Measurement of Arc Temperature, Electron Density and Electrical Conductivity in Fuse

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***Abstract*— Optical emission spectroscopy of the arc discharge in a fuse was conducted for the identification of the line spectra suitable for a measurement of the arc temperature and the electron density at current values 100A, 50A and 30A before current zero. In addition, we calculated the particle composition inside the arc discharge using the arc temperature in the fuse. Moreover, the conductivity distribution in the arc was calculated by using the arc temperature, the electron density and the particle composition. As a result of spectroscopic measurements, line spectra of Si^+ and Cu clearly appeared. The temperature was determined from Si^+ spectra using a Boltzmann plot method, and the electron density was determined from the Stark broadened spectral line of Si^+ 634.7 nm. The temperature inside the arc discharge was estimated at 17,000 to 25,000 K, the electron density was also estimated at 1.0×10^{18} to 3.5×10^{18} cm^{-3}. The conductivity was calculated at 90 to 130 S / cm. It was confirmed that the temperature, the electron density and the conductivity decreased as the current and voltage decreased. The arc observation with a high-speed video camera demonstrated that the light emission intensity decreased uniformly as the current decrease, which corresponded to the gradual decrease of the axially uniform electrical conductivity.**

***Keywords*—arc discharge, arc temperature, electrical conductivity, electron density, optical emission spectroscopy**

I. INTRODUCTION

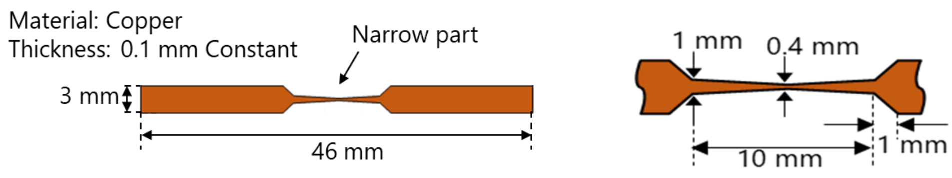
In general, fast-acting fuses and DC fuses open electric circuits and ignite arc discharges inside fuse-links during fault current flowing. Such a current is limited by the generation of arc voltage higher than the power supply voltage. Fundamental understanding of the interruption phenomena in the fuses requires the investigation on the inner physical and electrical properties from the ignition to the extinction of arc discharges, and the current and voltage waveforms are deeply related to these properties inside the fuses. Parameters such as the arc temperature, electron density and electrical conductivity are basically essential data for quantitatively analysis of the electrically conductive characteristics and arc extinction characteristics of the arc discharges. Some papers have previously reported the measurement of the arc temperature and the electron density inside the fuses [1], [2], but there is no paper presenting the electrical conductivity of the arc discharges inside the fuses. In this paper, we have identified the line spectra suitable for the measurement of the arc temperature and the electron density before the current zero point. The axial distributions of the electrical conductivity inside the arc discharges were calculated based on the measured arc temperature, the electron density and the particle compositions.

II. EXPERIMENTAL APPARATUS AND METHOD

A shape of the fuse element used in this experiment is shown in Fig.1. This fuse element is made of copper. It has a simple shape to observe the arc phenomenon in the fuse. The width at the center is narrow and becomes wide towards the end of the fuse element. The minimum cross-sectional area is 0.04 mm^2 at the center. It is possible to control the fusing point at the center. Then the arcing area extends to the end of the fuse element.

An interruption test together with the spectroscopy measurement is conducted by using a fuse box, in which the fuse element and arc extinguishing sand are set. The fuse box is constructed with plates made of acrylic acid resin as shown in Fig. 2. The electrodes connecting the fuse element and electric wires are installed through the both sides of fuse box. The fuse element is connected to the electrodes. A quartz glass plate is put below the fuse element to observe the arc discharge phase with a high-speed video camera or measure the arc light with a spectroscopic instrument. After filling the arc extinguishing sand in the fuse box, the upper lid is set and pressed by a hydraulic pump at 3.0 MPa. The inside of actual fuse link can be reproduced easily by using the fuse box. Fig. 3 shows the interrupting test circuit. The capacitor bank C_0 is charged to 100 V, and the switch is operated. The current flows as shown in Fig. 4 under the test condition of the interruption test for fuse. The maximum current value is 2.15 kA. The rise time constant of the current is 2.85 ms.

A spectrometer used was MS2004i manufactured by SOL instruments, the grating was set to 300 lines / mm, and the slit width was set to 50 μm. The slit was adjusted in the axial direction of the element. An ICCD camera (iStar manufactured by ANDOR) was connected to the spectrometer. An exposure time of the ICCD camera was set to 1 μs. A side-view type borescope manufactured by KARL STORZ was used to guide a light of the arc discharge to the spectrometer. These spectroscopic measurement system is possible to obtain the spectrum data emitting across the arc's axial direction. We also observed the arc discharge just before extinction with a high-speed video



(a) Overall view. (b) Enlarged view of narrow part.

Figure 1. Fuse element used in experiment.

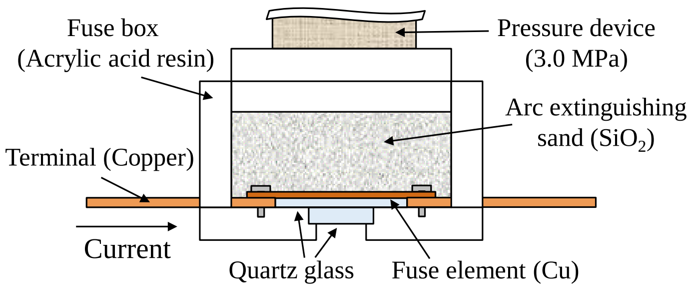


Figure 2. Cross sectional view of the fuse box.

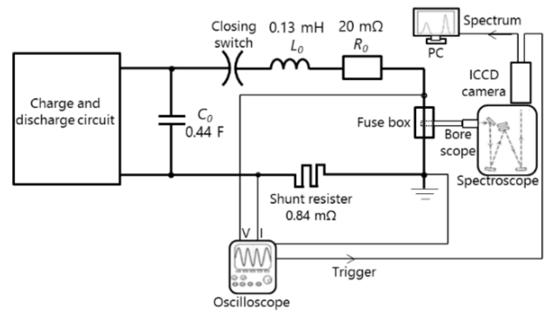


Figure 3. Test circuit and experimental equipment.

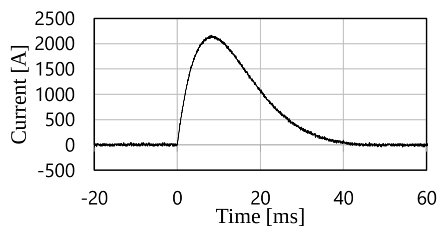


Figure 4. Calibration test waveform.

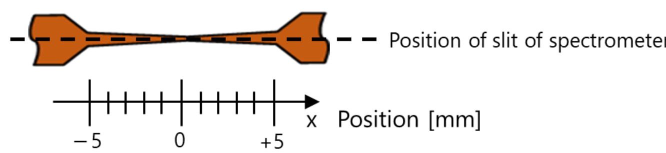


Figure 5. Measured position.

camera. A mirror was placed under the fuse box and arc light was measured from the bottom side of the fuse box by the high speed video camera. The video camera used was FASTCAM-1024 PCI manufactured by Photron.

The test method is shown below.

(1) Charging capacitor bank C_0 to 100 V.

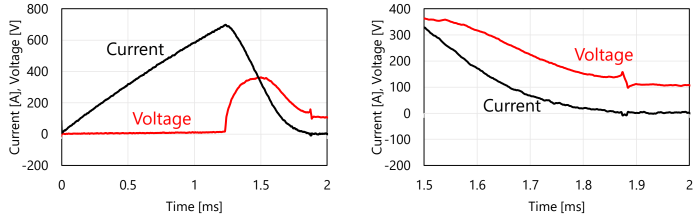
(2) Operating the switch to flow the current to the test fuse, and measuring the current and voltage waveform with an oscilloscope.

(3) Triggering at a predetermined time with the oscilloscope and measuring the emission spectrum of the arc discharge with the spectrometer.

III. Current and Voltage Waveforms and Emission Spectrum

Spectrum emitted by the arc discharge in the fuse box can be measured in an axial direction of the fuse element from -5 mm to +5 mm in this experiment. Such a spectrum was measured three times each at current values of 100 A, 50 A and 30 A in the arc extinction process before the current zero respectively. In this experiment, the spectroscopic measurement system can obtain the spectrum data only once in a certain timing during one interruption test. Therefore the spectrum data corresponding to the current values of 100 A, 50 A and 30 A are obtained from the different interruption test shot respectively. Fig.6 shows typical current and voltage waveforms measured by the fuse element as shown in Fig. 1. We previously confirmed the repeatability of current and voltage waveforms which have almost the same characteristics under using the same fuse element and the same circuit condition, for example, circuit element and charging voltage for C_0 capacitor. The voltage and current values are shown in TABLE I when the spectroscopy measurement was performed.

The spectrum at the current value of 30 A at the center of the fuse element is shown in Fig. 7. The line spectra of copper neutral atom Cu (510.6 nm, 515.3 nm and 521.8 nm) and those of silicon monovalent positive ion Si^{+} (504.1 and 505.6 nm, 595.8 and 597.9 nm, 634.7 and 637.1 nm) at any current value clearly appeared.



(a) Overall view. (b) Enlarged view of arcing time.

Figure 6. Typical current and voltage waveform.

TABLE I. CURRENT AND VOLTAGE VALUES WHEN SPECTRA WERE MEASURED

Current [A]	100	50	30
Voltage [V]	250	200	160

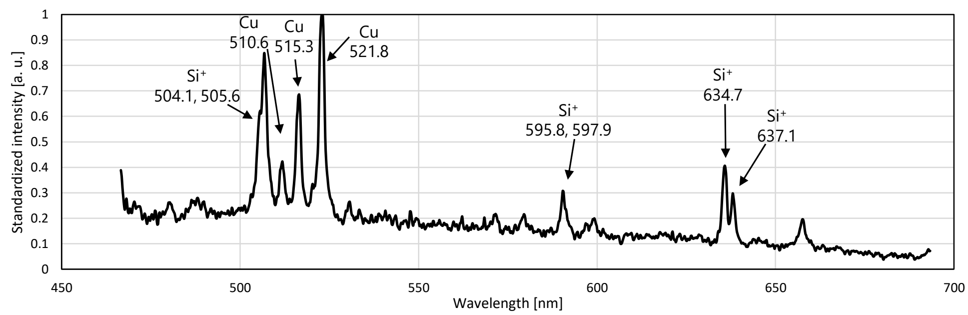


Figure 7. Measured spectrum of fuse arc discharge.

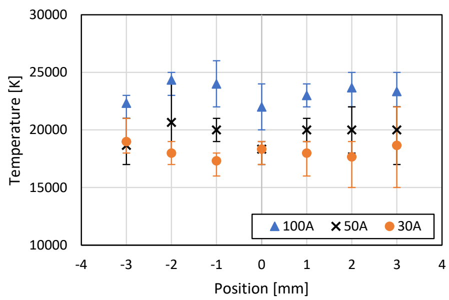


Figure 8. Axial distribution of arc temperature.

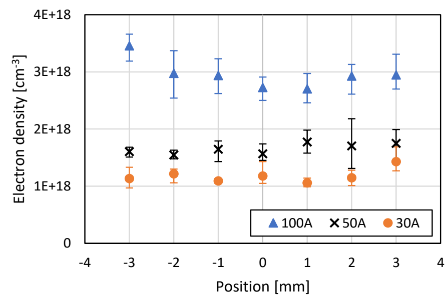


Figure 9. Axial distribution of electron density.

IV. TEMPERATURE INSIDE ARC DISCHARGE

The arc temperature was determined by the Boltzmann plot method. This is a method of calculating the temperature from the emission intensity of the same kind of atom when assuming a local thermal equilibrium, and is expressed by the following equation [1].

$$\log_{10}\left(\frac{I\lambda}{gA}\right) = -\frac{E\log_{10}e}{kT} + const. \qquad (1)$$

Where T : absolute temperature, E : upper level energy, k : Boltzmann's constant, A : transition probability, g : statistical weight, e : Napier number, I : emission intensity, λ : wavelength. In (1), the values except for the light emission intensity are used in values referred from NIST database [3]. Therefore, the arc temperature T can be calculated by plotting the left side of (1) at several points with respect to the upper level energy and determining the slope from the line of the plotting. In this paper, the line spectrum of 504.1 and 505.6 nm, 595.8 and 597.9 nm, 634.7 and 637.1 nm of Si^{+} were used for temperature measurement. Each line spectrum of Si^{+} was fitted with a pseudo Voigt function, and the arc temperature was determined by using the area as the light emission intensity.

The axial distribution of the measured arc temperature is shown in Fig.8. The plot means the calculated average value measured three times, and the error bars mean the maximum and minimum values at the same current value. Each temperature obtained the calculation under the current flowing condition corresponds to the temperature values from 22,000 K to 25,000 K at 100 A, from 18,000 K to 21,000 K at 50 A and from 17,000 K to 19,000 K at 30 A respectively.

V. Electron Density Inside Arc Discharge

The electron density was determined from Stark broadening, which is a kind of spectral broadenings. The Stark broadening depends on the electron density. Since the line spectrum which has large Stark broadening corresponds to the state of high electron density, it is possible to obtain the electron density from the Stark broadening measurement of the line spectrum. The Stark broadening of a monovalent ion is expressed as follows [2].

$$\Delta\lambda = 0.2\left[1 + 1.75 \times 10^{-4} n_e^{\frac{1}{4}} \alpha \left(1 - 0.11 n_e^{1/6} T^{-1/2}\right)\right] 10^{-16} w n_e \qquad (2)$$

Where $\Delta\lambda$: full width at half maximum of a line spectrum, n_e : electron density (cm^{-3}), T : electron temperature, α and w : constants that are weakly dependent on temperature, and are these values obtained from Griem's reference [4]. The apparatus broadening and the other broadening except for Stark broadening can be ignored because of very small value in this experiment. By fitting the spectrum obtained in the experiment with a pseudo Voigt function, the Stark full width at half maximum was determined, and the electron density was calculated.

Fig. 9 shows the axial distribution of electron density calculated by fitting the line spectrum of Si^{+} at 634.7 nm. Each electron density corresponds to 2.5×10^{18} to 3.5×10^{18} cm^{-3} at 100 A, 1.5×10^{18} to 2.0×10^{18} cm^{-3} at 50 A and 1.0×10^{18} to 1.5×10^{18} cm^{-3} at 30 A.

VI. Particle Composition Inside Arc Discharge

The particle compositions of arc discharges in fuses were calculated with reference to the literature [5] presented by Sakuta et al. The arc discharge in the fuse box consisted of SiO_2 arc extinguishing sand, a copper fuse element and the air. Therefore, as constituent particles inside the arc discharge generated in the fuse, a total of 20 types of N_2, O_2, NO, NO^{+}, N, O, N^{+}, O^{+}, N^{2+}, O^{2+} derived from high temperature air, SiO_2, SiO, Si_2, Si, Si^{+}, Si^{2+} derived from extinguishing sand, Cu, Cu^{+}, Cu^{2+} derived from the fuse element and electron "e" were considered. Among these particles, the particle composition can be uniquely determined by solving following simultaneous equations with designating the total pressure P, the copper vapor mixing ratio X_{Cu} and the temperature T. Here the simultaneous equations are as follows : Saha's equations for dissociation and ionization reaction of the particles, mixing rate's equation of copper vapor, equation for determining ratio of each element (= N: O: Si: Cu), ideal gas state equation and neutrality condition of electric charge. Calculations were made as follows. Assuming a copper vapor mixing ratio X_{Cu}, other particles except for copper were (100-X_{Cu}) %, and the ratio of air was 10 % of that percentage, which was obtained from the weight of arc extinguishing sand in the fuse box and the SiO_2 density. The remaining particle corresponded to SiO_2. Since the composition ratio of pure air is N: O = 78: 22, 78 % of the air corresponded to the proportion of nitrogen-based particles. Particles other than copper and air are derived from SiO_2 gas decomposed from arc extinguishing sand. 1/3 of the particles corresponded to silicon based particles.

Fig. 10 shows the particle composition of the arc discharge inside the fuse when P = 10 atm and X_{Cu} = 1 %. In calculating the particle composition, it was assumed that X_{Cu} = 1%. This is because the volume of the fuse element is small relative to that of the arc discharge, and the electron density does not depend on the copper vapor at about 10,000 K or more, as shown in Fig. 11. Thus, if the temperature T and the electron density n_e are determined, the total pressure P is determined from the ideal gas state equation, so that the particle composition satisfies T, n_e and P.

The calculated total particle density is shown in Fig.12. It ranged from about 5.0×10^{18} to 9.0×10^{18} cm^{-3} at 100 A, 4.0×10^{18} to 5.0×10^{18} cm^{-3} at 50 A, and 3.0×10^{18} to 5.0×10^{18} cm^{-3} at 30 A.

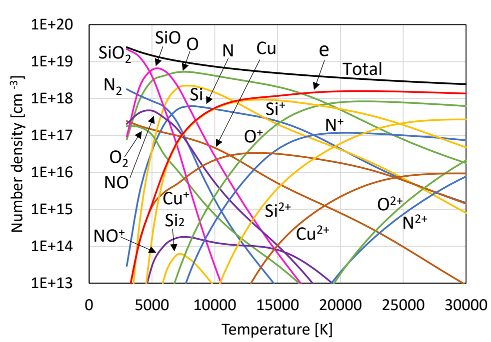


Figure 10. Temperature dependence of particle composition in the fuse, total pressure: 10 atm, fraction of copper atoms 1%.

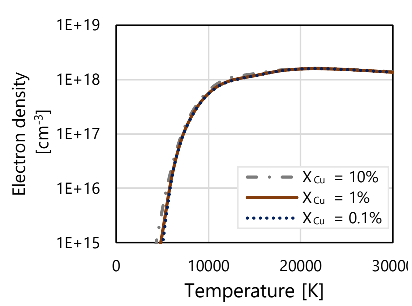


Figure 11. Temperature dependence of electron density with copper vapor contamination as a parameter.

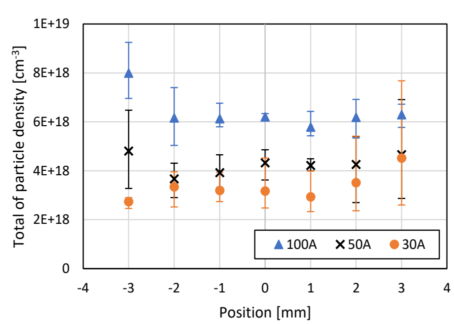


Figure 12. Axial distribution of total of particle density.

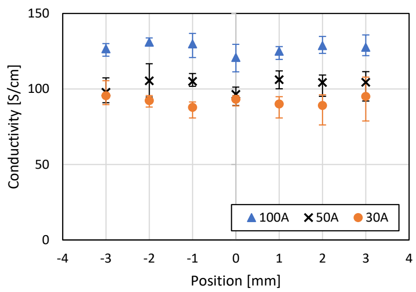


Figure 13. Axial distribution of electrical conductivity.

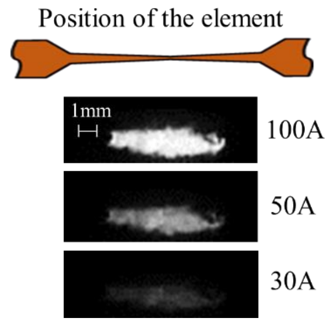


Figure 14. Image of arc discharge just before extinction.

VII. Electrical Conductivity Inside Arc Discharge

According to the Chapman-Enskog approximation of Yos's reference [6], the conductivity is expressed by the following equation.

$$\sigma = \frac{\frac{3e^2}{16kT}\sqrt{\frac{2\pi kT}{m_e}}n_e}{\sum_j^{n}{}^{*} n_j Q_{ej}} \qquad (3)$$

Where e : elementary electric charge, k : Boltzmann constant, T : absolute temperature, m_e : electron mass, n_e : electron density, n_j : number density of particle j, Q_{ej} : collision cross section between electron and particle, * of Σ term donates the summation of n_jQ_{ej} except for the value of n_eQ_{ee}. From the measurement results in Fig. 8, the temperature of the arc discharge inside the fuse was 13,000 K or more. In Fig.10, in the temperature range of more than 13,000 K, the number density of the oxygen neutral atom is about 10 times higher than the ion number density. However, the Coulomb collision cross section between electron-ion is about 100 times higher than the collision cross section between electron-neutral particles. Therefore, the Coulomb collision is considered to be dominant in this condition. In the calculation of (3), only the Coulomb collision cross sections were considered. The Coulomb collision cross section is calculated based on the value of Yos [6].

The axial distribution of the calculated conductivity is shown in Fig. 13. Each conductivity under the current flowing condition was estimated in about 130 S/cm at 100 A, about 110 S/cm at 50 A and about 90 S/cm at 30 A respectively. According to these conductivities characteristics, it was confirmed that the conductivity decreased as the arc current decreased.

VIII. Arc Observation with High-Speed Video Camera

Figure 14 shows the light emission images from the arc discharge just before extinction, observed by using a high-speed video camera. Each image was captured at 100 A, 50 A and 30 A respectively. Fig. 14 shows that the arc discharge covered about ± 3 mm from the center of the narrow part. Further, the axial distributions of the light emission intensity were almost uniform and they gradually decreased as the current decreased, which was considered to correspond to the decrease in electrical conductivity shown in Fig. 13.

IX. Summary

The axial distribution of arc temperature and electron density were measured by the analysis of the spectra before the current zero point of the arc discharge inside the fuse. From these spectra, the axial distribution of electrical conductivity inside the arc discharges were calculated. The arc temperature and the electrical conductivity decreased as the current decreased to zero. The light emission intensity decreased uniformly as the current decrease, which corresponded to the gradual decrease of the axially uniform electrical conductivity in the arc discharge inside the fuse.

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