An Analysis of the Instability Mechanism of a Low - Current Metal Vacuum Arc for Silver Based Cathode Material

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Abstract: - The purpose of this research was to investigate instability phenomena in low-current metal vacuum arc using the calculation data comparison with the experimental data. The instability phenomena are characterized by noise on the current trace prior to the actual current chopping. The instability current was investigated for various electrode materials. To study the parameters affecting the stability arc factors, the parameter scan of cathode materials and ion current fraction by numerical analysis, it was found that the critical current of the stable current is highly dependent on the thermal conductivity of the cathode material. However, the thermal conductivity effect on the instability phenomena of low-current metal vacuum arc was important for low surge switching electrode material development. Therefore, the experiment of major commercial switching electrode such as Ag-Pd is performed in this study. The arc during time and the maximum arc current were fixed to 8 ms and 100 A, respectively. The vacuum was maintained to about $1*10^{-6}$ Pa. The observed waveforms, instability current, chopping current are measured by the oscilloscope. As a result, the critical current of the stable current is inversely dependent on the thermal conductivity of the cathode material. This is very important result for the development of cathode materials for low-surge vacuum interrupters.

Key-Words: - Cathode spot model, instability, thermal conductivity, silver

1 Introduction

Ideally, in power vacuum switching device called upon to interrupt current in an arc circuit, a stability of arc discharge should persist between its separating contacts until the arc current reaches its natural sinusoidal zero. In reality, however, the arc current flow is interrupted prior to this moment at actual current values ranging 2-10 A. Failure to carry the arc current gradually to zero is called current chopping. In this way, overvoltages are generated, caused by the magnetic energy still trapped in the circuit's main inductance. Chopping current strongly depends on the contact material of vacuum switching devices [1]-[6]. Prior to the 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 phenomenon of cathode spot of low-current vacuum arc discharge continues to cause confusion in spite of progress in understanding the processes of instability phenomena. The qualitative discussion of physical mechanism of the stability phenomena of a low-current metal vacuum arc as shown in Fig. 1-2 remains unclear[4]-[8]. These investigations are very important for the development of cathode materials for low-surge switching vacuum circuit breakers. It is believed that the parameters of the instabilities directly reflect the interruption characteristics of the cathode material. However, in order to clarify the instability phenomena characterized by noise on the current trace prior to the actual current chopping, the chopping and instability current for the major commercial switching cathode material such as pure silver and compound silver with palladium were performed in this study. A single cathode spot of low-current vacuum arc as shown in Fig.3 is performed. In order to confirm the validity of the study, the analytical results are compared with experimental results.

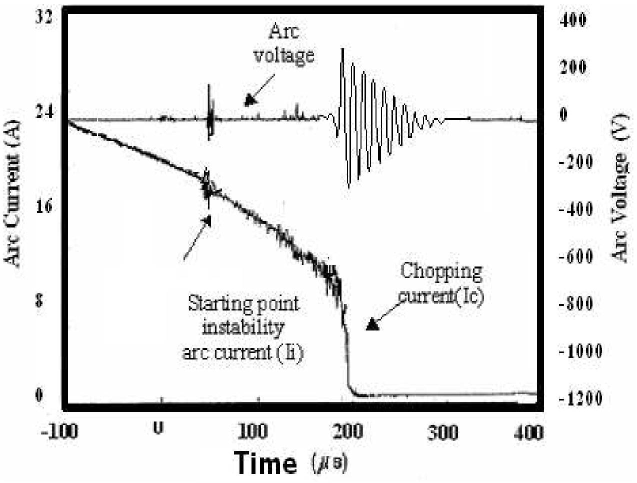

Fig. 1. Typical Instability Arc Current

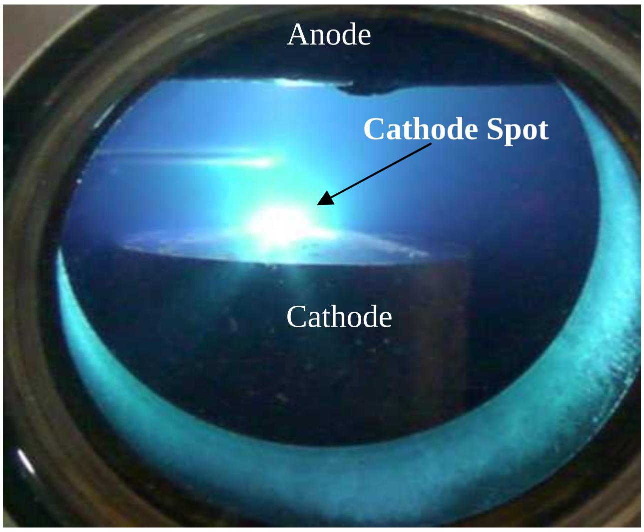

Fig 2. A Single Cathode Spot

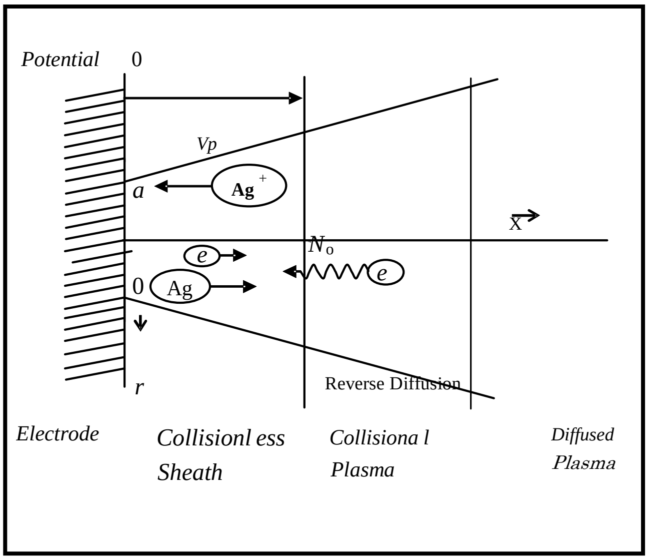

Fig.3. Cathode spot model

2. Analytical Model[4]

In order to confirm the effect of low thermal conductivity, the cathode spot model is used with various values of thermal conductivity as shown in Fig. 4.The cathode spot model assumes that the collisionless sheath and collisional plasma are directly connected by neglecting the transition region, as shown in Fig.6. All of the dependent variables have been treated as average values over the spot area $r \le a$. Eight equations arc 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. The experimental data of cathode input Veff (I) and ion current fraction δ(I) flowing towards the anode were applied to obtain the solution of an equation in eight dependent variables.

3. System of Equations [4]

3.1 Nomentclature

1. Independent Variable

I — Arc current (A)

2. Experimental Data

δ(I) — Ion current fraction flowing toward the anode (10% of arc current)

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

3. Dependent Variables

S — Electron current fraction
T — Temperature of cathode spot surface (K)
F_o — Cathode electric field (V/m)
a — Cathode spot radius (m)
T_e — Electron temperature (K)
V_p — Sheath voltage (V)
J — Current density (A/m^2)
N_o — Plasma density ($1/m^3$)

4. Physical Properties and Constant

P_{ev} — Evaporation energy (W/m^2s)
H_o(T) — Heat of evaporation per atom (J/atom)
Γ_{ev} — Evaporation rate (kg/m^2s)
K — Thermal conductivity (W/mK)
Φo — Work function of Silver (eV)
A — Richardson's constant (A/m^2K^2)
V_i — Ionization voltage of Silver (eV)
$\Phi(F_o, T)$ — Cooling effect of electron emission (eV)
q — Electronic charge (C)
k — Boltzmann's constant (J/K)
M — Mass of atom and ion of silver (kg)
m — Electronic mass (kg)

3.2 Sheath region equation

1) Current Equation

All of the cathode spot variables assumed constant across the cathode diameter, $2a$. The relationship between arc current, current density and cathode spot radius is expressed as equation (1).

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

2) Equation of Mass Flow and Ion Current

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

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 concluded as

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

3) Electron Current

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

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

4) Electric Field of the Cathode Surface

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.

$$F_0^2 = \frac{4}{\varepsilon_0}\left\{\left[\sqrt{\frac{M}{2q}}(1-S)J - \sqrt{\frac{m}{2q}}SJ\right]\sqrt{V_p} - \frac{2kT_eN_o}{\varepsilon_o}\left[1-\exp\left[\frac{-qV_p}{kT_e}\right]\right]\right\} \tag{5}$$

5) Energy Balance at the Cathode Spot Surface[14]

$$K_o(0.48T+164) = \frac{8a}{3\pi} JV_{eff} \tag{6}$$

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

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.

3.3 Equation of the Plasma Region

1) Particle Conservation

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

2) Energy Conservation of the Collision al Plasma.

The energy loss due to the flow of ions and electrons is equal to the acquired energy due to the electric field.

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

The first term of the left hand–side of equation (8) represents 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.

8. EXPERIMENTAL DATA

The experimental data for cathode input $V_{eff}(I)$ obtained using the calorimetric method [4] is shown in Fig. 3. The ion current fraction $\delta(I)$ is set to 0.1 [5-6].

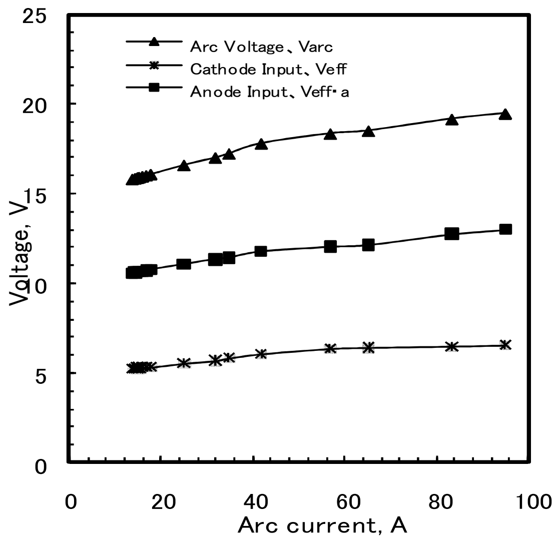

Fig. 4. Cathode input

9. Analytical Results

The simultaneous algebraic equation (1) – (8) are solved numerically using a bisection method. In the present study, the dependent variables are obtained for arc currents raging from 19-70 A, as shown in Figs.5-8. At the arc current of 21.4 A, the cathode electric field, Fo , and the electron current fraction, s, change rapidly. When the arc current decreases below 21.4 A, no real solution exists. As the arc current decreases, the current density increases in high value. For this condition, the plasma density also becomes very high. As a result, F_o^2 becomes negative due to the effect of the space charge of the electrons returning from the collisional plasma to the sheath. The current of 21.4 A may correspond to the instability onset current, as previously proposed.

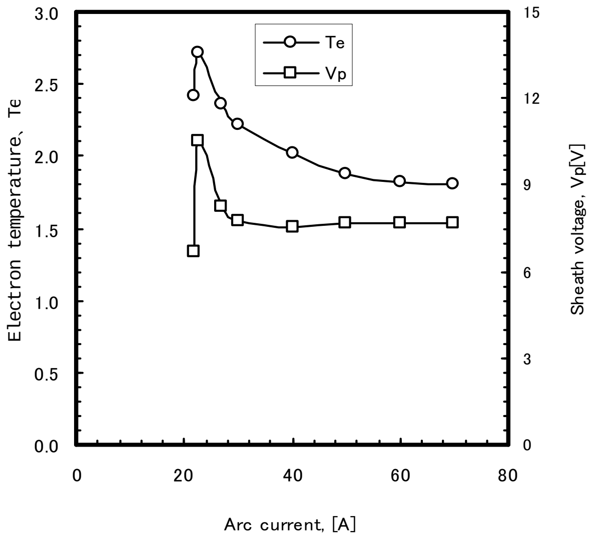

Fig.5 Electron temperature and sheath voltage

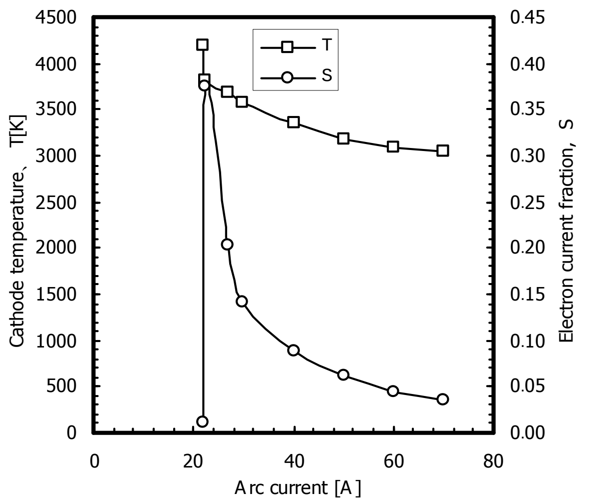

Fig.6. Cathode temperature and electron current fraction

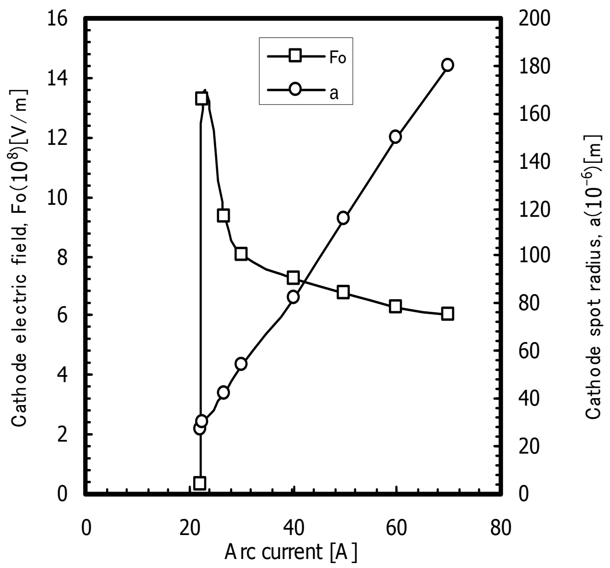

Fig.7. Cathode electric field and cathode spot radius

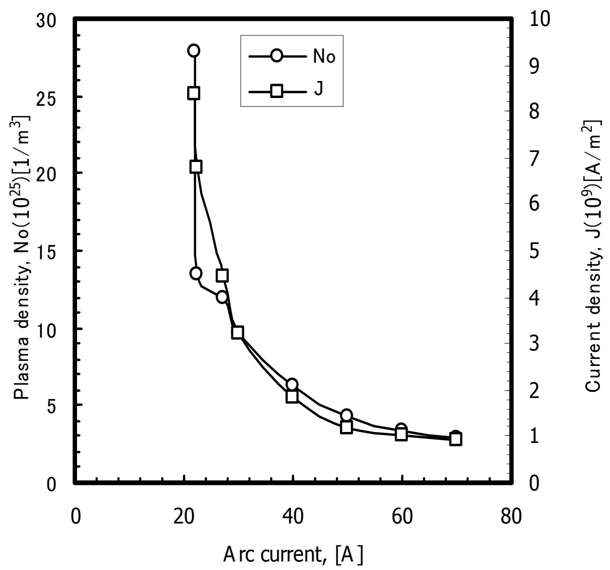

Fig.8. Current density and plasma density

10. Parameters Effect to Stable Arc Current

In this study, the effect of the physical characteristics of the cathode material, work function, thermal conductivity and the experimental data, ion current fraction flowing to anode are considered.

10.1 Ion current fraction effect

The value of ion current fraction is set ranging from 0.05 to 0.15 for checking the effect to minimum stable arc current. The calculation results are shown in Fig. 9.

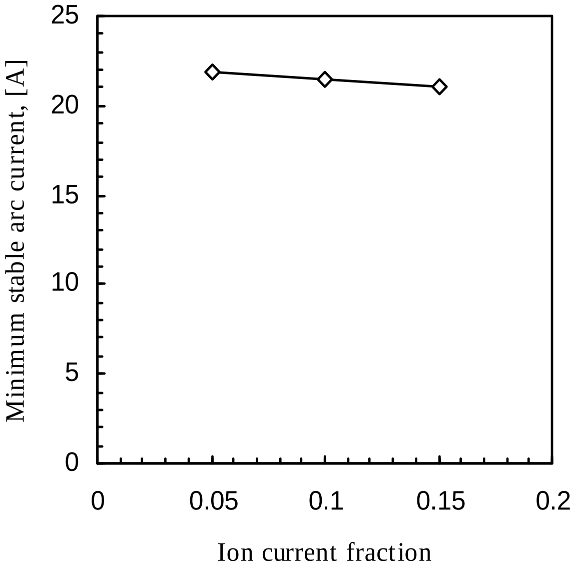

Fig.9. Ion current fraction vs Stable arc current

10.2 Work function effect

The value of work function is set ranging from 4.16 to 4.40 eV for checking the effect to minimum stable arc current. The calculation results are shown in Fig. 10.

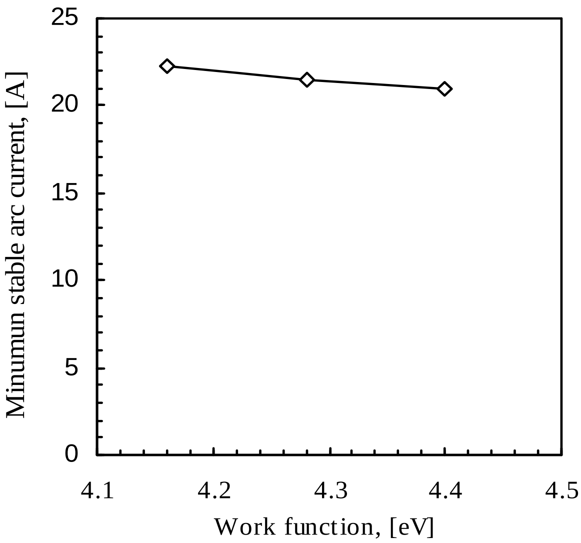

Fig. 10 Work function vs Stable arc current

10.3 Thermal conductivity effect

Pure silver Ag and Ag-Pd alloys were made using a vacuum melting process. The thermal conductivity for Ag-Pd alloys has been calculated from Wienemamn-Franz's law [7]. The relationship between the compositions and thermal conductivities of Ag-Pd is shown in Fig 11. The thermal conductivity is set ranging from 250 to 429 W/mK for checking the effect on minimum stable arc current. The calculation results are shown in Fig. 12.

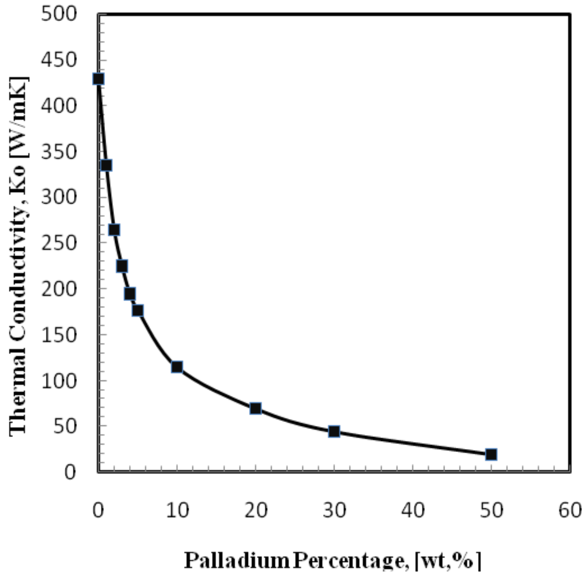

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Fig. 11 Silver thermal conductivity vs palladium percentage

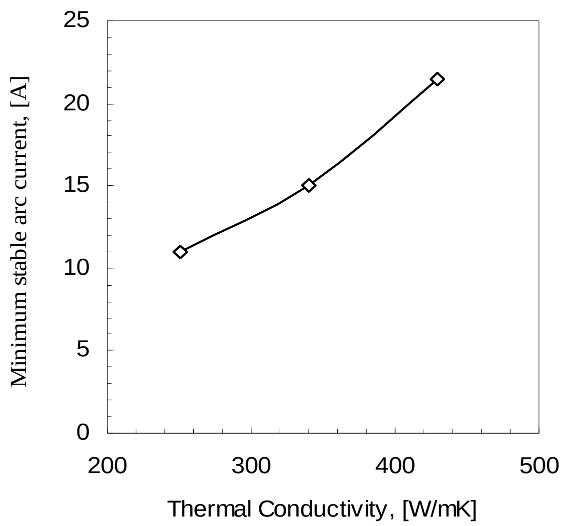

Fig. 12 Work function vs Stable arc current

To study the parameters affecting the stability arc factors, the parameter scan of cathode materials and the experimental data by numerical analysis, it was found that the critical current of the stable current is relatively insensitive to the work function and ion current fraction. However, it is highly dependent on the thermal conductivity of the cathode material [9]-[14]. This is a very important result for the development of cathode materials for low-surge vacuum interrupters.

11. Experimental setup

In order to carry out the experimental investigation of a single cathode spot vacuum arc, the experimental setup as shown in Fig.13 was used. The experiments were conducted in a vacuum-trigger gap with a 39-mm diameter silver cathode and 120-mm diameter anode and 25 mm separation. The vacuum chamber was evacuated as below 1×10^{-6} Pa. After triggering the vacuum gap, the maximum arc current 100 A with 8 ms discharge time was supplied by a capacitor bank through resistance to electrodes as shown in Fig. 15.

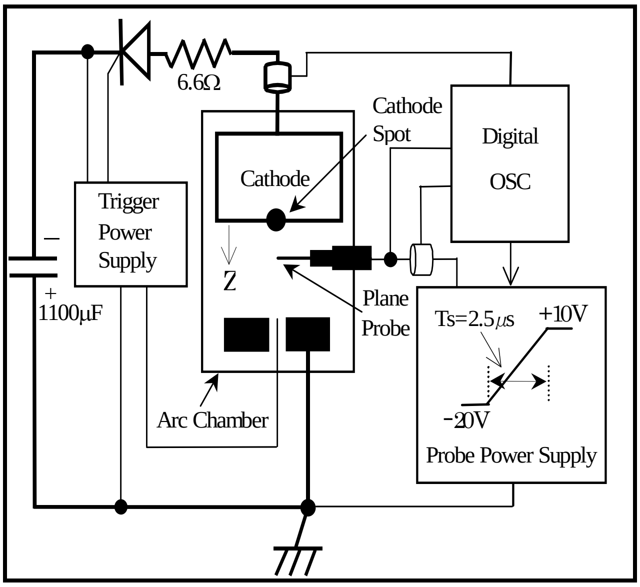

Fig 13. Experimental setup

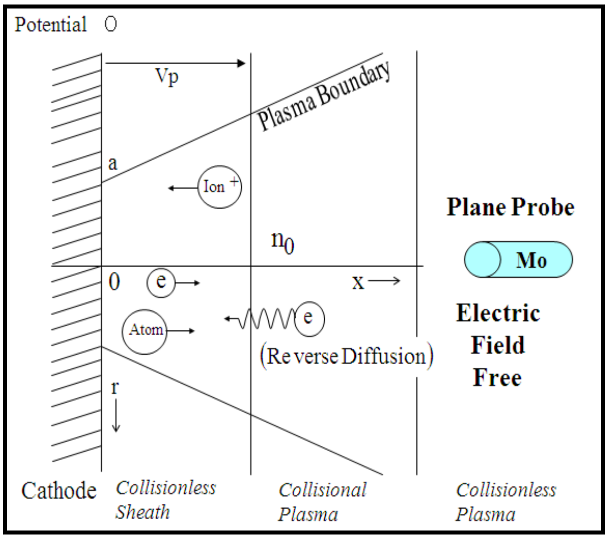

Fig. 14 Position of plane probe

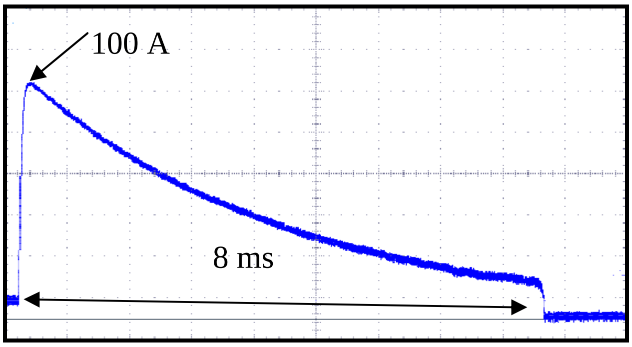

Fig.15. Arc current wave form

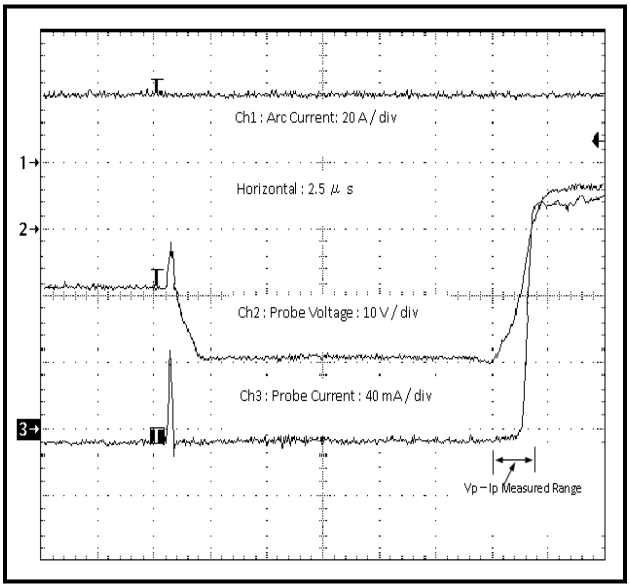

Fig. 16 Vp-Ip Characteristic

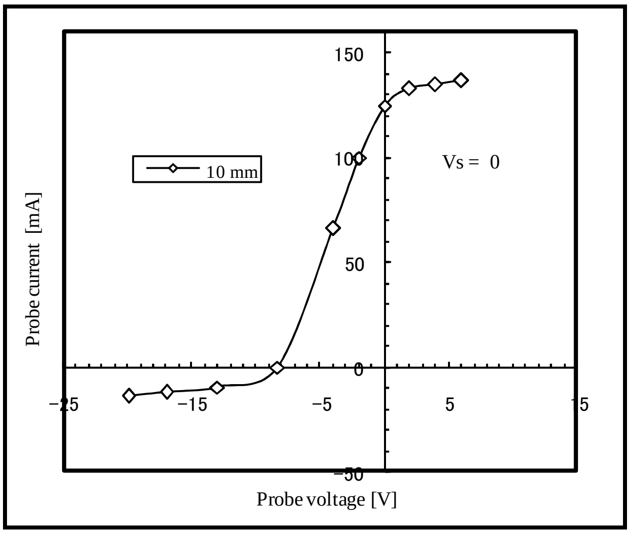

Fig. 17 V—I characteristic of probe at 10 mm from cathode.

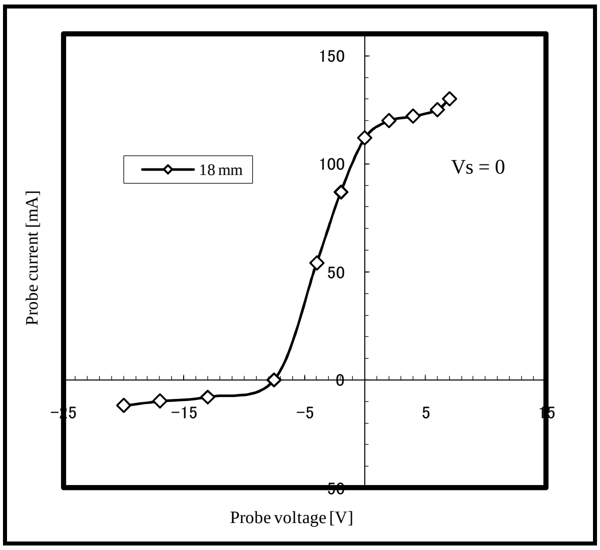

Fig. 18 V—I characteristic of probe at 18 mm from cathode.

12. Electrostatic Probe Measurement

12.1. V-I characteristic

In the present study, a single electrostatic probe measurement of electron temperature was conducted for a single spot vacuum arc as shown in Fig. 2. The electron temperature Te is derived from V-I characteristic as per the conventional procedure. A V-I characteristic of a single electrostatic probe was measured by supplying a sweep voltage ranging from –20 to +10 V. The sweep time of the probe voltage, typically T=2.5 μ s as shown in Fig. 13 and Fig. 15-16, was set to be longer than the time for plasma ion frequency in order to measure only the conduction current, and not include the capacitive current as in the usual measurement [6].

12.2 Collisionless plasma and electric-field-free condition

Typical plasma parameters of the diffused plasma were an electron temperature of 2.5 eV and an electron density of $4.5\times10^{19}m^{-3}$. The mean free path of the electron was estimated using the experimental data to be approximately 10-20 mm. Most of the diffused plasma was considered to be collisionless, except in the vicinity of the cathode spot area. In addition, the electric-field-free condition of the diffused plasma was confirmed by comparing the space potential of different points and the anode potential. The plasma space potential (Ez) at the points 10 mm and 18 mm from the cathode are equal to zero, which reveals the electric-field-free condition in the diffused plasma as shown in Fig. 17-18. The plasma space potential at 10 mm, 18 mm from cathode by V-I characteristic is $Vs = 0$ and $dVs/dZ = Ez = 0$.

13. Experimental Results

The measured electron temperature was found to increase with decreasing arc current, and the experimental values were similar to those obtained analytically, as shown in Fig. 19-20.

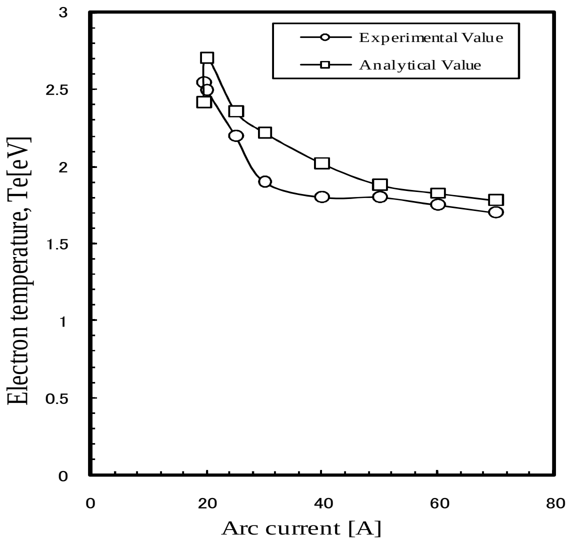

Fig. 19. Analytical value and experimental value.

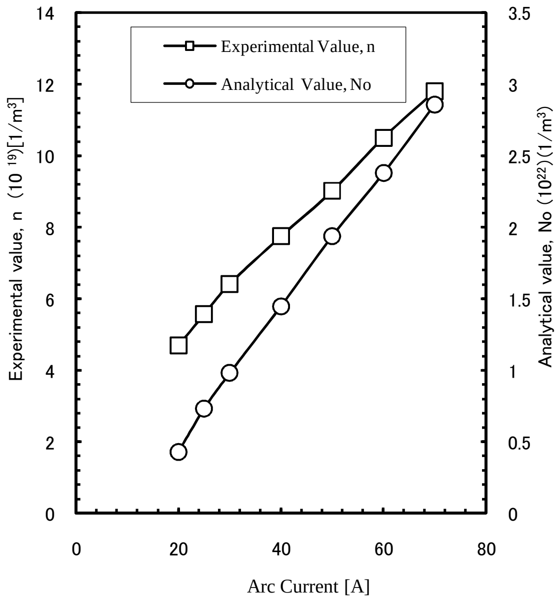

Fig. 20. Electron density : Analytical value No and experimental value n.

14. Conclusion

The instability arc phenomena are explained in the way that the electrons returning to the sheath region from the plasma one dominate over positive ions then the stable ion sheath criterion does not satisfy. This is the physical explanation for the initiation of arc current instability. To study the parameters affecting the stability arc factors, the parameter scan of cathode materials and the experimental data by numerical analysis, it was found that the critical current of the stable current is relatively insensitive to the work function and ion current fraction. [13]-15]. However, it is highly dependent on the thermal conductivity of the cathode material. 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 occurrence. The increase of stable arc current is performed by material composition for reducing thermal conductivity by increasing the percentage of palladium. It may be interpreted that the cathode spot is difficult to become cool and that its temperature remains higher as thermal conductivity becomes smaller [16]-[23]. For this reason, the cathode spot keeps stable at a smaller low arc current for supplying metal vapour to the vacuum discharge gap. According to Fig. 20-21, it was found that the experimental results of the instability-initiative current were similar to Analytical model results. This is very important result for the development of cathode materials for low-surge vacuum interrupters [24]-[28].

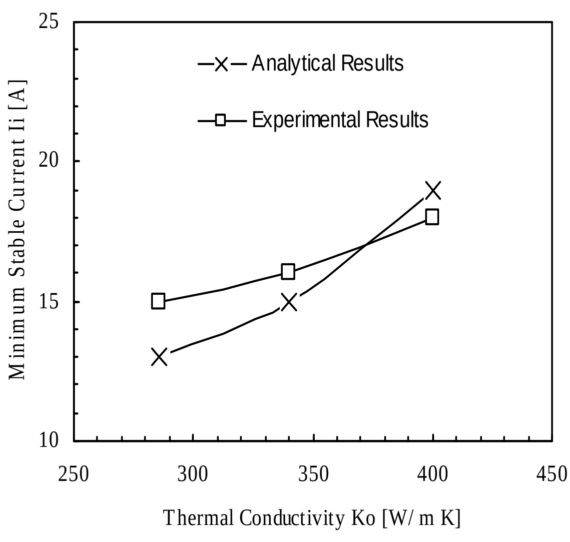

Fig 21. Comparison between Analytical results and Experimental results vs Thermal Conductivity

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