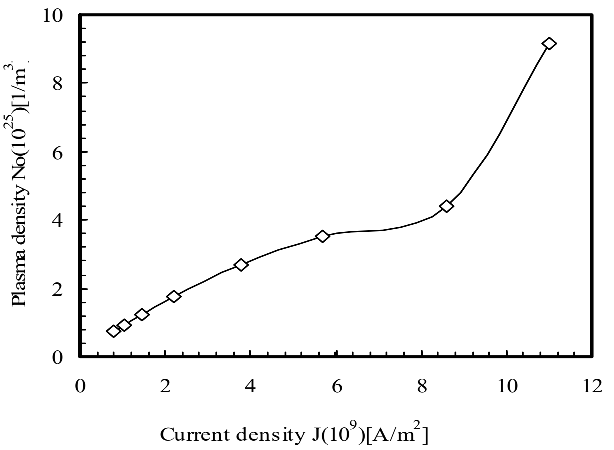

Fig. 7. Plasma density vs Current density

According to Fig.3, it could be seen that current density increases when arc current decreases. Due to the fact that in low current region, the cathode spot radius becomes low, the high current density occurs in cathode spot. In Fig. 4~7, it was found that cathode temperature, electron current fraction, plasma temperature, sheath voltage, plasma density and cathode electric field are increased with increasing current density. These plasma parameters are directly related to T-F emission and thermionic emission process. Alternatively, the cathode spot radius is inversely dependent on current density. The ion current and electron current density are shown in Fig. 8.

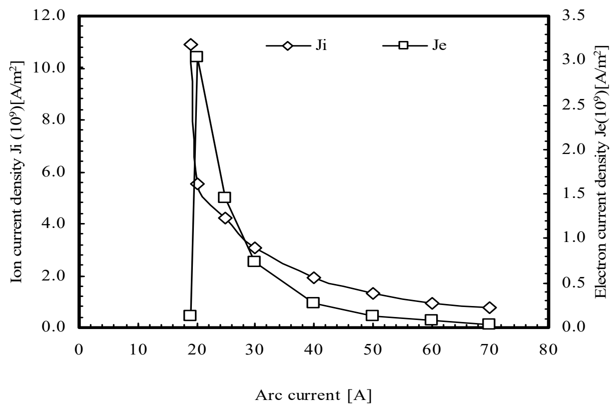

Fig. 8. Ion current density and Electron current density vs Arc current

It was found that in low current region the current density is higher than high current region. The spot power density is very high in lower current region as shown in Fig. 9.

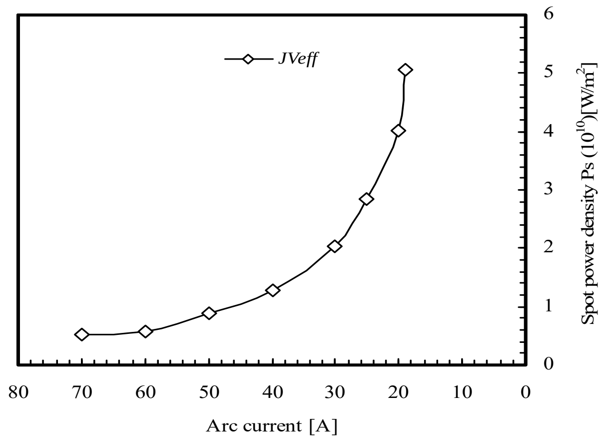

Fig. 9. Spot power density vs Arc current

These results show the mechanism of arcing in low current vacuum arc near zero point of current in which plasma parameters rapidly increased this region. These results comply with the data in [12,13] that plasma parameters increased when arc current decreases. These dependent variables are significantly related to T-F emission and thermionic emission process [3]. These analytical results also indicate the mechanism of instability phenomena. In the present study, when the arc current decreased below 19 A, no real solution was possible. The current level below which no real solution exists is proposed as the current instability region. In addition, the electrons returning to the sheath region from the plasma region were found to be dominant over positive ions. As a result, Mackeown's equation of the cathode electric field is an imaginary solution, and consequently, the stable ion sheath criterion cannot be satisfied[14-16]. This is the physical explanation for the initiation of arc current instability in low-current region which the current density affects instability phenomena. These results are related to T-F emission and thermionic theory.

Nomenclature

Independent Variable

I Arc current (A)

Experimental Data

$V_{eff}(I)$ Effective cathode heating voltage (V)

$\delta(I)$ Ion current fraction flowing toward the anode.

Dependent Variables

V_p Sheath voltage (V)

a Cathode spot radius (m)

J Current density (A/m^2)

S Electron current fraction

T Temperature of cathode spot surface (K)

F_o Cathode electric field (V/m)

N_o Plasma density (1/m^3)

T_e Electron temperature (K)

Physical Properties and Constant

Γ_{ev} Evaporation rate (kg/m^{2}s)

P_{ev} Evaporation energy (W/m^{2}s)

$H_o(T)$ Heat of evaporation per atom (J/atom)

K Thermal conductivity (W/mK)

V_i Ionization voltage of Copper 7.73 (eV)

Φo Work function of Copper 4.5 (eV)

A Richardson's constant 1.20×10^6 (A/m^{2}K^2)

$\Phi(F_o, T)$ Cooling effect of electron emission (eV)

M Mass of atom and ion of copper (kg)

m Electronic mass (kg)

q Electronic charge(C)

k Boltzmann's constant (J/K)

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