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Role of the Metallic Phase Arc Discharge on Arc Erosion in Ag Contacts

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Abstract—**The influence of a metallic phase arc discharge on contact phenomena was experimentally studied in the breaking Ag contacts. The parameters which were taken in this experiment were the whole arc duration (metallic phase arc duration plus gaseous phase one), metallic phase arc duration, contact resistance, bridge energy, and the electrode material mass change. Some experiments were performed under the various conditions of air pressure and contact current.**

From the results obtained through the process of arc duration and contact resistance, we found that the contact resistance was low in the metallic phase arc region, and high and almost constant in the gaseous phase arc region.

The relationship between material loss and transfer and the accumulated metallic phase arc duration was log-proportional, irrespective of air pressure condition, which led us to the conclusion that the electrode material mass change was closely related to the metallic phase arc discharge.

I. Introduction

An ARC DISCHARGE affects the greater part of degradation of switching contact, because of the material loss and transfer in contact electrode [1]. Many experimental results have shown that the material loss and transfer and the contact resistance are closely related to the arc duration. Thus the arc duration is an important index of degradation of the contact performance, but yet the mechanism of the degradation still remains to be solved.

One of the authors has investigated a relationship between the accumulated arc duration and the electrode material loss for Ag, Cu, and Pd contacts [2]. His result, presented in Fig. 1, shows that the electrode material loss was proportional to the accumulated arc duration at any circuit current for Cu and Pd contacts, while the ratio of Ag contacts depends on circuit current. Ag contacts are also characterized by a marked decrease in material loss and gain at the circuit current of 3 A (at 48 V).

A long term of arc duration generally consists of the metallic phase arc region and the gaseous phase arc region [3]. When the circuit current is small, the arc discharge becomes extinct in the metallic phase arc region. As the contact current increases, the arc transits from the metallic phase to the gaseous phase, and the transition probability has been measured by Takahashi *et al.* [4]. However, it is yet unknown how each phase arc affects the contact performance.

In this paper, the influence of the metallic phase arc on the contact phenomena will be made clear by measuring both the whole arc duration (metallic phase plus gaseous phase arc duration) and the metallic phase arc duration as well as contact resistance and electrode loss (transfer). Since the results have been obtained by using a newly developed arc measuring system, we will refer to the real-time measuring system of arc discharge phenomena in Section II. This paper will present the experimental results obtained so far, and the first experiment in Section III will be on the correlation between arc duration and contact resistance. Thermal effect in arc discharge on material loss or transfer, which is closely related to the bridge phenomena and the metallic phase arc, will be shown in Section IV. In Section V, measurement of correlation of metallic arc and electrode material loss will be made. We will summarize and discuss the results in Section VI, and present the conclusion in Section VII.

II. Real-Time Measuring System of Arc Discharge Phenomena

A. Measured Parameters and Testing Conditions

The testing system used in our experiment has a vacuum chamber in which the atmospheric condition can be controlled [5]. A standard operating condition in this experiment is shown in Table I. The system operates repeatedly, and the measured data are processed by each operation in a real time [6].

B. Digital Measurement System of Arc Voltage Waveform

The system has a waveform memory and A/D converters. The capacity of the waveform memory is 8 kb and the whole arc voltage waveform (Fig. 2) and the bridge voltage waveform (Fig. 11) are stored in it [6].

The waveforms are transferred to a microcomputer, displayed on a screen, and analyzed to obtain both the whole arc duration and the metallic phase arc duration.

Voltage drop across the contact is sampled just before the contact electrode opens, and contact resistance is calculated by dividing the voltage by the contact current.

C. Measurement System of Arc Duration and Metallic Phase Arc Duration

The arc duration t_a defined in Fig. 2 was obtained from the arc voltage waveform in every contact operation by reading the memory mentioned above. The accumulated arc duration was defined as Σt_a.

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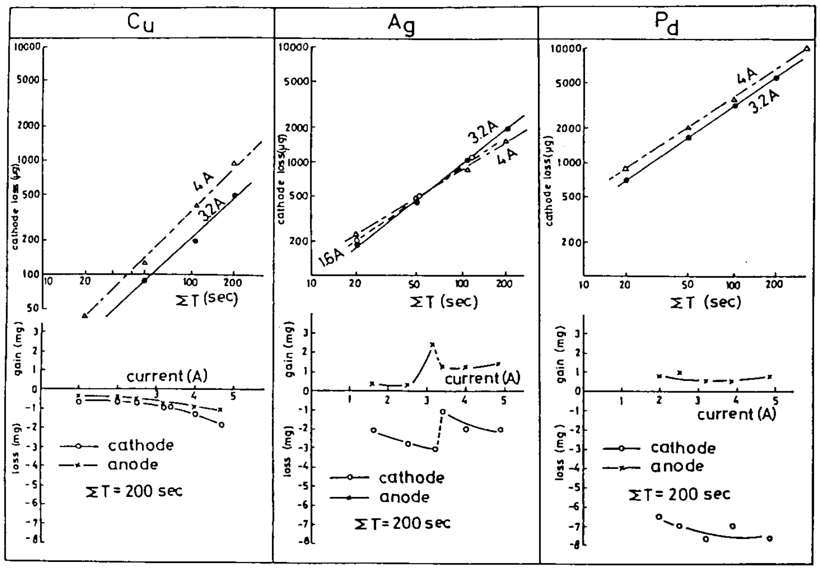

Fig. 1. Material loss and gain versus accumulated arc duration and circuit current [2].

TABLE I
OPERATING CONDITIONS

Term	Value
Circuit voltage	48 V
Circuit current (I)	2, 3, 4, 5 A
Circuit load	noninductive film resistor
Electrode	Ag, 1-mm diameter, cross bar
Opening velocity	5, 10, 14 mm/s
Contact weight	100 g
Air pressure (P)	50, 100, 200, 400, 760 mmHg
Operation	500 times

The metallic phase arc duration t_{am} defined in Fig. 2 was obtained by searching the transition from the metallic to the gaseous phase in arc voltage waveform. The transition was recognized by computer software [7]. The metallic phase arc duration t_{am} was defined as the time between the arc initiation and the transition, but when the arc becomes extinct in the metallic phase region it became $t_{am} = t_a$. Σt_{am} was defined to denote the accumulated metallic phase arc duration.

III. Correlation Between Arc Duration and Contact Resistance

A. Relationships Between Arc Duration, Contact Resistance, and Circuit Current

According to the measurement by the authors, the contact resistance of Ag switching contact showed a remarkable characteristic as shown in Fig. 3 [8]. Contact resistance decreased in inverse porportion to the circuit current above 2 A (at voltage 48 V), and it suddenly dropped when the current was 1.2 A. This noticeable current value of 2 A was also remarkable for arc duration, since the arc duration shown in Fig. 3 suddenly increased at current of 2 A again. In addition, the current value is nearly equal to the boundary where the transition to gaseous arc occurs [4].

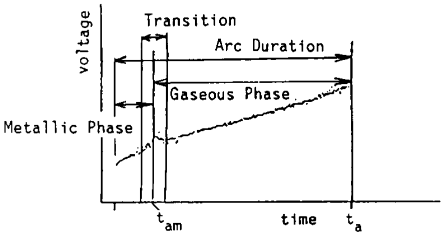

Fig. 2. Arc voltage waveform.

This measurement implied that a result that both the arc duration and the contact resistance suddenly changed at the same current, and they might have a close correlation between the arc duration and the contact resistance.

The authors have observed the waveform of the bridge voltage in Ag contacts, and they have found a close relationship between the contact resistance and the bridge voltage waveform [8]. When the circuit current increased in a small current region, both the melting and boiling voltages in the bridge voltage decreased from the initial values. The boundary in current corresponding to those changes in voltage waveforms was 2 A, and this value coincided with the boundary where the rapid change in the contact resistance occurred as shown in Fig. 3. This observation suggests that the effects of the metallic and the gaseous phase arc discharge on contact phenomena may be quite different from each other.

B. Detailed Observation on Correlation Between Arc Duration and Contact Resistance

Through a statistical treatment of the arc duration t_a and the contact resistance R_c after each contact operation, we have had the macroscopic relationship between arc duration and contact resistance as mentioned in Section III-A [8], [9]. However, our newly developed measuring system makes it possible to find a more detailed relationship.

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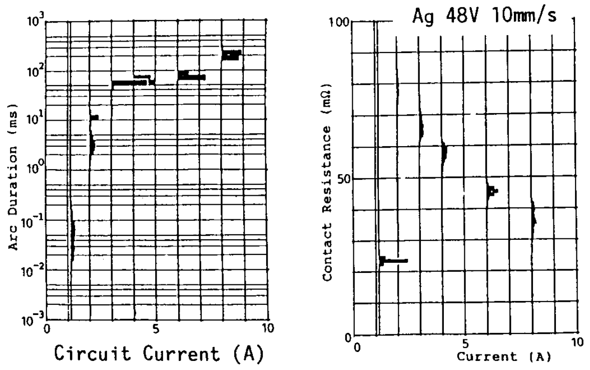


Fig. 3. Arc duration and contact resistance versus circuit current.

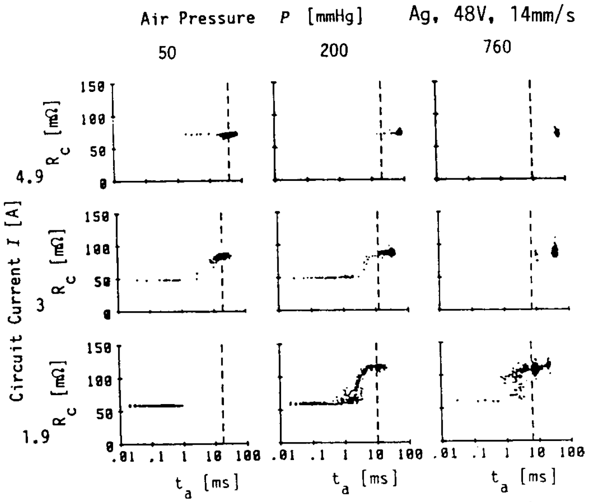


Fig. 4. Relationship between contact resistance R_c and arc duration t_a.

Fig. 4 shows the relationship between whole arc duration t_a and contact resistance R_c of Ag contact. Each dot in Fig. 4 designates a measured value in each contact operation [10]. Each figure in Fig. 4 shows the result with respect to distinct operating condition when the air pressure P and the circuit current I were changed. A dotted line in the figure shows the average of the critical time t_c when the contact gap reaches the critical distance [11] and the transition to the gaseous phase [3] occurs.

From the results shown in Fig. 4 we can find a close correlation between t_a and R_c, and their relationship can be divided into three parts A, B, or C as shown in Fig. 5.

Part A: When the arc duration t_a is very small, R_c is small and constant.

Part B: In a transition part from metallic phase to gaseous phase, t_a and R_c have a proporational relationship with each other.

Part C: The arc duration t_a always exceeds the critical time t_c and transits to the gaseous phase, and R_c in this part is stable and high.

The increase in R_c in a longer arc duration than the critical time t_c agrees with the former result shown in Fig. 3. From the above detailed observations, we can conclude that the contact resistance clearly depends on the arc duration in the metallic phase.

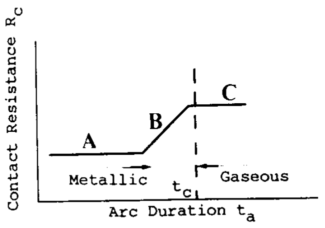
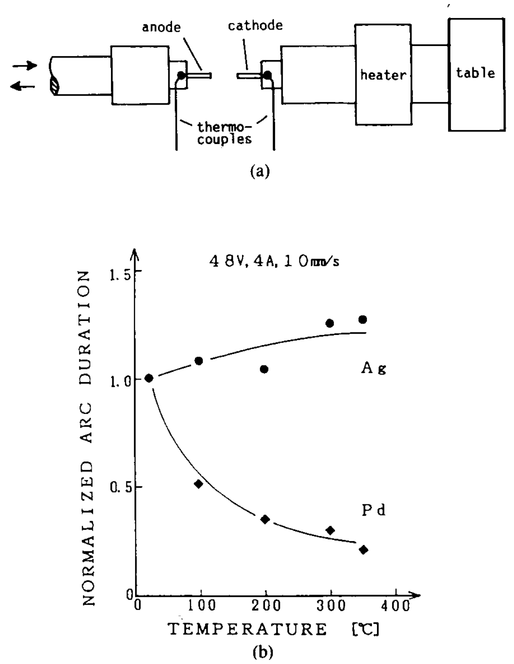


Fig. 5. Tendency of relationship between contact resistance R_c arc duration t_a.



(a)

(b)

Fig. 6. Temperature characteristics of arc duration with heated cathode. (a) Electrode heating system. (b) Measurement result.

IV. Thermal Effect on Arc Discharge Phenomena

A. Thermal Effect on Arc Duration and Material Loss

The thermal effect on the arc discharge phenomena in Ag and Pd contacts have been investigated by one of the authors. In the case where a cathode electrode was heated, the arc duration increased in Ag contact but fairly decreased for Pd contact as shown in Fig. 6 [12], [14].

The operating condition was the same for both Ag and Pd contacts in the above measurement, but the arcing in the Ag contact always went beyond the critical point and transited to the gaseous phase, while the arcing in the Pd contact was always extinct in the metallic phase region. Another measurement for Ag contacts has been made under the operating condition where the arc discharge does not transit to the gaseous phase [13]. According to this experiment, the thermal effect showed a similar tendency to that of Pd contact, and the arc duration decreased to one tenth by heating the cathode as shown in Fig. 7.

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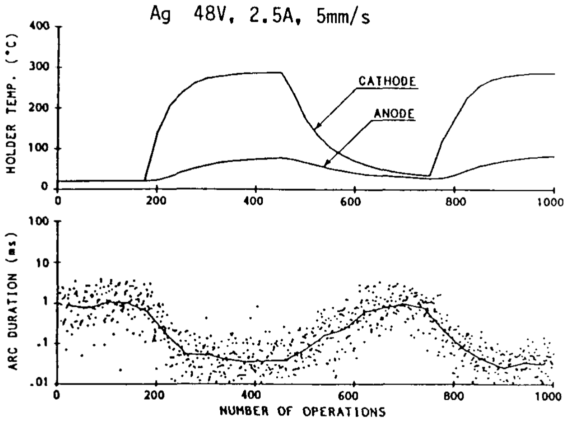


Fig. 7. A typical example of arc duration when cathode is heated.

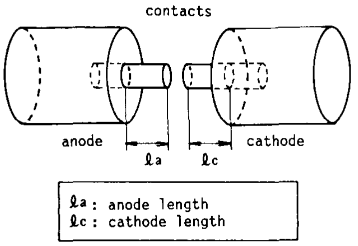


Fig. 8. Bar contact.

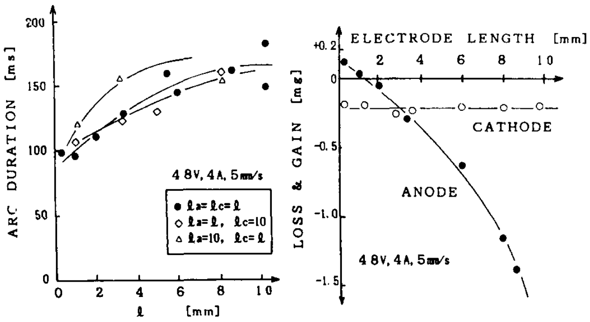
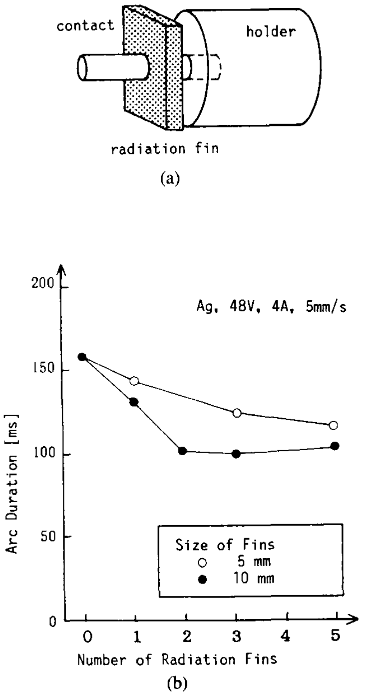


Fig. 9. Electrode length dependency of Ag contact arc phenomena.

The results mentioned above suggest that the metallic phase arc discharge in breaking contact is heavily affected by the thermal condition of the contact. Thus not only the arc duration but also related contact phenomena can be controlled by the thermal conditions in the contact.

The thermal condition of a bar contact is changed by its electrode length defined in Fig. 8. If the electrode length becomes shorter, the heat generated at contact travels and spreads easily into electrode holder, and the contact is cooled more. An example is shown in Fig. 9, which shows the variation of the arc duration and the material loss and gain of Ag contact when the electrode length is varied [14]. This shows that a higher contact temperature causes a longer arc duration and a higher anode loss.

According to the thermal analysis of the contact electrode with respect to the electrode length, the effect of electrode length is dominant in large thermal conductivity material such as Ag [15]. A similar tendency to that of Fig. 9 in relation to thermal effect has been found in our experiment where a cooling fin was attached to a electrode [14] as shown in Fig. 10.



(a)

(b)

Fig. 10. Effect of radiation fins for arc duration. (a) Radiation fin. (b) Measured results.

The results mentioned above show that the arc discharge phenomena are strongly affected by the thermal condition of the electrode and the material loss, and that transfer caused by the arc discharge can be reduced by controlling the thermal condition of the contact electrode.

B. Bridge Phenomena and Metallic Phase Arc

As mentioned previously, the thermal effect was evident in the metallic phase arc discharge. The medium of the metallic phase arc is an ionized vapor of electrode material, and it has been supplied from a ruptured bridge. The bridge between electrodes consists of molten and expanded metal from the heated electrode [16], [17].

The voltage waveforms across the bridge in Ag and Pd contacts are shown in Fig. 11, where parts (a) and (b) are for Ag contact and parts (c) and (d) are for Pd contact, and both (b) and (d) show cases where the cathode electrode was heated [13]. We can see that the bridge duration decreases when the electrode is heated, and that both the melting and boiling voltages [1] do not change by heating. The result means that the bridge energy, defined as integration of voltage current product through the bridge duration, decreases when the temperature in the electrode is raised. Calculated bridge energy and measured temperature of the electrode are shown in Table II.

The decrease of metallic arc duration mentioned in Section

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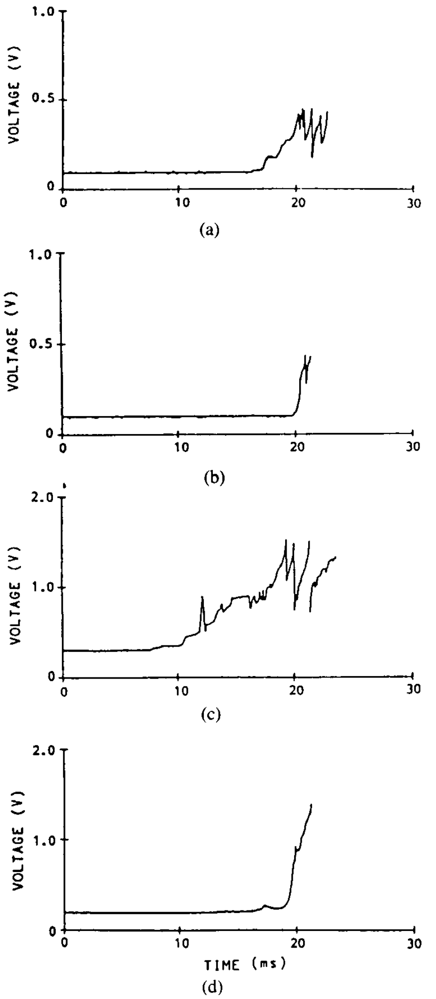

(a)

(b)

(c)

(d)

Fig. 11. Typical bridge voltage waveforms. (a) Ag, 48 V, 2.5 A, 5 mm/s, room temperature. (b) Heated. (c) Pd, 48 V, 4 A, 5 mm/s, room temperature. (d) Heated.

TABLE II
BRIDGE ENERGY

Ag Contact	Room Temperature	Heated
Bridge energy Temp. at holder	3.2 mJ 20°C	1.3 mJ 300°C
Pd contact	room temperature	Heated
Bridge energy Temp. at holder	24 mJ 20°C	15 mJ 300°C

IV-A can be explained from the viewpoint of the bridge energy. It is well known that the bridge ruptures when the temperature of the bridge reaches the boiling point of the material which is the maximum temperature in the bridge [1], [18]. The contact voltage at the initiation of the arc discharge is nearly the boiling voltage which is a constant value depending on the electrode material.

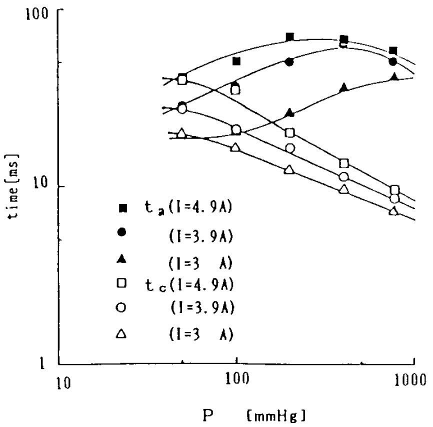

Fig. 12. Arc duration t_a and critical time t_c versus air pressure P.

If the electrode is heated, the temperature reaches the boiling point fast, then bridge duration decreases. The slope of bridge voltage waveform increases when the electrode is heated as shown in Fig. 11. When the electrode temperature is high, the bridge energy becomes small, then the molten material in the bridge and the metal vapor supplied from the ruptured bridge decrease. As a result of the decrease of metal vapor, the lifetime of the metallic arc discharge becomes short.

V. MEASUREMENTS ON CORRELATION OF METALLIC ARC DURATION AND ELECTRODE MATERIAL LOSS

A. Effect of Air Pressure in Metallic and Gaseous Phases

The experimental results in Section IV-B showed that the metallic phase arc discharge was closely related to the bridge phenomena. The metallic phase arc duration is the interval from the beginning of the arc discharge to the time when the contact gap reaches the critical distance. The critical distance r_c is a function of gas pressure P, and r_c is proportional to αth power of P where $-\alpha = 0.4$–0.5 [11].

The authors' measurement of the relationship between the arc duration t_a or the critical time t_c against the air pressure P showed almost the same tendencies as those shown in Fig. 12, but the slope of the curve of critical time t_c varies with respect to circuit current I. Of course, in a region where the arc duration t_a is shorter thant he critical time t_c, no gaseous phase appears and all arcs belong to the metallic phase.

The period below the line of t_c in Fig. 12 is the metallic phase arc duration t_{am} and the period between the lines of t_c and t_a corresponds to the gaseous phase arc duration. In a region where the air pressure is between 50 and 760 mmHg, the gaseous phase arc duration increases and the metallic phase arc duration decreases in proportion to the air pressure. Thus the arc discharge in two phases are quite different phenomena.

B. Correlation Between Metallic Phase Arc and Material Loss

An earlier study [2] presented in Fig. 1 showed that the proportional ratio of the relationship between the electrode loss and the accumulated arc duration was not constant for Ag

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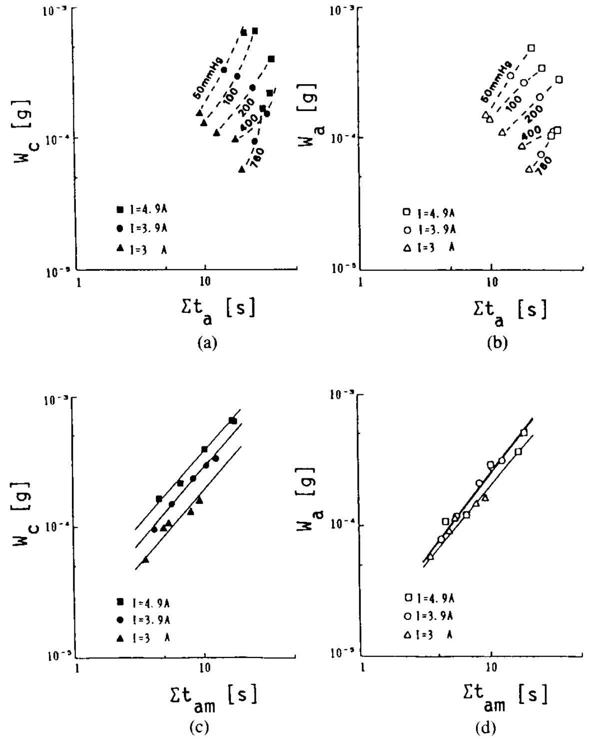

(a) (b)

(c) (d)

Fig. 13. Electrode mass change W_c and W_a versus accumulated arc durations Σt_a and Σt_{am}.

contacts when circuit current was varied. In this subsection, we will study this ambiguity by focusing on the metallic phase are duration.

The material mass changes W_c (cathode) and W_a (anode) were measured in various operating conditions where the circuit current and the air pressure were varied. The results for cathode loss W_c and anode gain W_a are shown in Fig. 13 (a) and (b). The material loss and gain with respect to the accumulated arc duration Σt_a seems to have no systematic relationship when the air pressure is varied.

However, if we adopt the accumulated metallic phase arc duration Σt_{am} instead of Σt_a, the electrode mass changes W_c and W_a have a log-proportional relationship with Σt_{am} as shown in Fig. 13 (c) and (d). Moreover, no dependency appears on the air pressure P when the circuit current I is fixed. The slopes of all lines in Fig. 13 (c) and (d) are almost equal and they shift only according to the current condition.

VI. Discussion on the Role of Metallic Phase Arc Discharge

We can summarize the investigations on the Ag contact mentioned in Sections III as follows.

a) In a low-current region (below 2 A at 48 V), both contact resistance and arc duration are low. This suggests that there may be some relationship between them (Section III).

b) The metallic phase arc duration is fairly dependent upon the bridge energy, and the metallic arc duration decreases as the electrode temperature is raised (Section IV).

c) Both material loss and transfer gain are log-proportional to the metallic arc duration, and they are independent of the ambient air pressure. They have irregular dependency on the air pressure as far as we observe the whole arc duration (metallic plus gaseous phases) (Section V).

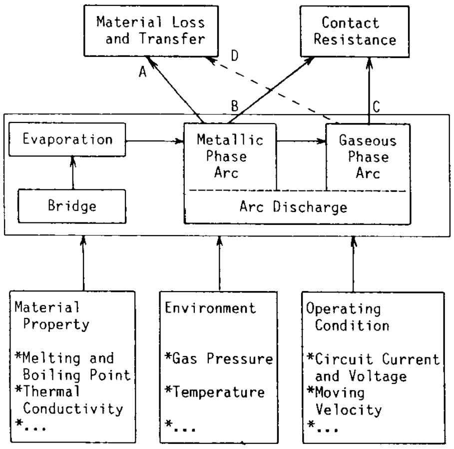

Fig. 14. Role of metallic phase arc in Ag contact.

From the above results, we consider the role of the metallic phase arc in Ag contact and summarize it as shown in Fig. 14, in which the arrows A–D are shown. As for the relationship between arc and material loss and transfer gain:

Arrow A: Material loss and transfer gain almost depend on the metallic phase arc, and a little on the gaseous phase arc (arrow D).

As for the relationship between the arc and contact resistance, there are two different effects of arc on the contact resistance, which are indicated by arrows B and C, respectively.

Arrow B: In the metallic phase arc region, that is the case of very short arc duration, the contact resistance R_c is low and stable. R_c depends on the arc duration when the arc duration becomes large even in the metallic phase region.

Arrow C: In the region of longer term of arc which consists of the metallic phase arc and gaseous phase arc, R_c is large compared with the case of arrow B.

Arrow D: As mentioned in relation to arrow A, the gaseous phase arc has little effect on the contact erosion.

We obtained a new interpretation in this paper that the effect of gaseous phase arc on the contact erosion is small, and we may be able to explain the large decrease in cathode erosion of Ag contact shown in Fig. 1 as follows. The measured data in Fig. 1 were of the accumulated arc durations ΣT, and the transition to the gaseous phase arc occurred at the current above 3 A. Since the loss has been measured at $\Sigma T = 200$ s fixed, the gaseous phase arc duration in the longer arc duration becomes dominant at above 3 A and the accumulated metallic phase arc duration decreases, thus the erosion becomes small.

We obtained a very important conclusion from this work, namely, that the role of metallic phase arc is very important in contact erosion (loss and gain) caused by arc. Thus the low erosive contact may be designed if we can shorten the metallic phase arc duration.

One way to attain such an aim is to control the bridge energy

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by controlling the electrode temperature. In Fig. 14, the bridge energy can be controlled by the electrode temperature. The energy in the bridge increases the evaporation of the material, and if the energy becomes lower the amount of the vapor becomes lower, thus the metallic phase arc duration becomes shorter.

VII. CONCLUSION

By employing a real-time digital measuring system and a novel analysis method, the relationships between arc duration, metallic phase arc duration, contact resistance, bridge energy, and the electrode material loss and transfer were measured for breaking Ag contacts. The tests have been carried out under the various conditions of air pressure and circuit current.

The relationships were well investigated and it was found that the metallic phase arc duration was very important. The bridge energy and the material loss and transfer have a close correlation with metallic phase arc duration, although almost no relationship could be seen between material mass change and the whole arc duration over the different air pressure conditions.

This result means that the arc duration in the metallic phase arc region strongly affects the material loss and transfer and the contact resistance, and the gaseous phase arc has little influence.

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REFERENCES

[1] R. Holm, *Electric Contacts,* 4th ed. Berlin, Germany: Springer, 1979.

[2] T. Takagi and H. Inoue, "Distribution of arc duration and material wear due to arc for Ag, Cu, and Pd contacts," *IEEE Trans. Comp., Hybrids, Manuf. Technol.,* vol. CHMT-2, pp. 20-24, Mar. 1979.

[3] E. W. Gray, "Voltage fluctuations in low-current atmospheric arcs," *J. Appl. Phys.,* vol. 43, pp. 4573-4575, Nov. 1972.

[4] A. Takahashi, N. Takashima, and K. Yoshida, "Transition from metalic to gaseous phase for Ag breaking arc in low air pressure," *Trans. IEICE,* vol. E70, pp. 1054-1055, Nov. 1987.

[5] T. Takagi, "Variation of arc duration of electric contacts due to controllable atmospheric condition," *IEEE Trans. Comp., Hybrids, Manuf. Technol.,* vol. CHMT-8, pp. 29-33, Mar. 1985.

[6] H. Sone and T. Takagi, "Automatic data acquisition and processing system of contact phenomena based on advanced microelectronics," in *Proc. IC-CEMCA Nagoya* (July 1986), pp. 939-946.

[7] H. Sone, M. Nakai, and T. Takagi, "Automatic measurement of critical point and features of breaking arc voltage in Ag contacts," *Trans. IEICE,* vol. E70, pp. 1051-1053, Nov. 1987.

[8] H. Sone and T. Takagi, "Current dependencies of contact resistance, arc duration and bridge voltage in Ag and Pd contacts," *Trans. IEICE Pt. C,* vol. J70-C, pp. 1561-1563, Nov. 1987.

[9] ——, "A measurement and a classification of arcing phenomena of AgPd alloy contacts in low pressure," *Trans. IEICE Pt. C,* vol. J70-C, pp. 1569-1574, Dec. 1987.

[10] H. Sone, M. Nakai, and T. Takagi, "Measurements on the influence of metallic phase arc on electrode surface for breaking Ag contacts," *Trans. IEICE, Pt. C,* vol. J71-C, pp. 1368-1372, Oct. 1988.

[11] P. J. Boddy and T. Utsumi, "Fluctuation of arc potential caused by metal-vapor diffusion in arcs in air," *J. Appl. Phys.,* vol. 42, pp. 3369-3373, Aug. 1971.

[12] T. Takagi, "Electrode temperature dependency of arc duration in contact break," in *Proc. 11th ICECP* (Berlin, 1982), pp. 251-255.

[13] K. Sato, T. Sato, H. Sone, and T. Takagi, "Relationship between bridge energy and metallic phase arc duration in electric contacts," *Japan. J. Appl. Phys.,* vol. 26, pp. L261-L263, Apr. 1987.

[14] T. Sato, H. Ishida, H. Sone, H. Echigo, and T. Takagi, "An experimental study on the effect of heat conduction through holder on arc phenomena in bar contacts," *Trans. IECE Japan,* vol. J69-C, pp. 457-463, Apr. 1986.

[15] H. Ishida, H. Sone, H. Echigo, and T. Takagi, "A study of thermal effect on arc duration in Pd and Pt contacts," *Trans. IEE Japan,* vol. 106, pp, 203-209, May 1986.

[16] M. J. Price and F. L. Jones, "The electrical contact: The properties and rupture of the microscopic molten metal bridge," *Brit. J. Appl. Phys.,* vol. 2, pp. 589-596, 1969.

[17] T. Utsumi, "Theoretical and experimental investigations of the dynamic molten bridge," *IEEE Trans. Parts, Hybrids, Packag.,* vol. PMP-5, pp. 62-68, 1969.

[18] F. L. Jones, *The Physics of Electrical Contacts.* Oxford, UK: Clarendon, 1957.

[19] H. Sone, M. Nakai, and T. Takagi, "A measurement on the relationship between metallic phase arc duration and electrode mass change in Ag contacts," *Trans. IEICE,* vol. E71, pp. 268-271, Apr. 1988.

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