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Arc extinction characteristics in power supply frequencies from 50 Hz to 1 MHz

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Abstract. It is well-known that arcing phenomena at the break of contacts affect seriously the reliability and lifetime of contacts. Therefore, many papers have reported arc duration, arc extinction current and other characteristics. Recently, in mobile communication application an electro-mechanical switch is said to be superior to a semiconductor switch in insertion loss and isolation, and a RF (radio frequency) MEMS relay has been intensively developed. Based on the above background it is one of important research topics how the frequency of interrupted current affects the characteristics of breaking arc. However, there are few papers on that topic. In this paper the effect of frequency on arc characteristics is investigated in range of the frequency of interrupted current from 50 Hz to 1 MHz. Consequently the followings can be made clear. At the interruption of peak current 2 A arc extinguishes in terms of arc characteristics and circuit conditions up to the frequency of 200 Hz. Above 200 Hz the arc extinguishes at current zero. The current zero extinction takes place up to 500 kHz. Therefore, arc duration decreases with high frequencies and the contact damage caused by arc is reduced with frequency. However, at frequencies higher than 600 kHz an arc is re-ignited after the current zero and failed to extinguish.

1 Introduction

The movement to high frequency is strong in communication systems. But semiconductors used in such systems are known to have various problems in high frequency. Certainly, the switching speed is fast as one of good characteristics of GaAs semiconductors but they have problems in power consumption [1], isolation and insertion loss that are important RF characteristics.

Consequently electro-mechanical switches have begun to attract attention now. It is expected to bring the good characteristics of insertion loss and isolation in high frequency. Mechanical contacts have especially good isolation because they can be separated by air layer. However in switching between the electric contacts, the arc discharge is a problem because it damages and influences contact performance greatly. So many research works have been done from various aspects for the reliability improvement and long contact lifetime. But arc characteristics in high frequency are not necessarily clear [2].

So the authors have studied breaking arc characteristics in various power supply frequencies [3]. Further, the damage to contacts given by arc is reported from the viewpoint of arc duration and gap length.

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2 Experimental procedure

2.1 Measurement of arc duration

A current value is usually changed every switching in ac. So in our setup, contact break takes place when the current reaches the peak value. The break timing of the tested switch S_L is controlled by the switch S_T as shown in Figure 1, where a relay used as tested contacts (S_L) is shown in Figure 2.

Load currents with variable frequencies are supplied by a function generator and amplifier in the range of 50 Hz up to 1 MHz. “1 MHz” is a performance limitation of the amplifier. Experimental conditions are shown in Table 1.

In the experiment, waveforms of the arc voltage and current were measured with an oscilloscope. These waveforms were measured five times at each frequency.

2.2 Surface observation of contacts

In order to examine the difference due to frequency, the surfaces of contacts after a long operation test are compared at 100 Hz, 1 kHz, 10 kHz, 50 kHz, 100 kHz, 500 kHz and 1 MHz. The experiment was performed by using the same relay as shown in Figure 2. And the relay driving circuit was made as shown in Figure 3. The frequency of the driving circuit is 11 Hz.

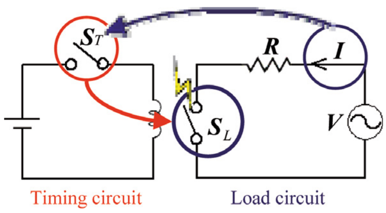
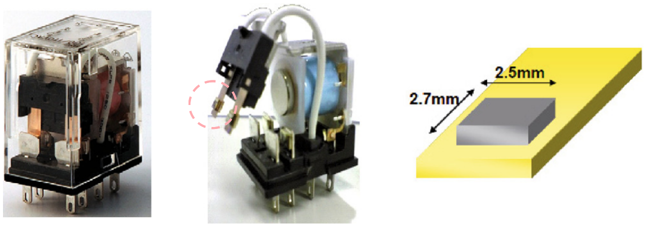


Fig. 1. (Color online) Model of measurement.



(a) Overview image of relay (b) Movable contact [observation point] (c) Contact part [closeup the part ◌ in(b)]

Fig. 2. (Color online) Relay used in this experiment.

Table 1. Experimental conditions.

contact material	Ag
peak current	2 A
supply peak voltage	40 V
load circuit	resistive load
surrounding atmosphere	laboratory

The tested relay is switched about 500 000 times. During the test arc voltage and current were measured. Contact surfaces were observed before and after the test.

2.3 The measurement of separating speed

In considering arcing phenomena, a separating speed is one of the most important parameters. That is because arc duration is dependent on it. So the separating speed was measured to obtain the gap length when arc extinguishes.

The displacement sensor is one of the laser beam optical sensors (Fig. 4). The movement of the movable contact was measured. The result is shown as the curved line of Figure 5. Another waveform of Figure 5 is a voltage between contacts connected with 2.0 V voltage source. So, the time when the voltage suddenly rises shows actual contact break.

3 Results and discussion

3.1 Arc duration and T/4

A typical arc behavior obtained by the experimental procedure is shown in Figure 6. The voltage rises up to arc voltage around $t = 0$. And it can be seen that the load current is interrupted at its peak value of 2 A. Further, the phase between voltage and current is not shifted due

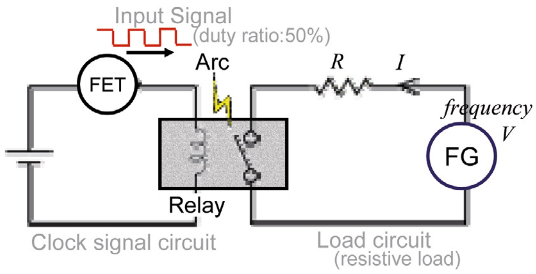


Fig. 3. (Color online) Experimental apparatus of the switching experiment.

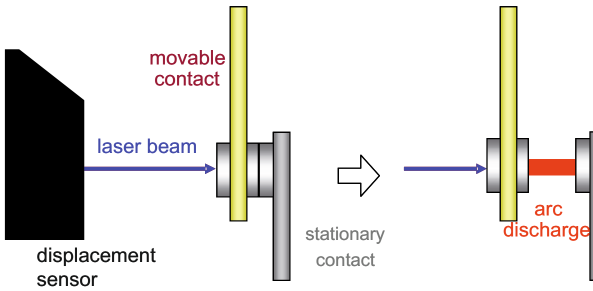


Fig. 4. (Color online) Measurement of separating speed (Left: ON state, Right: OFF state).

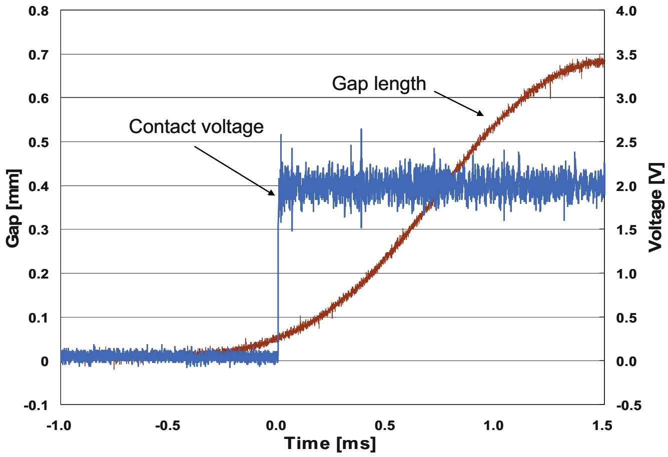


Fig. 5. (Color online) Gap length and voltage between contacts at dc power.

to a resistive load. From arc voltage waveform at each frequency like Figure 6, the arc duration can be obtained.

Arc generally extinguishes when the current becomes zero in a half cycle in ac. The load current is interrupted at its peak value in this experiment. In other words, arc starts to ignite at peak current and should extinguish at current zero. In case of a resistive circuit, a voltage equation during arc ignition is as follows:

$$Ri_a + v_a = e(t), \tag{1}$$

where R: circuit resistance, i_a: arc current, v_a: arc voltage and $e(t)$: source voltage.

In our test circuit condition, $R = 20\ \Omega$ and $e(t) = 40 \cos \omega t$, because voltage or current is the maximum

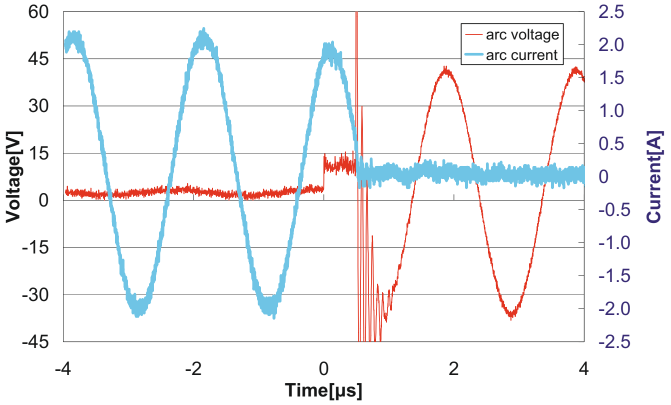


Fig. 6. (Color online) Arc behavior at 500 kHz.

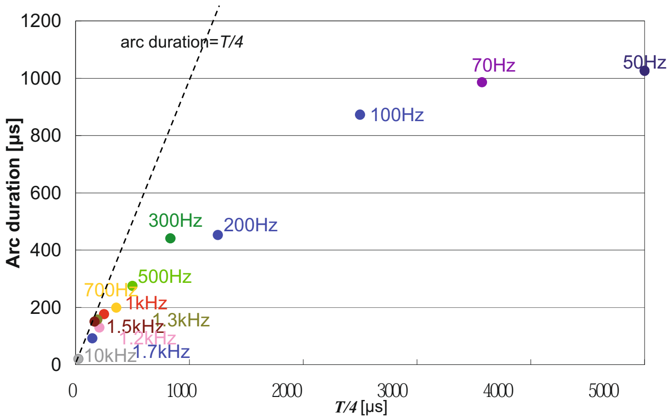


Fig. 7. (Color online) Relationship between arc duration and $T/4$ [from 50 Hz to 10 kHz].

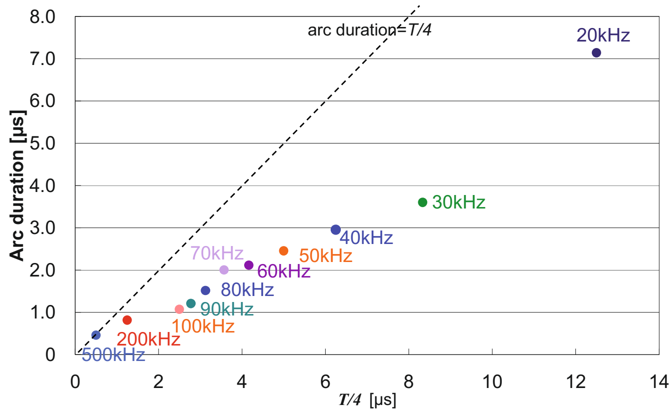


Fig. 8. (Color online) Relationship between arc duration and $T/4$ [from 20 kHz to 500 kHz].

value at break of contacts by using a switch timing control system.

If the arc voltage is zero, the arc current will be zero at $\omega t = \pi/2$, that is, $t = T/4$, where T is a period of the ac source voltage.

It means that the arc duration is $T/4$ at maximum, if no arc re-ignition occurs. So, $T/4$ is used as a parameter of arc duration.

Figure 7 is the relationship between arc duration and $T/4$ from 50 Hz to 10 kHz. The dotted line in Figure 7 shows that arc duration is equal to $T/4$. It can be seen that the behaviors from 50 Hz to 200 Hz are different from ones over 300 Hz and that the arc duration is much shorter than $T/4$. It means that the arc extinction does not take place at current zero. The gap length at arc extinction is large at low frequencies up to 200 Hz due to long arc duration. Therefore arc extinction is decided in terms of arc characteristics and circuit conditions at such low frequencies.

Figure 8 shows the relationship between arc duration and $T/4$ at from 20 kHz to 500 kHz. It is found that the arc duration is shorter than $T/4$, but the arc seems to extinguishes around the current zero in the frequency of this range until 500 kHz. In other words, the arc duration decreases inversely with higher frequencies even when the same current is interrupted. Consequently, it is expected that the contact damage caused by arc is reduced with frequency increase.

3.2 Re-ignition

But another phenomenon comes out when the frequency increases further. At high frequency, the interval that the current decreases from peak to zero is so short that the arc duration also becomes small. But this means that the voltage can re-build up from zero to next peak rapidly. Generally speaking, after arc extinction residual plasma exists in the contact gap. In this case, it is well-known that arc discharge easily ignites again when the voltage is supplied. In addition, it is known that residual plasma exists more at high frequency than in low frequency [4]. In the low frequency, the plasma density is reduced with the current decrease, but in high frequencies it becomes hard to follow the current change. Due to these two conditions, in high frequency the arc is supposed to fail to extinguish at the current zero and continue for several periods without extinction.

Therefore the experiment on whether re-ignition happens was conducted. Frequency increases from 500 kHz up to 1 MHz. When the frequency is higher than 500 kHz, the arc duration comes to exceed $T/4$ as shown in Figure 9. As was expected, arc which has longer duration than one cycle is observed as shown in Figure 10. Figure 10 shows the waveform when re-ignition happens at 1 MHz. In spite of the experiment at 1 MHz, the arc duration is almost the same at 80 kHz. It can be made clear that the re-ignition is observed at higher than 500 kHz. It maybe indicates that the re-ignition will cause more damage to contact by arc in higher frequencies than 600 kHz.

3.3 Surface observation of the contacts with optical microscope and SEM

From experimental results of arc duration at various frequencies, it was investigated whether the damage to contacts caused by arc becomes less in higher frequency or

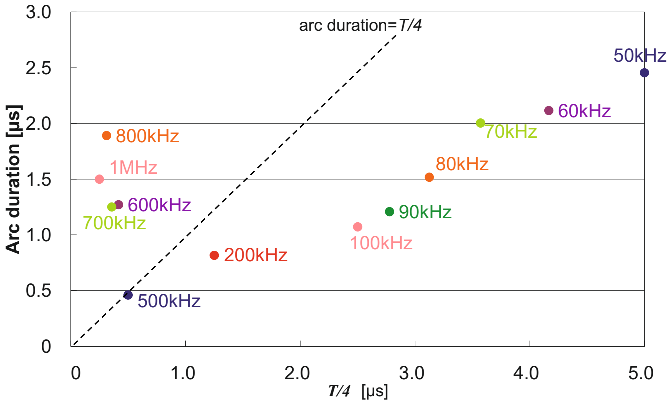


Fig. 9. (Color online) Relationship between arc duration and $T/4$ (from 50 kHz to 1 MHz).

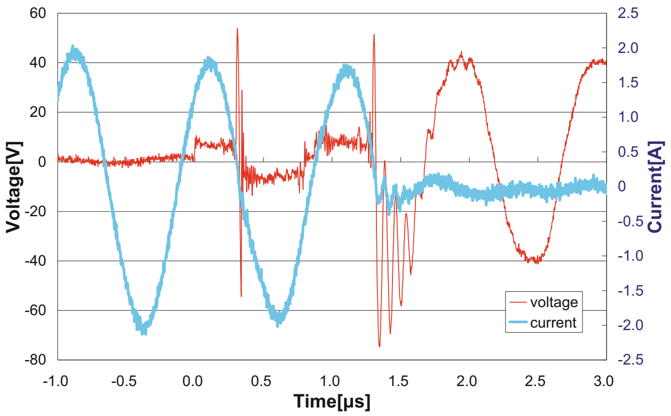


Fig. 10. (Color online) Re-ignition waveform at 1 MHz.

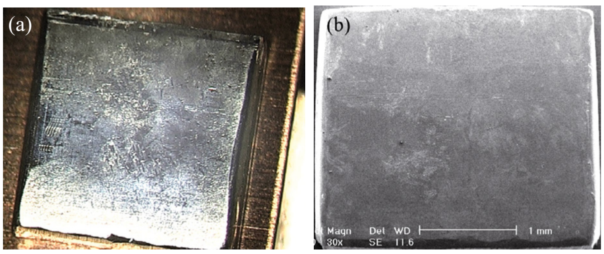


Fig. 11. (Color online) Surfaces of contact before experiment. (a) Optical microscope, (b) SEM.

not and what is the influence of re-ignition. Then surfaces of contacts were observed after 500 000 operations.

The surface morphologies of contact in 100 Hz, 1 kHz, 10 kHz, 50 kHz, 100 kHz 500 kHz and 1 MHz are compared before and after the experiment. A relay has stationary and movable contacts but its anode and cathode are switched in ac. Therefore their damage is almost same, and so movable contact shown in Figure 2b is observed with an optical microscope and SEM.

Figure 11 shows the surface before the experiments. Figures 12–18 are all results of surface observation of contacts. Damage by arc discharge can be seen on these contacts. Their details are explained as follows.

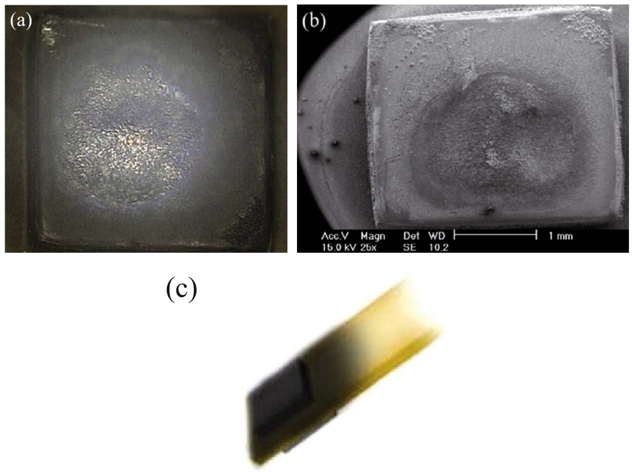


Fig. 12. (Color online) Surface observation of contact at 100 Hz. (a) Optical microscope [zoom:75], (b) SEM, (c) image of contact and its electrode support.

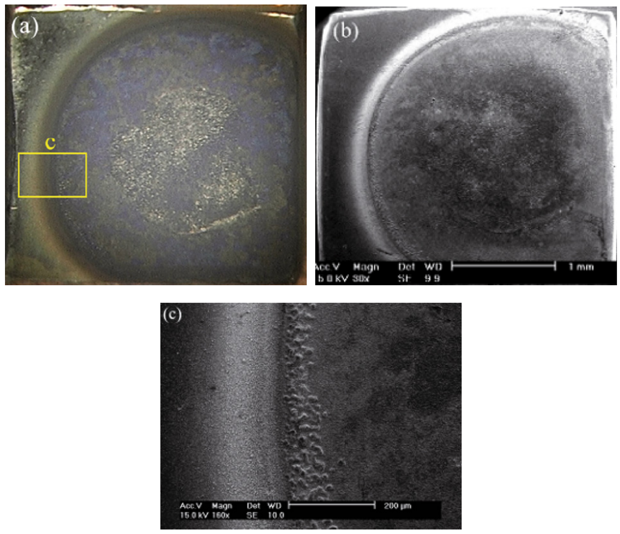


Fig. 13. (Color online) Surface observation of contact at 1 kHz. (a) Optical microscope [zoom:75], (b) SEM, (c) magnified view of square of (a).

At 100 Hz, the whole surface of contact is black in color as shown in Figure 12a and damaged so seriously, but it can't be clear in details with an optical microscope. So the surfaces of contacts are observed by SEM, then we can see the most damaged part. And small particles produced by arc can be seen at the edge of contact in Figure 12b.

At 1 kHz, the black part becomes smaller than at 100 Hz as shown in Figure 13a. Figure 13c is a close-up of the part marked in Figure 13a. The products can be seen on the surroundings of contact because particles evaporated from the electrodes were deposited again on the surroundings. In other words, evaporated particles are easily scattered in lower frequencies. In this experiment, similar results are observed at both 100 Hz and 1 kHz.

However, in case of 10 kHz by comparison with the surfaces at 1 kHz of Figure 13a, the black part becomes smaller as shown in Figure 14a. The central part which

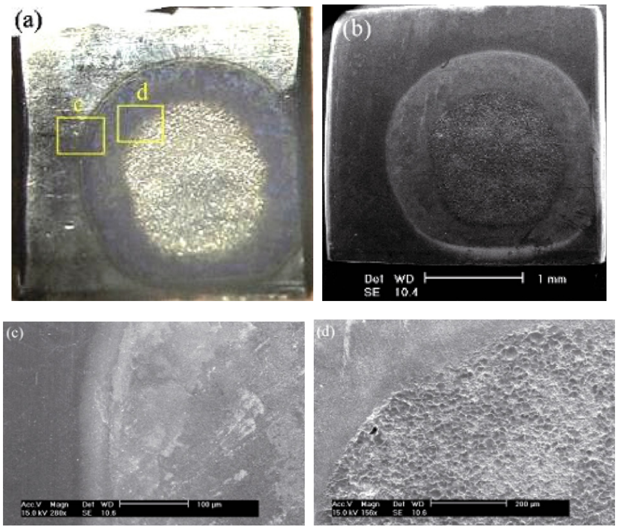


Fig. 14. (Color online) Surface observation of contact at 10 kHz. (a) Optical microscope [zoom:75], (b) SEM, (c, d) magnified view of square of (a).

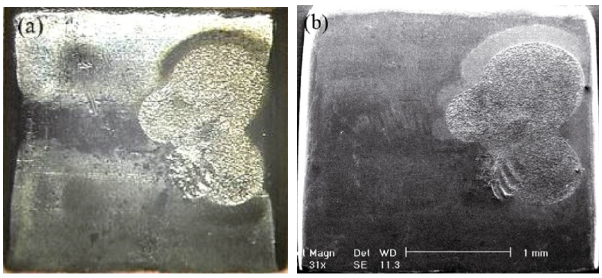


Fig. 15. (Color online) Surface observation of contact at 50 kHz. (a) Optical microscope [zoom:75], (b) SEM.

was eroded by the arc discharge is entirely black in color at 1 kHz. On the other hand the black part is observed only at the surroundings of the circular eroded part at 10 kHz. And the metallic luster can be seen at the central part of the surface eroded by arc as shown in Figure 14a. And Figure 14c taken by SEM is an enlarged image at the boundary of black part and almost original surface as shown in Figure 14a. Both parts are greatly different in color, but serious erosion is not seen on the surface. It means that this black part is not damaged directly by arc, but it seems to be oxidized. In Figure 14d which is boundary between black part and metallic luster part, we can see numerous arc traces clearly on the circular and inside part. Therefore the inside part is damaged directly by arc.

At the higher frequency of 50 kHz, the black part is not clearly seen any more, and the metallic luster part becomes a main part as shown in Figure 15. The eroded part has numerous small arc traces like the central glossy part in Figure 14a, but the surrounding black part is not clear unlike Figure 14a.

At 100 kHz, the black part which is observed until 50 kHz completely disappears from the contact surface as shown in Figure 16a. And the glossy part which is only

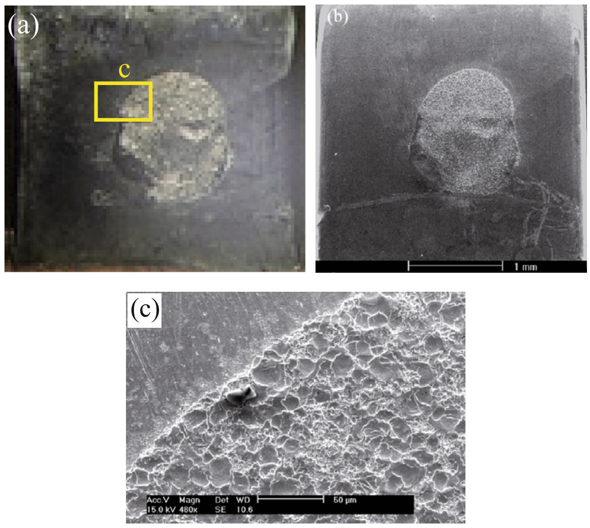


Fig. 16. (Color online) Surface observation of contact at 100 kHz. (a) Optical microscope [zoom:75], (b) SEM, (c) magnified view of square of (a).

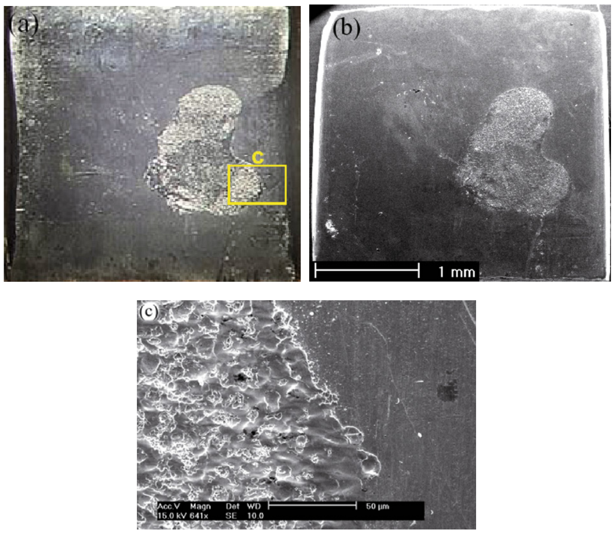


Fig. 17. (Color online) Surface observation of contact at 500 kHz. (a) Optical microscope [zoom:75], (b) SEM, (c) magnified view of square of (a).

seen on the damaged surface is eroded directly by arc as shown in Figure 16c. Figure 17 at 500 kHz shows a similar result as that at 100 kHz. It can be seen that the depth of arc trace is shallower than at 100 kHz. But this may depend on the magnified part.

From the above results, damage on the contact by arc is decreased at higher frequencies. At higher frequencies than 100 kHz, the oxidized black part disappears. This is because the oxidation effect by the electrical discharge would change into the cleaning effect that makes the eroded surface shiny at high frequencies. From these results, it becomes clear that the oxidation or cleaning effect by arc is changed at the frequency between 50 kHz and 100 kHz.

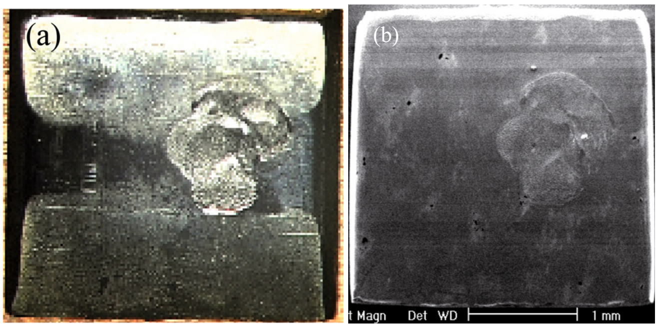


Fig. 18. (Color online) Surface observation of contact at 1 MHz. (a) Optical microscope [zoom:75], (b) SEM.

Table 2. Gap length in experimented frequencies.

Frequency	Arc duration	Gap length
100 Hz	1772 μs	0.34 mm
1 kHz	198 μs	0.05 mm
10 kHz	22.5 μs	6.0 μm
50 kHz	3.38 μs	2.0 μm
100 kHz	1.58 μs	<2.0 μm
500 kHz	0.36 μs	<2.0 μm
1 MHz	1.25 μs	<2.0 μm

Finally, at 1 MHz where the re-ignition is found to happen form the result of Section 3.2 the eroded surface is also observed. Through the test at 1 MHz, the re-ignition doesn't happen sometimes, but the re-ignition is observed at almost all switching. The results are shown in Figure 18.

On the surface the black part is not seen and only the metallic shiny part can be observed. Re-ignition happens but its arc duration at 1 MHz (1.25 μs) is shorter than 3.38 μs at the boundary frequency of black part appearance, 50 kHz and close to 1.58 μs at 100 kHz as shown in Table 2. So, re-ignition doesn't make the arc duration so longer to cause oxidation effect. Therefore it can be said that the influence of the re-ignition on the contact damage is not significant in this test.

3.4 Evaluation of eroded part

From the observed surfaces of the contact, the ratio of contact area of black part or metallic shiny part to the whole contact surface is evaluated. The whole contact surface is subdivided to 500 μm square elements, and then the elements of black oxidized part or metallic shiny part are counted and the area is obtained. Figure 19 shows the proportion of both damaged parts by arc to whole contact area. And in Figure 19 "100% or more" at 100 Hz means that the damage by arc expands beyond the whole contact surface as shown in Figure 12c.

From Figure 19, it can be seen that the black part becomes smaller with the frequency increase. From the viewpoint of contact resistance, black oxidized part is not good but the metallic shiny part doesn't affect the contact resistance greatly. On the boundary between 50 kHz and 100 kHz, the oxidation effect will disappear. Beyond 100 kHz only metallic shiny part is observed, but the eroded area is almost same at both 500 kHz and 1 MHz.

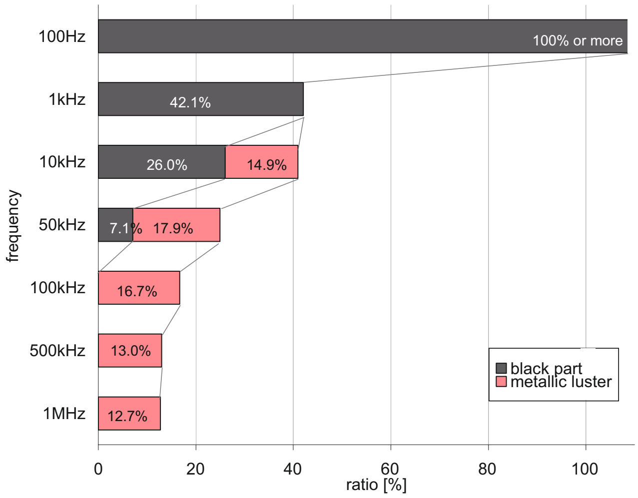


Fig. 19. (Color online) Proportion of the damage by arc to whole contact area.

The above results are only the surface observation, and the evaluation for the depth direction is not done. A result different from Figure 19 might be obtained from the observation of the depth direction, but it is a future subject.

3.5 Gap length at arc extinction

According to the separating speed obtained in the Section 2.3, each gap length when the arc extinguished at 100 Hz, 1 kHz, 10 kHz and 50 kHz was obtained as shown in Table 2. However, the gap length at frequencies higher than 50 kHz cannot be measured, because the resolution of the sensor is 2 μm and the extinction gap is smaller than the resolution at higher frequencies.

In Ag contacts, it is said that the anode arc occurs at the gap length smaller than 3–4 μm [5]. According to Table 2, this critical value of the gap length exists between 10 kHz and 50 kHz. This boundary value is almost the same with the boundary frequency between the oxidation and the cleaning effect. In other words, two kinds of arc, cathode and anode arc seem to make the effect on the contact surface different.

4 Conclusions

Compared with dc arc, arc extinction characteristics are not clear in ac, especially at high frequencies. Therefore, breaking arc characteristics in various power supply frequencies have been examined. The effect of frequency on arc characteristics in the range of 50 Hz to 1 MHz is investigated at the peak value 2 A of interrupted current and the followings can be made clear:

- arc extinction is mainly due to the current zero at higher frequencies than 300 Hz;
- over 500 kHz arc re-ignition happens, and arc duration becomes longer again;
- at frequencies lower than 50 kHz the contact surface is mainly black in color, but at higher frequencies the black part disappear and the eroded part shows metallic luster;
- contact damage by arc is reduced with frequency increase. It seems to be related to the fact that the arc changes cathode arc to anode arc at the frequency between 10 and 50 kHz;
- from the surface observation the re-ignition does not causes serious erosion, because the arc duration including the re-ignition is shorter than that at 50 kHz.

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