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An Investigation of the Cu-Ni Compound Cathode Materials Affecting on Transient Recovery Voltage

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***Abstract*—**The purpose of this research was to analyze and compare the instability of a contact surface between Copper and Nickel an alloy cathode in vacuum, the different ratio of Copper and Copper were conducted at 1%, 2% and 4% by using the cathode spot model. The transient recovery voltage is predicted. The cathode spot region is recognized as the collisionless space charge sheath connected with singly ionized collisional plasma. It was found that the transient voltage is decreased with increasing the percentage of an amount of Nickel in cathode materials.

***Keywords*—**Vacuum arc, Instability, Low current, Cathode spot, copper, Nickel, Transient Recovery Voltage.

I. Introduction

Many studies have been proposed in the literature in an effort to explain the instability phenomena mechanism of vacuum metal arc discharges in a vacuum system. The instabilities are thought to be caused by electron current starvation effect from plasma region [1] - [7]. In this way, overvoltages are generated, caused by the magnetic energy still trapped in the circuit's main inductance. In recent years, the current level at which the arc collapses ("chopping level") has been reduced considerably thanks to the development of novel low-surge-type vacuum interrupter contact material**.** It is the aim of the study presented here to compare the characteristics of typical instabilities in arcs on various Copper-Nickel contact material**.** It is believed that the parameters of the instabilities directly reflect the interruption characteristics of the contact material. These investigations are very important for the development of low-surge-type vacuum interrupter contact materials [8]–[10]. Prior to the sudden extinction (chopping current) of a metal vacuum arc shortly before the natural sinusoidal current zero, the instability phenomena characterized by noise occurs on the current trace. The current level below which no real solution exists is proposed as an unstable current region and this current corresponds to the point at which a vacuum arc becomes unstable. In order to clarify the cause of instability phenomena for low-current vacuum arc, the cathode spot model as shown in Fig. 1 is proposed. The cathode spot model assumes that the collisionless ion sheath and singly ionized collisional plasmas are directly connected by neglecting the transition region [11]-[12].

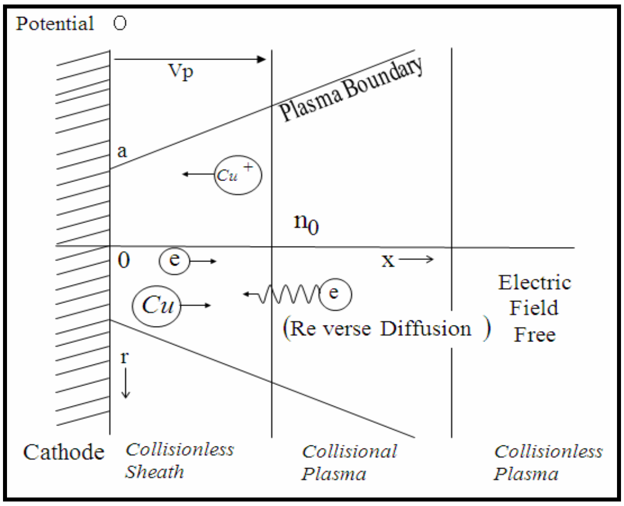

Fig. 1 Cathode spot model

II. System of Equations

The cathode spot model assumes that the collisionless sheath and collisional plasma are directly connected by neglecting the transition region, as shown in Fig. 1. All of the dependent variables have been treated as average values over the spot area $r \leq a$. Eight equations are required to determine the eight dependent variables. Due to the lack of a simple exact formula to determine the sheath voltage Vp, some other means is required. In the present study, the experimental data of cathode input Veff (I) and ion current fraction δ(I) flowing towards the

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anode were applied to obtain the solution of an equation in eight dependent variables.

A. Nomenclature

1. Independent Variable

I	Arc current (A)

2. Experimental Data

$V_{eff}(I)$	Effective cathode heating voltage (V)
$\delta(I)$	Ion current fraction flowing towards the anode

3. 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)

4. 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 (eV)
Φo	Work function of Copper (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)

B. Sheath Region Equation

1. Current Equation

The relationship between arc current, current density, and cathode spot radius is expressed as

$$I = \pi a^2 J. \tag{1}$$

2. Equation of Mass Flow and Ion Current

$$\Gamma ev(T) - NoM\left[\frac{kTe}{2\pi M}\right]^{\frac{1}{2}} = \frac{\delta J}{q}M \tag{2}$$

The right hand-side of equation (2) is the mass flow to the anode provided by the 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 (3) is obtained as

$$(1-S)J = qNo\left[\frac{kTe}{2\pi M}\right]^{\frac{1}{2}} \tag{3}$$

3. Electron Current

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

$$SJ = AT^2 \exp\frac{-q\left(\Phi o - \sqrt{\dfrac{qFo}{4\pi\varepsilon o}}\right)}{kT} \tag{4}$$

4. Electric Field of the Cathode Surface

The equation for the electric field of the cathode surface is given by the Mackeown equation, which includes the effect of the space charge of the electrons returning from the collisional Plasma to the sheath

$$Fo^2 = \frac{4}{\varepsilon o}\left\{\left[\sqrt{\frac{M}{2q}}(1-S)J - \sqrt{\frac{m}{2q}}SJ\right]\sqrt{Vp} - \frac{2kTeNo}{\varepsilon o}\left[1 - \exp\left[\frac{-qVp}{kTe}\right]\right]\right\} \tag{5}$$

5. Energy Balance at the Cathode spot Surface

The solution of the heat equation with $\nabla(K\nabla T) = 0$ at the boundary is given by

$$-K\frac{\partial T}{\partial X} = JVeff, \quad r \le a \text{ At } X = 0$$

$$K_o(0.45T + 348) = \frac{8a}{3\pi}JV_{eff} \tag{6}$$

where Ko is the thermal conductivity at room temperature and X is the normal direction to the cathode surface as shown in Fig.1. The temperature dependence of the thermal conductivity of Copper mix nickel is considered [5]. Heat loss due to thermal conduction into the cathode is

$$JVeff = (1-S)J\left(Vp + Vi - \Phi o + Ho(T)\right) - SJ\Phi(Fo, T) - Pev(T) \tag{7}$$

where the first term of the right-hand side of equation (7) 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.

C. Equation of the Plasma Region

1. Particle conservation

The equation of particle conservation is same with equation (2)

2. Energy conservation of the collision al Plasma

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The energy loss by transport flow of ions and electrons is equal to the acquired energy due to the electric field. This will be considered. By integrating over the entire collision Plasma, the energy conservation equation is expressed as follows:

$$2nkTe\int\nabla.Vdv = \int E.Jdv$$

By considering the physical meaning of $2nkTe\int\nabla.Vdv$ and approximating the solution of $\int E.Jdv$, the equation of plasma energy conservation is expressed as

$$\frac{kTe}{q}J(2+2\delta-S)+qVi\frac{\Gamma ev}{M}=0.851d\eta J^2 \qquad (8)$$

where 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, which is the plasma resistance expressed by Spitzer formula.

III. Experimental Data

The effective cathode heating voltage, Veff is the experimentally obtained using the calorimetric method [3], and the ion current fraction δ(I) flowing toward the anode is set to 10% of arc current [13].

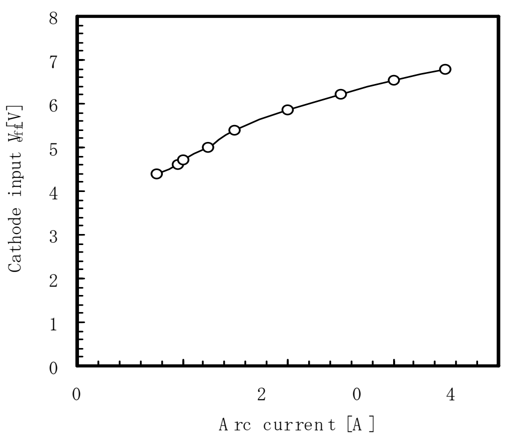

Fig. 2 Cathode input

IV. Calculation of Thermal Conductivity

Pure copper Cu and Cu-Ni alloys were made using a vacuum melting process. The thermal conductivity for Cu-Ni alloys has been calculated from Wienemamn-Franz's law [14].

V. Numerical Method

In order to predict instability arc current and transient recovery voltage, simultaneous algebraic equations (1)-(8) are solved numerically by a bisection method. The real solutions are restricted using the equation of cathode electric field of cathode surface.

VI. Numerical Results

The dependent variable is obtained for arc currents ranging from 10-70 A, as shown in Figs. 4-11. At the difference ratio of copper and nickel were conducted at 1%, 2% and 4% of nickel. The thermal conductivity was calculated as 401 W/mk, 225 W/mk and 162 W/mk, respectively. The numerical result is obtained for arc current to analyze eight dependent variables. Therefore, cathode surface temperature, electron current ratio, electron temperature of plasma, current density, plasma density, cathode electric field, decreases below consistent. When the arc current increases, the part of sheath voltage decrease below and the arc current increases as the voltage becomes stable. Cathode spot radius increases when the arc current increases.

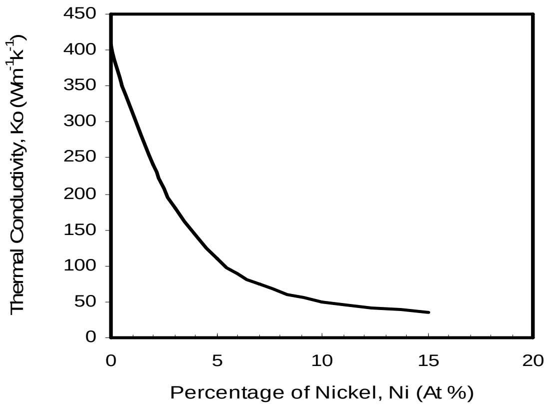

Fig. 3 Dependence of percent nickel on thermal conductivity

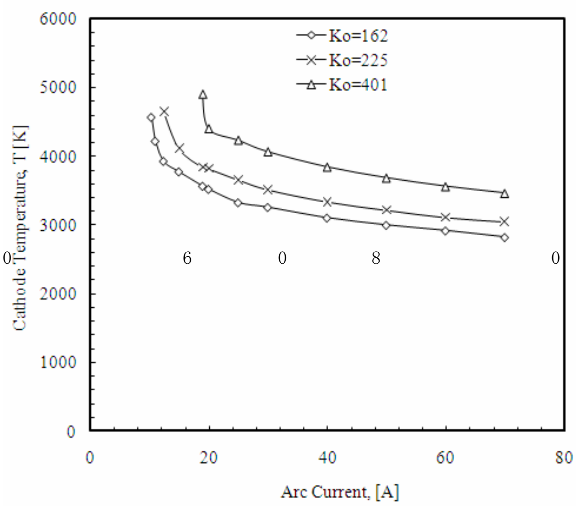

Fig. 4 Dependence of thermal conductivity on cathode temperature and instability - initiation arc current

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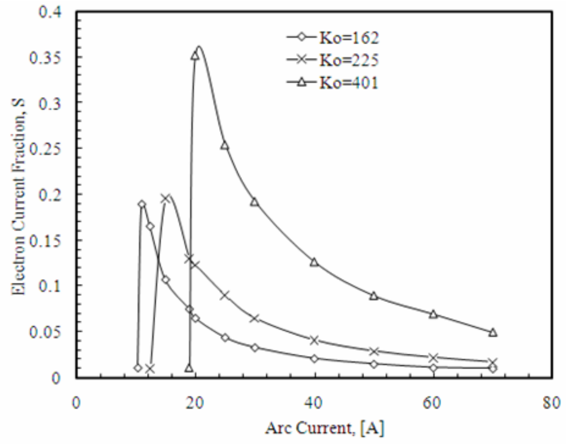

Fig. 5 Dependence of thermal conductivity on electron current ratio and instability - initiation arc current

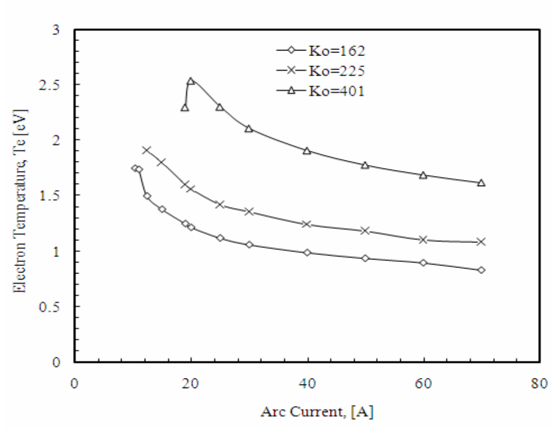

Fig. 6 Dependence of thermal conductivity on plasma temperature and instability - initiation arc current

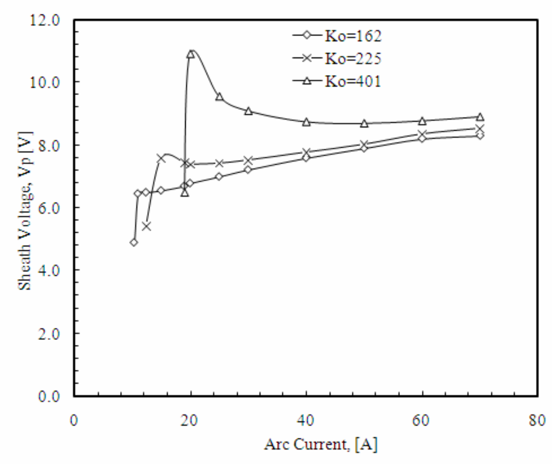

Fig. 7 Dependence of thermal conductivity on sheath voltage and instability - initiation arc current

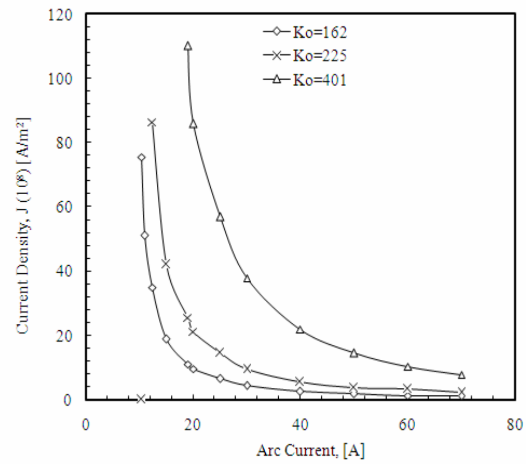

Fig. 8 Dependence of thermal conductivity on current density and instability - initiation arc current

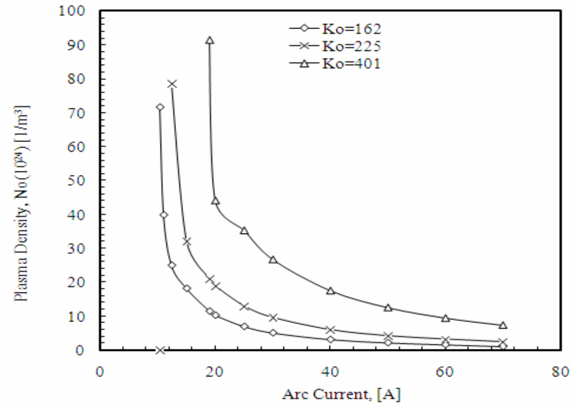

Fig. 9 Dependence of thermal conductivity on plasma density and instability - initiation arc current

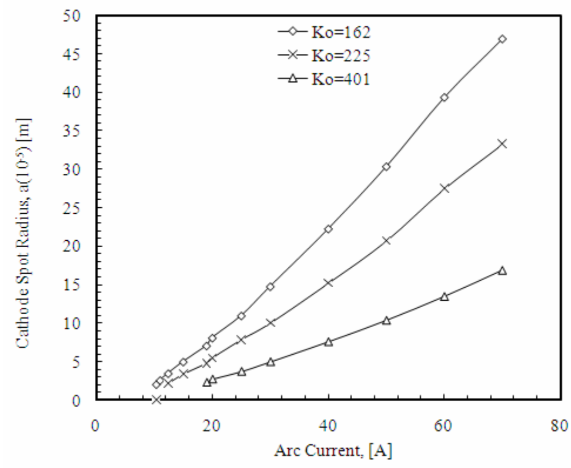

Fig. 10 Dependence of thermal conductivity on cathode spot radius and instability - initiation arc current

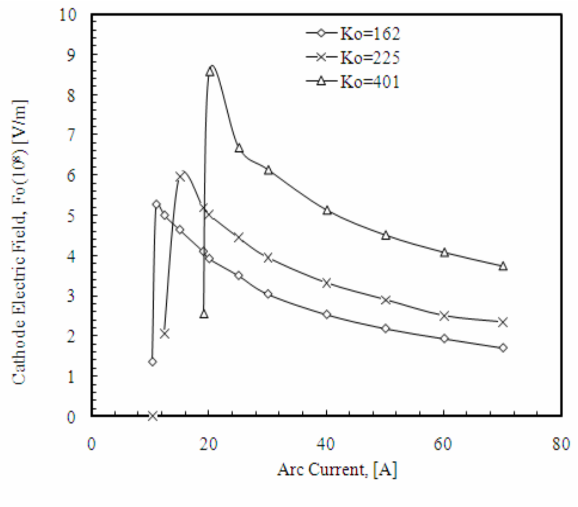

Fig. 11 Dependence of thermal conductivity on cathode electric field and instability - initiation arc current

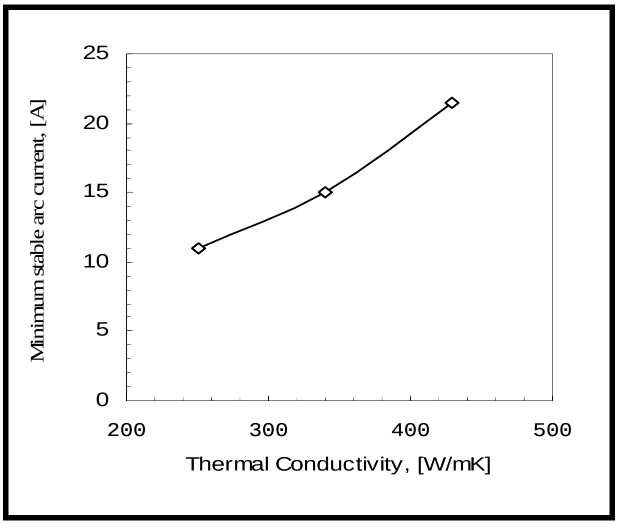

Fig. 12 Dependence of thermal conductivity on minimum stable arc current

VII. Thermal Conductivity Scan

In order to study thermal conductivity effect on stability arc, the thermal conductivity is performed. Figs.4-12 shows plasma parameters with various values of thermal conductivity. The left hand side of last point of each line shows instability arc current region. The minimum stable arc current of each thermal conductivity is plotted in Fig. 12.

VIII. Transient Recovery Voltage Prediction

As previously mentioned, it is believed that the parameters of the instabilities directly reflect the interruption characteristics of the contact material. These investigations are very important for the development of low-surge-type vacuum interrupter contact materials. As Fig. 12, the minimum stable arc current decreases with decreasing thermal conductivity. These results reflect directly to chopping current level. The maximum value of transient recovery voltage (Vp) is expressed as follows: [15]-[17].

$$V_P \cong \sqrt{\frac{L}{C}} \bullet I_C \tag{9}$$

According to the equation above, if circuit parameters in all cases are equal, then the value of *Vp* is directly proportional to chopping current *Ic*. In case the minimum stable arc current is reduced, the chopping current is also reduced.

IX. Conclusion

When the current decreases below 21 A, the electrons returning to the sheath region from the plasma region were found to dominate over positive ions, and thus the cathode electric field has an imaginary solution. When the arc current was decreased below the stable region, the electrons returning to the sheath region from the plasma region were found to be dominant over positive ions. As a result, the cathode electric field by Mackeown's equation yields an imaginary solution, and consequently, the stable ion sheath criterion is not satisfied. This results show the physical explanation for the initiation of arc current stability due to the effect of reverse diffusion electrons from the plasma region. The instability arc phenomena are explained that the electrons returning to the sheath region from the plasma one dominate over positive ions then the stable ion sheath criterion does not satisfied. This is the physical explanation for the initiation of arc current instability.

In order to predict the maximum value of transient voltage, the value is calculated using equation (9). These show that if the chopping current is reduced then the peak of transient recovery voltage will be reduced. It was found that the instability arc current depends upon cathode characteristic. This is a very important result for the development of cathode materials for low – surge vacuum interrupters.

Finally, it can be concluded that the results obtained by this study clearly demonstrate the physical mechanism of current instability and transient recovery voltage occurrence. If the minimum stable arc current is low value then the chopping current also become low value.

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