Abstract: The effects of supply voltage and gap distance on the arc erosion behavior of silver electrical contact by using a static-gap electrical erosion tester with a single arc discharge. Results show that the minimum electrical field strength at arc initiation occurs at 70 V/µm up to 175 V, at 10 µm at 330 V, and 40 µm at 500 V. Since the gap distance becomes bigger during the arc duration, the residual voltage is always positive at smaller gap distance with lower supply voltage. The negative residual voltage occurs at larger supply voltage due to the effect of metallic phase arc. This negative residual voltage is caused by positive metallic ions accumulated on the cathode. At the supply voltage less than 200 V, the erosion area is linearly increased with increasing gap distance, but this relationship becomes parabolic at the supply voltage larger than 200 V. At gap distance below 5 µm, the erosion area increases with increasing arc energy, but it decreases with increasing arc energy at gap distance beyond 5 µm due to the increase amount of gaseous phase arc. It is seen from the eroded anode surface that the metallic phase arc mainly causes the crater with many strip-like metallic particles, but the gas phase arc significantly results in many silver powders. These results with negative residual voltage are in good agreement with the particle sputtering-depositing model.

Keyword: Arc discharge, Gap distance, Erosion area, Residual voltage, Arc energy, Particle sputtering-depositing

1. INTRODUCTION

The electrical contacts are widely used in control and communication systems. The electrical erosion of contacts due to arcing has always been an important problem in the design of the switching system. This erosion occurs whenever contacts are closed to complete the energized circuit, or when they are pulled apart to break it. The formation of pips and craters has been recognized by Homes and Slade [1] on the silver and its alloy contacts. Many other experiments have also investigated the erosion and contact resistance variation of silver and its alloy contacts [2-6].

In a dynamic test of switching contact, the contact erosion is the result of melting and vaporizing metal when the contacts are brought together. Two types of arcs (i.e. the metallic and gaseous phases) have been recognized by Germer [2]. They significantly influence the erosion behavior and mass transfer. Generally, if the metallic phase arc is dominant, the material transfers from the anode to the cathode, while if the gaseous phase arc becomes predominant, the material transfers from the cathode to the anode. Recently, according to the transition of contact morphology, mass transfer, and arc duration of the metallic and gaseous phases, a particle sputtering and deposition model has been proposed by Chen and Sawa [6]. In this model, the evaporation and sputtering of the contacts were discussed to explain this mass transfer during arcing.

It has been known that the arc causes the erosion, but the surface morphology also influences the arc behavior during the dynamic test of switching contact. Moreover, mechanical stresses, molten bridges, and chunk transfer due to welding also result in the erosion. Consequently, it is very difficult to develop a quantitative understanding in the erosion behavior of a material related to the arcing condition alone. To avoid the influence of the complex mechanics of a particular switching device, static-gap experiments have been conducted in recent years [7-11]. In this paper, the static-gap experiments with single arc discharge are conducted to reduce the complexity due to numerous arcs striking. Furthermore, the supply voltage, the arc duration, and the gap distance in this static gap experiment can be precisely controlled. The effects of supply voltage and gap distance on the arc erosion behavior of silver contact are investigated. The minimum electrical field strength at arc initiation is established. Using the particle sputtering and deposition model discuss the residual voltage and the erosion pattern of the anode surface.

2. EXPERIMENTAL APPARATUS AND PROCEDURES

2.1 Experimental apparatus

The experiments are conducted on a horizontal static-gap and single-arc discharge tester with a measuring system shown in Fig. 1. In this tester, two micrometer heads of non-rotating spindle type are employed. In each micrometer head, one revolution of the thimble moves the spindle the distance of 0.5 mm. In order to adjust the gap distance in the graduation of 0.025 µm, a 1:50 worm gear reducer is employed to drive the micrometer head. A stepping motor with the resolution of 0.9°/step drives the worm and a PC program can control the stepping motor. A disk specimen is attached to the spindle of a 1st micrometer head. Hence, it can be moved right and left through the spindle of a 1st micrometer head. To eliminate the effect of the backlash of micrometer head on the precision of the micro-movement of the disk specimen, a 2nd micrometer head is used to calibrate the micro-movement of the disk head.
specimen through the reference plate attached to the spindle of the 1st micrometer, as shown in Fig. 1. A cartridge head probe mounted on a 2nd micrometer head is connected to an electrical comparitor or differential type analog mu-checker with a graduation of 0.1 μm. Hence, the micro-level shift of the disk specimen through this device can be calibrated by the analog mu-checker. The sequence of operation for this device is described in section 2.3 experimental procedure.

Fig. 2 shows a DC R-C circuit with charging and discharging branches. The charging branch of the circuit includes a high voltage power supply (10 – 600 V DC), a variable resistor (0.1 МΩ), and capacitor bank (0.94 μF). The discharging branch consists of the capacitor bank, appropriately spaced electrodes, and 1 Ω resistor. The variable resistor is used to adjust the charging time, and the 1 Ω resistor is used to measure the arc current. When the capacitor bank is charged by the power supply to a certain value of voltage, the charging circuit is manually switched to the discharging circuit. A digital oscilloscope HP 54645A records the voltage and current across the electrode pair during arcing. Since it has two channels, sampling all channels simultaneously at a maximum rate of 200 MSa/s with 1 M samples of memory depth per channel, the variation of the voltage and the current across the electrode pair can be observed with high precision.

2.2 Test specimens
The contacts are mounted horizontally and isolated from the body of the tester, with the cathode at the left and the anode at the right, as shown in Fig. 1. The cathode is an iron needle to confine the erosion of anodes to a small designed area. The anode specimen is made of pure silver. The size and the shape of the electrode specimens are shown in Fig. 3. All experiments are conducted in a common laboratory atmosphere. Before each experiment, the anode specimen is polished with grade 400, 1000, 1500, and 2000 emery papers in order, and then with alumina slurry, so that its surface roughness $R_a$ is about 0.01 μm or $R_{\text{max}}$ of 0.05 μm.

2.3 Experimental procedure
Before each test, the electrodes are cleaned with acetone in ultrasonic cleaner. The anode is fixed at the jig of the 1st micrometer head, and the cathode is fixed at the stand through an insulator. When the anode comes into contact with the cathode slightly with the graduation of 0.025 μm, a digital multi-meter also monitors the contact condition between the electrodes. Generally, when the anode do not contact the cathode, the contact resistance achieves infinity. Hence, if the contact resistance is in the range of 10 to 30Ω, then the gap distance between electrodes is assumed to be zero. Moreover, to eliminate the effect of the backlash of micrometer head on the precision of the gap distance between the electrodes, an analog mu-checker with a graduation of 0.1 μm is employed to calibrate it.

When the gap distance has been adjusted to a certain value, the supply voltage is preset from 40 V to 500V through a DC power supply. The test parameters used are 0.1-40 μm gap distance at increments of 0.1 μm. When the gap distance is adjusted to a certain value, turn the switch on to supply a certain value of voltage. During the test, the digital oscilloscope and the data acquisition system record the waveforms for the interface voltage and current between electrodes. The eroded area can be calculated by using a powerful software program on the photomicrograph of the scanning electronic microscope. The experiments are limited to contacts in atmospheric air. The average room temperature for the test is 25°C and the average relative humidity is 85%.

3.EXPERIMENTAL RESULTS AND DISCUSSION
3.1 Arc discharge diagram
In this experiment, a digitizing oscilloscope records the voltage and the current across the electrode pair. Since it has two channels, sampling all channels simultaneously at a maximum rate of 200 MSa/s with 1 M samples of memory depth per channel, the variation of the voltage and
the current across the electrode pair can be observed in detail. Fig. 4 shows the typical waveforms of voltage and current during arcing across the electrode pair. It has been known that the short arc occurs when the gap distance between the electrodes is in the sub-micron range in low voltage systems.

![Typical voltage and current waveforms of various arc discharges](image)

Fig. 4 Typical voltage and current waveforms of various arc discharges.

(a) Supply voltage of 40 V and gap distance of 0.2 µm.

(b) Supply voltage of 500 V and gap distance of 0.2 µm.

The electric field at arc initiation is of the order of $10^6$ V/cm. Figure 4(a) shows the voltage and current waveforms across the electrode at the gap distance of 0.2 µm and the supply voltage of 40 V. The electric field strength in this case is $2 \times 10^6$ V/cm. This value is enough to initiate an arc. In this experiment, the capacitor bank is charged by the power supply to a certain value of voltage, and then it discharges in fixed spaced electrodes. Since the electric field strength is enough to initiate the arc, the current starts from zero and increases to a peak value $I_p$ of 7 amperes during the single-arc discharge period. During this period, the voltage across the electrode pair decreases from the breakdown voltage $V_b$ (about 20 V) to the residual voltage $V_r$ until the end of arcing. This residual voltage results from the residual electrical charge in the capacitor bank when the arc is expired. The arc duration in this experiment is about 5.8 µs. It has been found by Boyle and Germer [12] that the anode crater grows very slowly for the arc duration below the microsecond range. Hence, in this study, the capacitance in the capacitor bank is given a constant of 0.94 µF. This case is a typical result for small gap distance and low supply voltage. Contrary to this case, Fig. 4(b) shows a similar result for bigger gap distance and higher supply voltage. It is seen from this figure that the voltage across the electrode pair suddenly drops from the breakdown voltage $V_b$ (about 260 V) to a negative value of residual voltage $V_r$ until the end of arcing. It is seen from Figs. 4(a) and (b) that this residual voltage can be positive or negative value. Hence, the residual voltage is influenced not only by the capacitor bank, but also by the test conditions.

![Boundary between the arcing and no-arcing regions](image)

Fig. 5 Boundary between the arcing and no-arcing regions in terms of the supply voltage and the gap distance.

Since the air between an electrode pair possesses high resistance at a certain gap distance, the current does not start to flow until the breakdown voltage is achieved. Hence, at a certain supply voltage and a certain gap distance, the arcing effect on the electrodes can be easily distinguished by observing the voltage and current waveforms across the electrode pair. Moreover, the scanning electron photomicrographs can also be used to certify the eroded surface. Fig. 5 shows the boundary between the arcing and no-arcing regions under a wide range of supply voltage and gap distance. It is seen from this arc discharge diagram that as the gap distance is less than 2.5 µm, the critical supply voltage between the arcing and no-arcing regions is linearly proportional to the gap distance with the slope of 70 V/µm. It was indicated by Germer [2] that the slope is of order of 500 V/µm for clean or inactive surface, and it is of the order of 60 V/µm for active surface. Hence, at gap distance less than 2.5 µm, the slope or the minimum electrical field strength at arc initiation obtained in this study is in the range between active and inactive surfaces obtained by Germer [2]. Contrarily, when the gap distance is greater than 2.5 µm, the critical supply voltage is gradually increased with increasing gap distance. This critical supply voltage, $V_c(V)$, for the gap distance greater than 2.5 µm expressed in term of gap distance $d(\mu m)$ is given by

$$V_c = 120 \ln[d] + 62$$

Hence, it is seen from Fig. 5 that at the small gap distance, the arcing phenomenon is dominated by the gap distance,
while it is significantly influenced by the supply voltage at the bigger gap distance. The air breakdown occurs at 70 V/µm up to 175 V at 10 µm at 330 V, and 40 µm at 500 V.

3.2 Arc discharge behavior on the interface

Fig. 6 shows the effects of supply voltage and gap distance on the residual voltage. It is seen from this figure that the residual voltage is zero for the supply voltage close to 200 V. When the supply voltage is less than 200 V, the residual voltage keeps positive value, and it decreases with increasing supply voltage and gap distance. When the supply voltage is greater than 200 V, the residual voltage becomes negative and its absolute value decreases with increasing supply voltage and gap distance. Hence, the residual voltage is influenced not only by the capacitor bank, but also by the arc discharge behavior. When the residual voltage is zero, it implies that all the energy in the capacitor bank is released into the arc energy. As the residual voltage is positive, it implies that part of energy in the capacitor bank is released into the arc energy. These cases occur at lower supply voltage (below 200 V) and small gap distance (below 2.5 µm). Generally, the gap distance becomes bigger during the arc duration. As a result, the energy in the capacitor bank can not completely be released into the arc energy due to the bigger gap distance during the arcing. Hence, the residual voltage is always positive at smaller gap distance and lower supply voltage. As the residual voltage is negative, it implies that not only all the energy in the capacitor bank is released into the arc energy, but also the interface between the electrodes produces the opposite voltage. This phenomenon occurs at high supply voltage (larger than 200 V), and it can be explained by the particle sputtering-depositing model [6]. It is seen from this model that the negative residual voltage results from the metallic phase arc. In the metallic phase, electrons emit from the cathode to the anode due to the electrical field. During the process, the metal vapor is ionized by electron bombardment, resulting in the formation of metallic ions and new electrons. The metallic ions impact in the cathode, and then deposit on the cathode due to the electrical field and the higher cohesive ability between the ionized metal vapor particles and the cathode. As a result, a lot of positive metallic ions accumulate on the cathode. Furthermore, all the energy in the capacitor bank has been released into the arc energy. Consequently, the residual voltage becomes negative due to metallic ions accumulated on the cathode. At the same time, this voltage is not enough to initiate the arc due to the bigger gap.

![Fig. 6 Effects of supply voltage and gap distance on residual voltage.](image)

![Fig. 7 Effects of supply voltage and gap distance on arc discharge energy.](image)

3.3 Erosion area on the surface of silver electrode

It is very difficult to measure precisely the variation of gap distance, pip area on the iron needle, and the crater depth on the cathode after each test. Moreover, it has been found by Wang et al. [10] that the ratio of the crater diameter to the crater depth is greater than 10 under the
supply voltage of 1000 V. This indicates that the erosion craters are shallow. Hence, in this paper, only the crater area on the eroded anode is calculated by using a powerful software program.

Figure 8 shows the relationship between the erosion area and the gap distance at various supply voltages. It is seen from this figure that at the supply voltage less than 200 V, the erosion area is linearly increased with increasing the gap distance, but the relationship between the erosion area and the gap distance becomes parabolic at the supply voltage larger than 200 V. At gap distance below 5 \( \mu \text{m} \), the erosion area increases with increasing arc energy, but it decreases with increasing arc energy at gap distance beyond 5 \( \mu \text{m} \) due to the increase in the amount of gaseous phase arc.

4. CONCLUSIONS

The effects of supply voltage and gap distance on the arc erosion behavior of silver electrical contact by using a static-gap electrical erosion tester with a single arc discharge. From the experimental results, the following conclusions can be drawn.

1. The boundary between the arcing and no-arcing regions has been obtained at supply voltage (up to 500 V) and gap distance (up to 40 \( \mu \text{m} \) with the increment of 0.1 \( \mu \text{m} \)). The minimum supply voltage, \( V_s \), at arc initiation expressed in term of gap distance \( d(\mu \text{m}) \) is given by

\[
V_s = \begin{cases} 
70d & \text{for } \ d \leq 2.5 \mu \text{m} \\
120\ln(d) + 62 & \text{for } \ 40 \mu \text{m} \geq d \geq 2.5 \mu \text{m}.
\end{cases}
\]

2. The residual voltages is always positive at smaller gap distance and lower supply voltage because the energy in the capacitor bank can not completely be released into the arc energy. The negative residual voltage occurs at supply voltage larger than 200 V due to the action of the metallic phase arc. This negative residual voltage is caused by positive metallic ions accumulated on the cathode, it can be explained by the particle sputtering-depositing model [11].

3. At the supply voltage less than 200 V, the erosion area is linearly increased with increasing the gap distance, but the relationship between the erosion area and the gap distance becomes parabolic at the supply voltage larger than 200 V. At gap distance below 5 \( \mu \text{m} \), the erosion area increases with increasing arc energy, but it decreases with increasing arc energy at gap distance beyond 5 \( \mu \text{m} \) due to the increase in the amount of gaseous phase arc.

References


