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Analysis of the Thermal Conductivity Mechanism Affecting on the Plasma Parameters in Instability Low Current Vacuum Arc

***Abstract**. This analysis used the cathode spot model to describe the physical mechanism of the thermal conductivity effect on the instability phenomena. An analysis of stable arc current is performed by changing the thermal conductivity of copper by compound material. The minimum stability arc was found to be inversely proportional to the thermal conductivity. Low thermal conductivity is more critical in a more stable arc than a high thermal conductivity cathode material. The thermal conductivity is reduced to increase stable arc current by reducing reversed electrons from the plasma region. These results were similar to the obtained data, indicating that this analysis by the cathode spot model, which is used to investigate the thermal conductivity effect in low-current vacuum arc, may be valid for volatile materials.*

***Streszczenie.** W analizie tej opisano fizyczny mechanizm wpływu przewodności cieplnej na zjawiska niestabilności za pomocą modelu plamki katodowej. Analizę stabilnego prądu łuku przeprowadza się poprzez zmianę przewodności cieplnej miedzi przez materiał złożony. Stwierdzono, że minimalny łuk stabilności jest odwrotnie proporcjonalny do przewodności cieplnej. Niska przewodność cieplna odgrywa ważną rolę w zapewnianiu większej stabilności łuku niż materiał katody o wysokiej przewodności cieplnej. Przewodność cieplna jest zmniejszona, aby zwiększyć stabilny prąd łuku przy redukcji odwróconych elektronów z obszaru plazmy. Wyniki te były podobne do uzyskanych danych, co wskazuje, że analiza za pomocą modelu plamki katodowej, który jest stosowany do badania wpływu przewodności cieplnej w niskoprądowym łuku próżniowym, może mieć zastosowanie w przypadku materiałów lotnych. (**Analiza mechanizmu przewodnictwa cieplnego wpływającego na parametry plazmy w niestabilnym łuku próżniowym o niskim natężeniu prądu**)*

Keywords: cathode spot model, thermal conductivity, low current, stability arc, copper cathode.
Słowa kluczowe: model plamki katodowej, przewodność cieplna, niski prąd, łuk stabilności, katoda miedziana.

Introduction

The main purpose of this study was to clarify the physical mechanism of current instability of a low current vacuum arc for copper cathode. The instability phenomena are characterized by the onset of noise on the current trace of the oscilloscope prior to actual current chopping[1-2]. When the arc current decreased below the stable region, the electrons returning to the sheath region from the plasma region were dominant over positive ions. This is the physical explanation for the initiation of arc current instability.

Despite widespread qualitative discussions on the mechanism of the thermal conductivity effect in a low-current vacuum arc, the mechanism remains to be determined.

The cathode spot model assumes that the collisionless ion sheath and the singly ionized collisional plasmas are directly connected by neglecting the transition region, as shown in Fig.1. Eight equations are required in order to determine the eight dependent variables. For the lack of a simple exact formula by which to determine the sheath voltage, some other means are required. In the present study, the experimental data of cathode input and ion current fraction flowing toward the anode are applied. The same model is used in this study, as previously presented in detail elsewhere [3-4]. The model is used to show the minimum point of stable arc current and plasma parameter when the thermal conductivity is changed. This analysis described the physical mechanism of the thermal conductivity effect on the instability phenomena.

Sheath Region Equation

Current equation

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

Mass flow equation

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

The first term of the left-hand side of equation (2) is atom flux due to evaporation from the cathode, and the second term is the return flux of ions from the plasma to the cathode. The right-hand side of equation (2) is a mass flow to the anode provided by the ion current.

Ion current equation

The ion current density (1-S)J in the pace charge sheath is assumed to equal the ion saturation current density of the collisional plasma. Thus, equation (3) is concluded as

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

Electron emission current equation

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

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

Electric field equation

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.

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

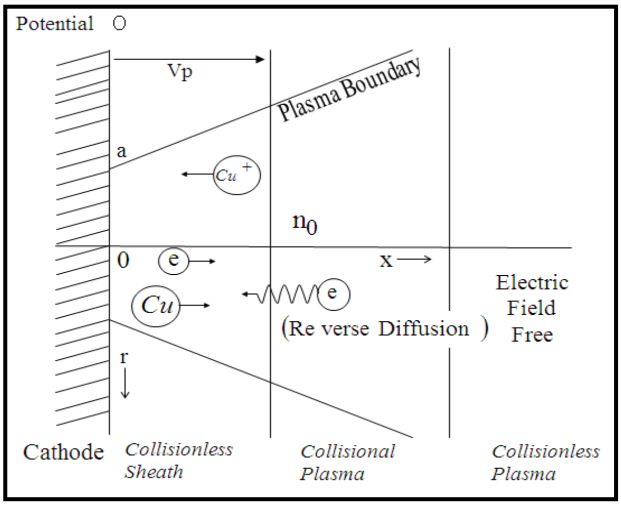

Fig.1. Cathode Spot Model

Energy balance equation

The equation (6) is the solution of heat of conduction at the boundary condition, which is as follows:

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

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

Where K_0 is the thermal conductivity at normal temperature, the temperature dependence on the thermal conductivity of copper is considered [5]. The heat loss due to thermal conduction into the cathode is as follows:

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

The first term of the right-hand side of the equation (7) is the input due to the ion bombardment, the second term is power dissipated by the electron emission, and the third term is the power dissipated by vaporization.

Equation of the plasma region[6-8]

Particle conservation

The equation of particle conservation is as same the equation (2).

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Energy conservation of the collisional plasma.

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

The first term of the left-hand–side of the 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, where η is the Spitzer formula expresses the plasma resistance.

The experimental data

The effective cathode heating voltage, $V_{eff}(I)$ is the experimentally obtained using the calorimetric method [4] as in Fig.2, and the ion current fraction $\delta(I)$ flowing toward the anode is set to 10% of arc current [9]

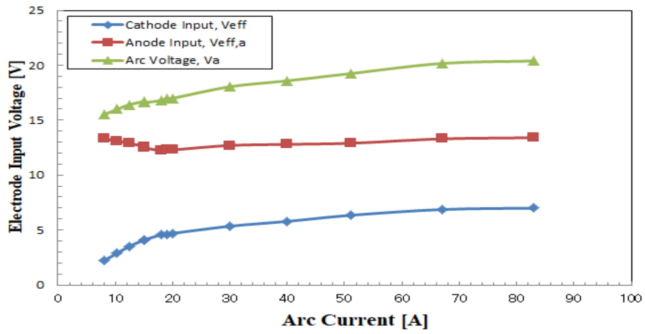

Fig. 2. Copper Cathode Input and Arc Current

Results and discussions

The simultaneous algebraic equation (1) – (8) are solved numerically using a bisection method. The eight dependent variables are obtained for arc currents ranging 8 – 70 A. The thermal conductivity Ko (W/mK) as equation (6) are defined as 401, 225, 162, 128 and 100,respectively. The analytical results are shown in Fig. 3-11.

Fig. 3. shows cathode temperature with various thermal conductivity. It was found that cathode temperature is decreased with decreasing the thermal conductivity.

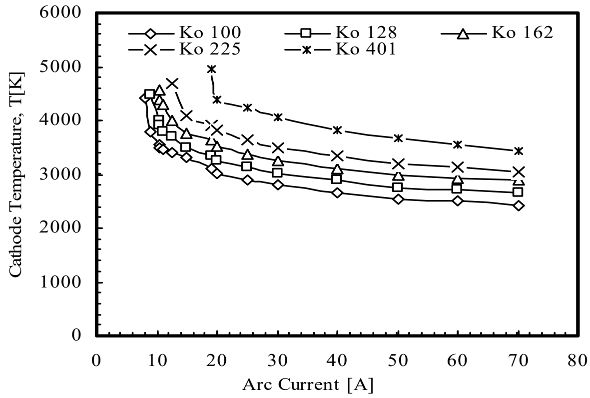

Fig. 3. Cathode temperature vs Arc current

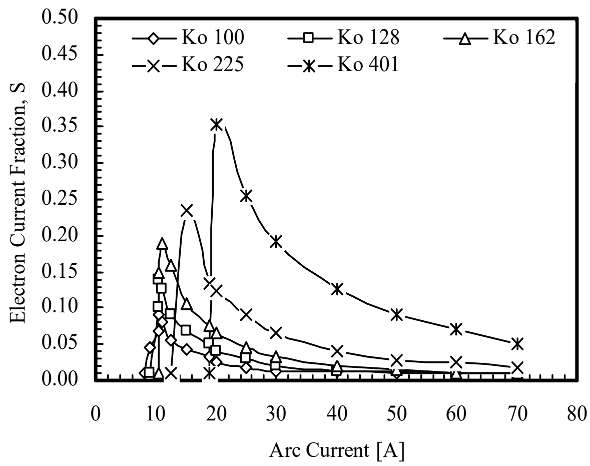

Fig. 4. Electron current fraction vs Arc current

Fig. 4. shows electron current fraction from cathode surface. It was found that electron current fraction decreased with decreasing the thermal conductivity.

Fig. 5. shows plasma temperature with various thermal conductivity. It was found that plasma temperature decreased with decreasing the thermal conductivity.

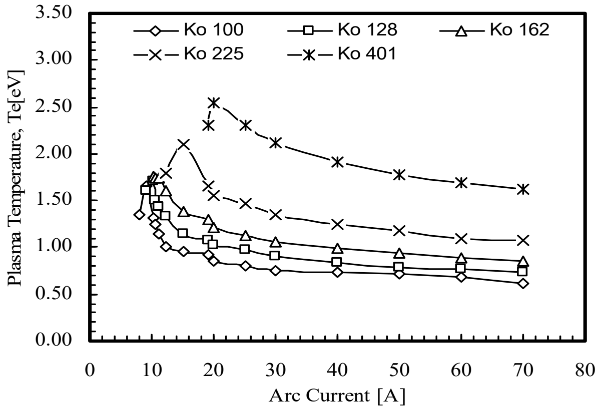

Fig.5. Plasma temperature vs Arc current

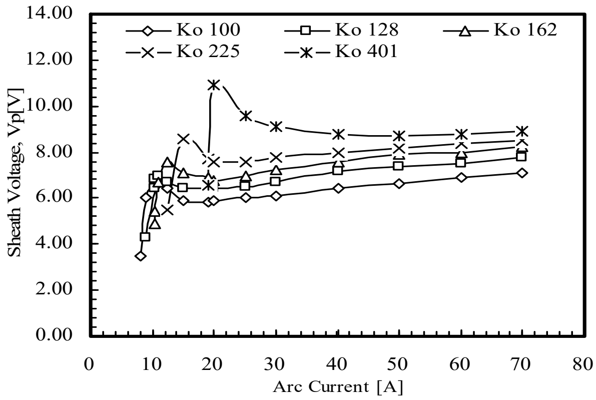

Fig. 6. Sheath voltage vs Arc current

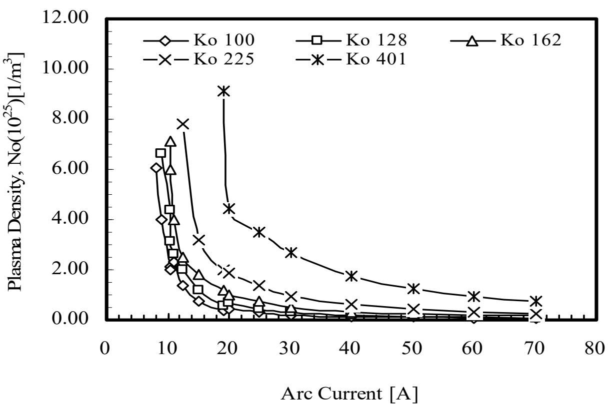

Fig. 7. Current density vs Arc current

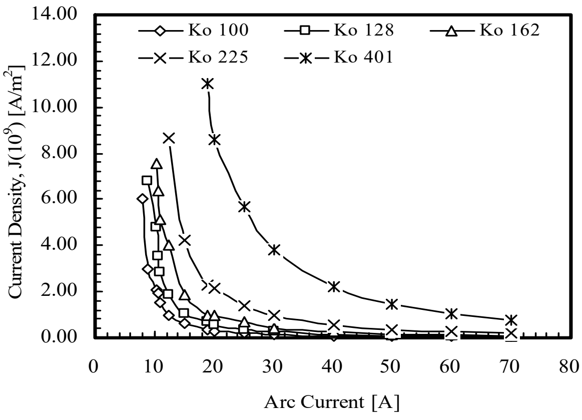

Fig.8. Plasma density vs Arc current

Fig. 6 shows sheath voltage with various thermal conductivity. It was found that sheath voltage decreased with decreasing the thermal conductivity.

Fig. 7. shows the current density with various thermal conductivity. It was found that current density decreased with decreasing the thermal conductivity.

Fig.8. shows plasma density with various thermal conductivity. It was found that plasma density decreases with decreasing thermal conductivity.

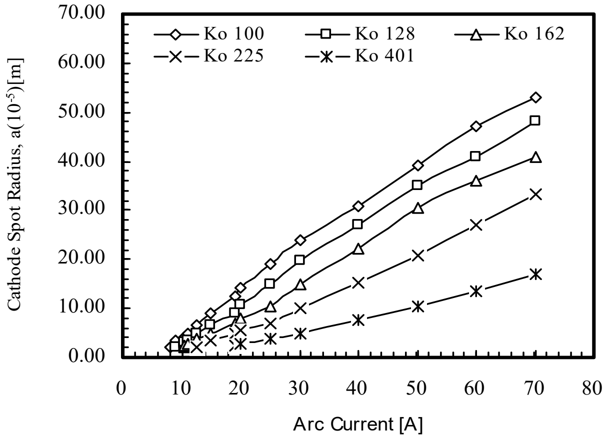

Fig. 9. Cathode spot radius vs Arc current

Fig. 9. shows the cathode spot radius with various thermal conductivity. It was found that the cathode spot radius increased with decreasing the thermal conductivity.

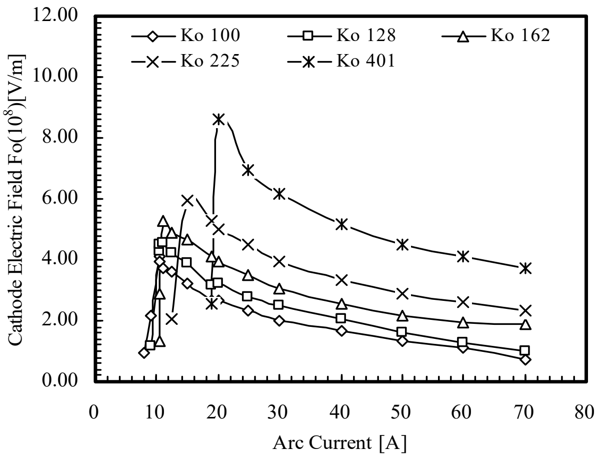

Fig. 10. Cathode electric field vs Arc current

Fig. 10. shows a cathode electric field with various thermal conductivity. It was found that the cathode electric field decreased with decreasing the thermal conductivity.

From eight dependent variables, when the cathode spot radius is increased with decreasing the thermal conductivity. Therefore, the current density will be reduced. Consequently, the cathode temperature is reduced with decreasing thermal conductivity. For these results, the electron current is reduced by decreasing the cathode temperature. As a result, the cathode electric field is decreased with a decrease in the cathode temperature. When the electron current is reduced, the last term of equation (6) is also decreased. The cathode electric field is used to explain the meaning of instability phenomena. When the arc current was decreased below the stable region, the electrons returning to the sheath region from the plasma region in the last term of equation (6) were found to be dominant over positive ions[10-11]. As a result, the cathode electric field by Mackeown's equation has an imaginary solution, and consequently, the stable ion sheath criterion is not satisfied. These results show the physical explanation for the initiation of arc current stability due to the effect of reverse diffusion electrons from the plasma region [12-13]. The thermal conductivity is reduced to increase stable arc current with reducing reversed electron from the plasma region, as shown in Fig. 1. In order to clarify this study, the analytical value is compared with the experimental value, and it was found that the analytical value agrees with the experimental value as shown in Fig. 11. Due to increasing of cathode spot radius, the current density becomes low thus the temperature is also reduced.

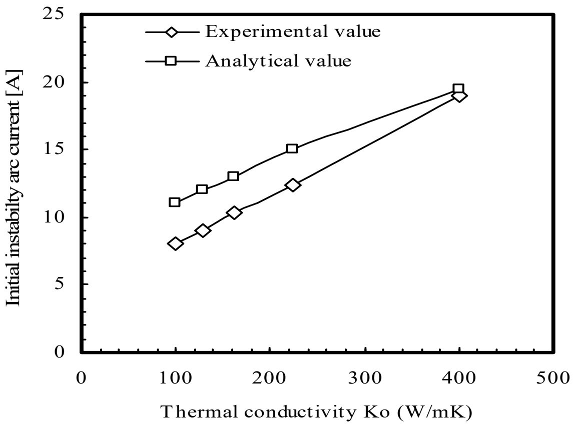

Fig.11. Initial instability arc current vs Thermal conductivity

Conclusion

The thermal conductivity is reduced with increasing the stable arc current region. The current density is reduced by increasing the cathode spot radius. Consequently, the cathode temperature is decreased. The electron current from the cathode is also reduced. It can be concluded that the electron current is reduced by lower cathode temperature. These results were similar to the obtained data in [5], indicating that this analysis by the cathode spot model of the present study, which is used to investigate the thermal conductivity effect in low-current vacuum arc, may be valid for volatile materials.

Equation system

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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