

Broken Mechanism of Straight Copper Wires near Terminal due to Lightning High Impulse Current

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abstract

When a lightning current flows through a copper wire, the copper wire would be broken at the terminal affected by electro-magnetic force. A straight thin copper wire such as $0.1\text{mm}\Phi$ is melted due to the specific melting Joule integral: $(j^2t)_m$ in an adiabatic condition. However, in these experiments it has been recognized that the thicker copper wires of $1\text{mm}\Phi$ are not completely melted, but sheared mainly at the connecting terminal by a relatively low impulse current. Therefore, electro-magnetic mechanical shearing stress, etc. are discussed adding to the ordinary Joule heating. New broken mechanisms were presumed and proved in additional experiments.

1 Introduction

It is heard that straight lightning rods are frequently curved by a lightning current in the winter of Hokuriku district in Japan. So we designed the experiments to research these phenomena. In the experiments the current was passed through copper wires and the damage, curve, broken situations of copper wires were analyzed theoretically and experimentally[2][3]. Ordinarily, copper wires from $0.1\text{mm}\Phi$ to $1.0\text{mm}\Phi$ class are melted by the impulse current according to the specific pre-arcing Joule Integral (in an adiabatic state). Furthermore, they are melted by the Direct Current (DC) according to the Joule heating and stable heat transfer from the surface to surroundings atmosphere[1][6]. In this paper, straight copper wires from $0.1\text{mm}\Phi$ to $1.0\text{mm}\Phi$ class were electrified by the lightning impulse current and the experimental broken values were examined, they were clearly lower than the theoretical values which are calculated from the specific pre-arcing Joule integral, so electro-magnetic mechanical shearing stress, etc. were discussed adding to the ordinary Joule heating.

2 Experimental conditions

The experimental circuit is shown in Fig. 1. Annealed copper wires of JIS C-3102 were used. The effective length is $Le = 1\text{m}$ and the diameter is $D = 0.25 \sim 1.4\text{mm}$. Both ends of the copper wire were fixed in electrodes of copper plates in perpendicular direction to the earth ground. The terminal voltage $V_c(t)$ is measured by a single-ended High Voltage Probe. The shunt resistance is $R_i = 2.7\text{m}\Omega$, and the magnification of a divider voltage is $1/4,000$. The broken situations and arc were captured by a still camera (SC). The terminal voltage $V_c(t)$ across the copper wire and current wave shape $i(t)$ were recorded by an oscilloscope(OS). The current wave shape with peak value I_p is described as $8/22\mu\text{s}$. The input impulse current and voltage waveform are shown in Fig. 2. Since the voltage measuring leads were only fixed in electrodes, only the terminal voltage was measured.

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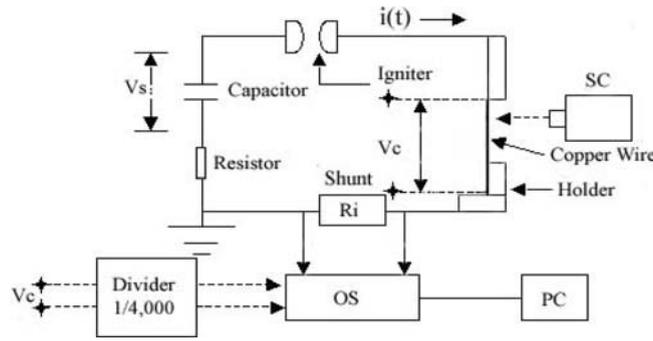


Fig. 1 Experimental circuit

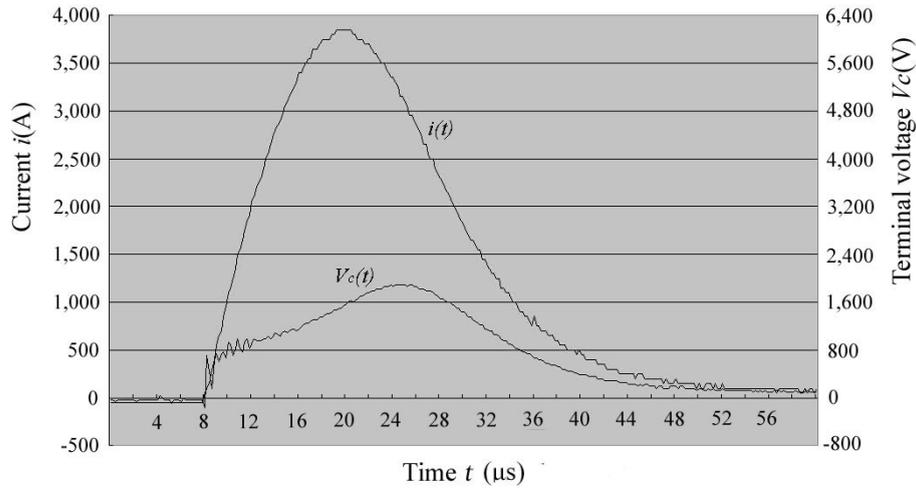


Fig. 2 Input impulse current & terminal voltage ($D = 0.25 \text{ mm}$, $L_e = 1 \text{ m}$)

3 Calculations of broken straight copper wires by impulse high current

When the straight copper wires are passed by impulse current, the theoretical value of minimum melting current is given[5]. Specific pre-arcing melting Joule integral $(j^2t)_m$ of copper and melting diameter D_m are shown in Table 1.

Table 1 Calculated specific pre-arcing melting Joule integral $(j^2t)_m$ of copper & maximum melting diameter D_m

Material	Melting Temp. T_m [°C]	Specific pre-arcing Joule integral $(j^2t)_m$ ($\text{A}^2\text{s}/\text{m}^4$)	Expected maximum melting diameter D_m [mm]	
			$I_p = 81 \text{ kA}$	$I_p = 159 \text{ kA}$
Cu	1,083	10.45×10^{16}	1.00	1.40

4 Experimental results of broken straight wires by impulse high current

4.1 Broken situation of copper wires

Figs. 3~6 show the photographs of the experimental devices and broken wires. As shown by arrows in Fig. 3(1), the wire was vertically fixed in electrodes. Both sides of the wire were fixed with a nut and washers. Fig. 3(2) shows the luminescence of the copper wires captured by the still camera

during the electrifying. It is considered that the luminescence comes from the occurred arc when the connections between the electrode and the wires are sheared by the electromagnetic force.

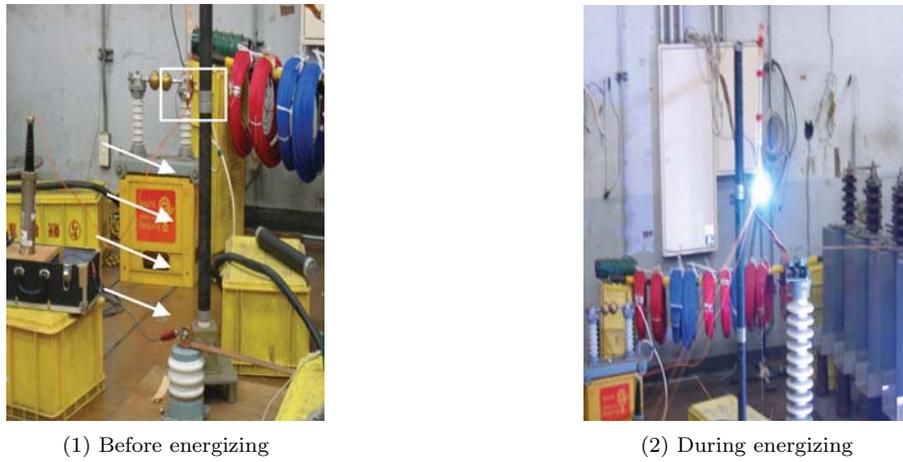


Fig.3 Situation of copper wires

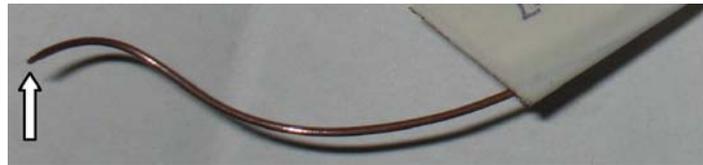


Fig. 4 Broken view of a copper wire of 0.8 mm in diameter



Fig. 5 Melted situation of a copper wire of 0.25 mm in diameter



Fig.6 Enlarged broken surfaces of wires (1.0 mm Φ)

When the copper wires of 0.25 mm Φ were passed by the lightning current, the whole wire momentarily became crimson then melted. As shown in Fig. 5, melted gem is formed along the copper wire. Basing on these melted gems, the thin wires of 0.25 mm Φ are regarded to be completely melted. The luminescence at the connecting terminal was not observed by visual check. However, for the copper wires of 0.4, 0.6, 0.8, and 1.0 mm Φ , the luminescence at the connecting terminal was observed by

visual check. And they were broken accompanying with loud sound. Fig. 4 shows the broken copper wire of 0.8 mm Φ . As shown by a white arrow in Fig. 4, this wire was broken only at the electrode. In fact they were almost straight except the broken part. Comparing the Fig. 4 with Fig. 5, it is presumed that the thin wires of 0.25 mm Φ are completely melted, whereas the thick wires of 0.8 mm Φ are not completely melted but broken at the electrode. As shown in the left of Fig. 6 the broken tip becomes thinner. It is considered that the temperature rises and the arc is formed. Right photograph of the Fig. 6 shows a new copper wire which is cut by pincers for the comparison.

4.2 Broken characteristic of straight copper wires

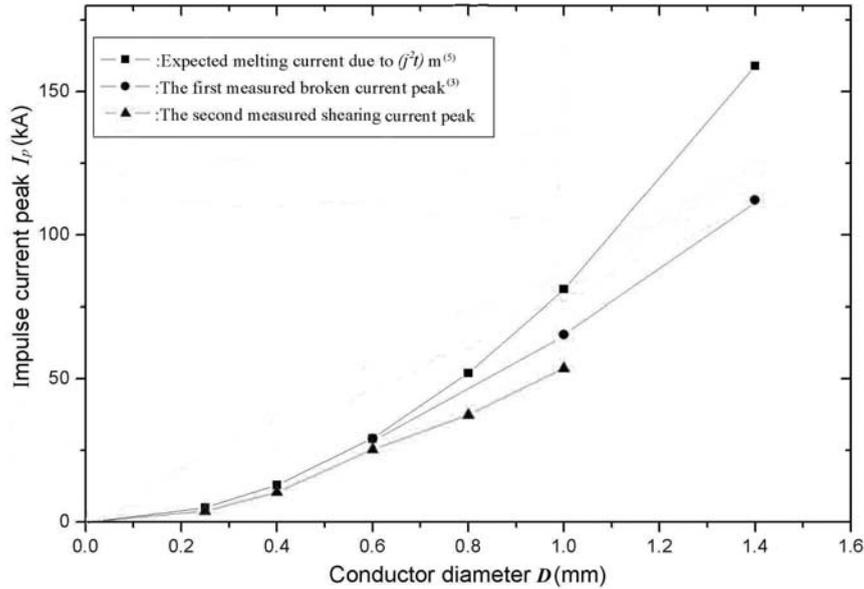


Fig. 7 Broken characteristics of straight Cu wire

Fig. 7 shows the measured broken current values and theoretical melting current values of 0.25 mm, 0.4 mm, 0.6 mm, 0.8 mm, 1.0 mm, and 1.4 mm Φ . The measured broken impulse current values of 0.25 mm, 0.4 mm Φ are almost same with the theoretical melting impulse current values expected from its $(j^2 t)_m$ respectively, however the measured broken impulse current values of 0.6 mm, 0.8 mm, 1.0 mm, and 1.4 mm Φ is clearly lower than the theoretical melting impulse current and the difference between measured broken impulse current values and theoretical melting impulse current values becomes larger and larger with the increase of the diameter. The theoretical melting current peak values of 0.25 mm, 0.4 mm, 0.6 mm, 0.8 mm, 1.0 mm, and 1.4 mm Φ are 5.0 kA, 13.1 kA, 29.2 kA, 52.0 kA, 81.1 kA, and 159.0 kA respectively. In the first former experiments which were made at an university of TUM, the measured broken impulse current peak values of 0.6 mm, 1.0 mm, and 1.4 mm Φ was 29.1 kA, 65.5 kA, and 112.1 kA respectively. And they are shown in Fig. 7 by the \bullet stamps. In the second present experiments which were made at Toko corporation, the measured broken impulse current peak values of 0.25 mm, 0.4 mm, 0.6 mm, 0.8 mm, and 1.0 mm Φ was 3.9 kA, 10.5 kA, 25.4 kA, 37.4 kA, and 53.7 kA respectively. And they are shown in Fig. 7 by the \blacktriangle line. The difference between first and second measured values is regarded as the result of the electro-magnetic force influence.

The straight copper wires of 0.25 mm and 0.4 mm Φ were shortened from 1.0 m to 0.51 m, then the broken experiments were made under the same conditions. The measured broken impulse current

values of 0.25 mm, 0.4 mm Φ in length of 0.51 m were 3.6 kA, 10.5 kA respectively. They were almost same with the 3.9 kA, 10.5 kA in length 1.0 m. The average difference is less than 4%. So the broken impulse current value of straight copper wires has no relationship with the length.

5 Theoretical analyses

5.1 Effect of fusion Joule

Because of the effect of the fusion Joule, the temperature of the copper wire rises to high, then the copper wire becomes solid-liquid mixture state, next the copper wire is melted. Mechanical expansion of the solid-liquid copper wire becomes an important factor to break the wire.

1) Uniform temperature distribution model along the axis

Because of the high thermal conductivity of the copper, temperature distribution in the radius direction of the wire becomes almost uniform when the Direct Current goes through. The radial temperature distribution in a copper wire at 1 atmospheric pressure and room temperature is calculated. The temperature difference between the center and the surface is less than 1°C.[4]

2) Temperature calculation of broken copper wires

As the electric specific resistance and the specific heat capacity of the copper has temperature-dependent property, Equations (1) and (2) are adopted.

$$R_T = \rho_0(1 + \alpha T + \zeta T^2)L/S \quad (1)$$

$$C_T = C_0(1 + \beta T + \eta T^2) \quad (2)$$

$$i_t^2 R_t dt = C_T m dT \quad (3)$$

where, i_t : Instantaneous impulse current value [A]

R_T : Instantaneous resistance of the copper wire at T (°C) [Ω]

C_T : Instantaneous specific heat capacity of the copper wire [J/(kg · °C)]

m : Mass of the copper wire [kg]

L : Length of the copper wire [m]

S : Cross sectional areas of the copper wire [m²]

ρ_0 : Copper specific resistance at 0°C [Ω m]

α : Coefficient of variation of resistance with temperature [K⁻¹]

ζ : Coefficient of variation of resistance with (temperature)² [K⁻²]

C_0 : Specific heat capacity at 0°C [J/(kg · °C)]

β : Coefficient of variation of specific heat capacity with temperature [K⁻¹]

η : Coefficient of variation of specific heat capacity with (temperature)² [K⁻²]

T : Temperature [°C]

t : Time [s]

By inserting equations (1)&(2) in formula (3), and integrating, then the relationship curve[5] between T and $\int_0^{t_2} J^2 dt$ with $t_1 = 0$ could be obtained, which is shown in Appendix 1. And equation (4) would be given by this relationship curve picture.

$$T = d \int_0^{t_2} J^2 dt + \varepsilon \left(\int_0^{t_2} J^2 dt \right)^g \quad (4)$$

where, $J = i_t/S$: Current density [A/m²], t_2 : Current duration time [s], and d , ε and g are constants[5]. When the temperature range is from 10–1000°C, d is $0.481 \times 10^{-14} \text{°Cm}^4/(\text{A}^2\text{s})$,

$$\varepsilon = 3.646 \times 10^{-36} \text{C}[\text{m}^4/(\text{A}^2\text{s})]^{2.25}, g = 2.25.$$

3) Energy calculation of 8/20 μs impulse lightning current:

$$\int_{t_1}^{t_2} J^2 dt (\text{A}^2\text{s}/\text{m}^4) = 11.31 \cdot I_p^2/S^2 \tag{5}$$

where, t_1 : Beginning time of applying the current [s], I_p : Peak value of current [A].

For the lightning stroke pulse, the specific pre-arcing Joule integral is defined as Equation (5). Using equations (4) and (5), the temperature of broken copper wires could be calculated. The calculated results are shown in Fig. 8. This figure shows that the highest temperature of broken copper wires becomes lower with the increase of diameter except the copper wires of 0.25 mm and 0.4 mmΦ.

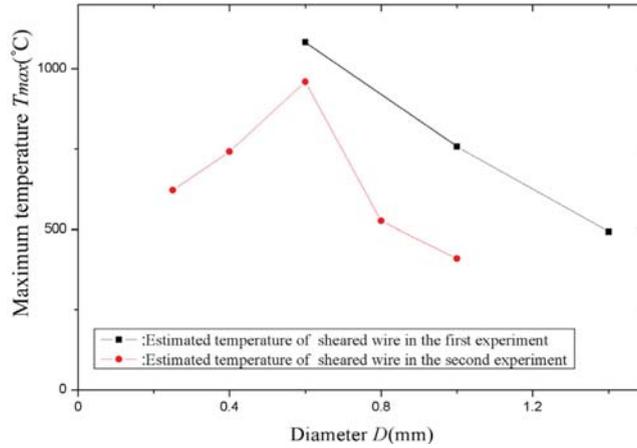


Fig. 8 Maximum temperature of straight copper wire

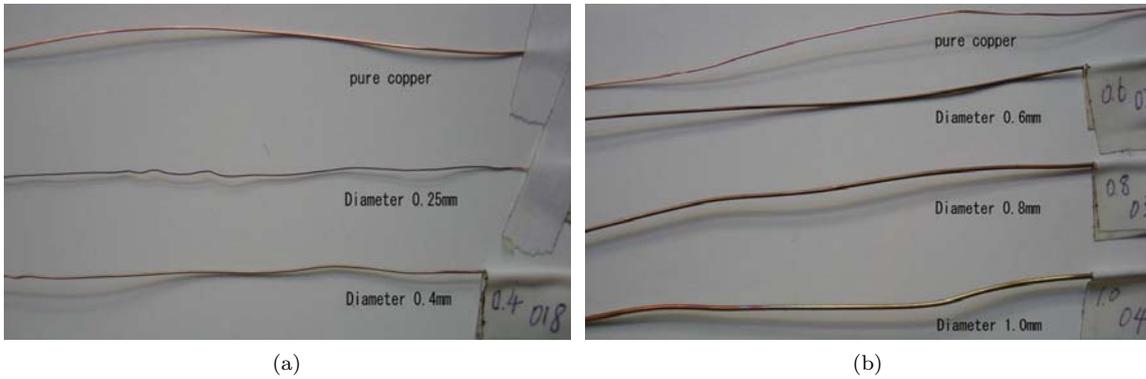
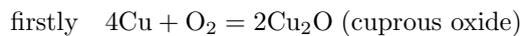


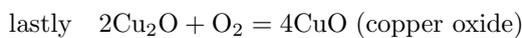
Fig.9 Color photographs of broken straight copper wires

4) Temperature analysis from experimental side

The copper is quickly oxidized under the conditions of high temperature and enough oxygen in the air. The oxidation process of copper is divided into two phases. Firstly cuprous oxide is formed. Then if the copper is completely oxidized, the copper oxide is formed. That is,



If the oxidation process continues,



The copper is so-called copper-color, the cuprous oxide is shaded red, and the copper oxide is completely black. From the oxidation processes it is known that if the temperature of the copper wire becomes higher, the oxidation degree becomes higher, so the color of broken copper wires becomes blacker. Reverse if the color of the wire is blacker we could presume that the oxidation degree would be higher and the temperature is higher. As shown in Fig. 9(b), the surface color of the broken copper wires of $0.6\text{ mm}\Phi$ and more lightens with the increase of the diameter. Thus, we could presume that the highest temperature of the broken wire of $0.6\text{ mm}\Phi$ and more becomes lower with the increase of diameter.

Thus, by the above-mentioned calculation results and the photographs it is admitted that the highest temperature of broken copper wires becomes lower with the increase of diameter over $0.6\text{ mm}\Phi$.

5.2 Electro-magnetic force

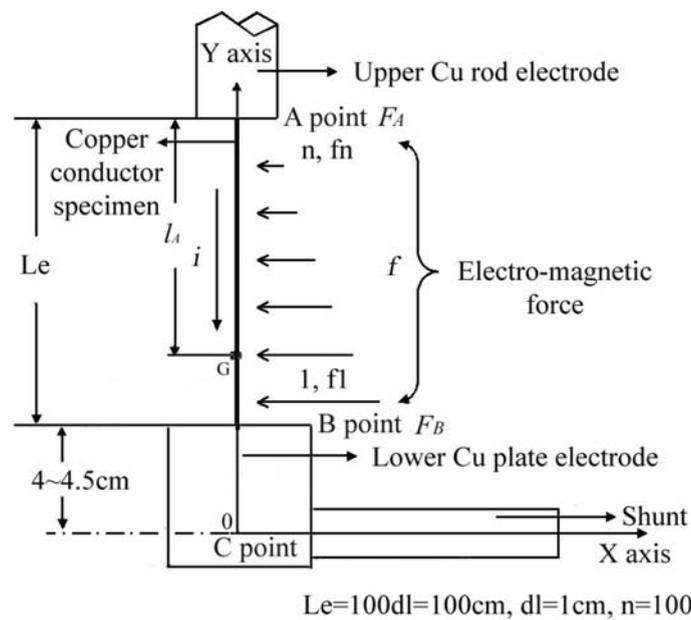


Fig. 10 Distribution of electro-magnetic force along wire

1) Calculation of electro-magnetic force

Fig. 10 shows the distribution of the electro-magnetic force along the straight copper wire. Because the current route bends squarely in the lower electrode, the magnetism of the copper wire is generated by this square part. And the electrode configuration is shown in Fig. 11. The copper wire system is converted into a mathematics model. When the lightning impulse current is at peak I_p , in a moment $di_t/dt = 0$, we use this peak value to calculate the electro-magnetic force.

2) Calculation of composite force and gravity point to the A point

Here, An example is used to explain the calculation process. When the Fig. 10 is converted into a mathematics model and put on the coordinate system, the C point is regarded as an original point and copper wire direction is regarded as Y axis. Then the total electro-magnetic composite force Σf is calculated as

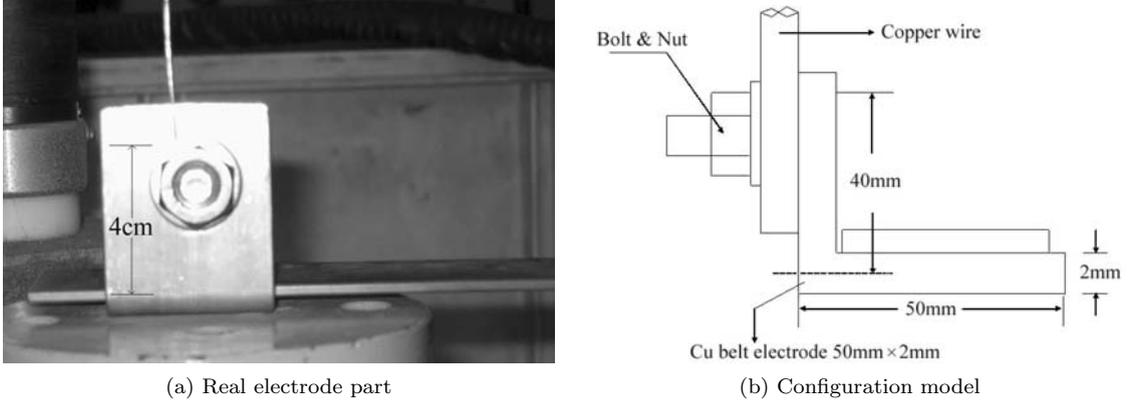


Fig.11 Configuration of lower electrode

$$\sum f = \int_{0.04}^{1.04} \frac{\mu_0 i_t^2}{4\pi y} dy = 3.26 \cdot \frac{\mu_0 i_t^2}{4\pi} \quad (6)$$

where, $\mu_0 = 4\pi \times 10^{-7}$: Vacuum permeability [$\text{N} \cdot \text{A}^{-2}$], Σf : Total electro-magnetic composite force on the wire [N], y : value of Y coordinate [m].

For the distribution of electro-magnetic force is not uniform along the copper wire, firstly the gravity point G of the electro-magnetic force must be calculated. Then the supporting force F_A , F_B of A, B points could be calculated by using the mathematics model of Fig. 10.

$$\begin{aligned} \sum M_A &= \left(\sum f \right) \cdot l_A \\ \int_{0.04}^{1.04} [\mu_0 i_t^2 / (4\pi y)] \cdot (1.04 - y) \cdot dy &= 2.38 \cdot \frac{\mu_0 i_t^2}{4\pi} \\ \left(\sum f \right) \cdot l_A &= [\mu_0 i_t^2 / (4\pi)] \cdot 3.26 \cdot l \\ \therefore l_A &= 0.73 \text{ m} \end{aligned}$$

$$F_B = \frac{\sum M_A}{L_e} = 2.39 \cdot \frac{\mu_0 i_t^2}{4\pi} \quad (7)$$

$$F_A = \sum F - F_B = 0.87 \cdot \frac{\mu_0 i_t^2}{4\pi} \quad (8)$$

where, ΣM_A : Resultant moment of electro-magnetic composite force to the A point [$\text{N} \cdot \text{m}$]

G : Gravity point of the electro-magnetic force to the A point

F_A, F_B : Supporting force of A, B points [N].

l_A : Moment length of the copper wire to the A point [m].

3) Calculation of Shear stress

τ [N/m^2] is a stress state where the stress is parallel to a sectional face of the material, as opposed to normal stress when the stress is perpendicular to the face. The definition of shear stress at point B is

$$\tau = F_B / S \leq [\tau] \quad (9)$$

F_B : The shear force at point B [N]

$[\tau]$: Allowable shear stress of material [N/m^2] or [Pa]

$$[F_B] = S \times [\tau] = \frac{\pi}{4} D^2 \cdot 210 \text{MPa} = 165 D^2 [\text{MN}] \quad (10)$$

where, $[F_B]$: Allowable shear force of copper wires.

$$F_{Bmax} = 2.38 \cdot \frac{\mu_0 I_P^2}{4\pi} = 2.38 \times 10^{-7} \cdot I_P^2 \quad (11)$$

Because the maximum electro-magnetic force is generated at the lower electrode, F_B is used to calculate the shear stress. Fig. 12 shows the maximum shear force of wires at the lower terminal. As shown in Fig. 12, the shear force increases with the diameter. To guarantee the security, the shear force could not exceed the allowable shear force of the material. the allowable shear stress of copper is 210 MPa at 20°C[7]. The calculated results are extremely over the allowable shear force of the copper. So shear stress is one of the main reasons to break the copper wire. In the experiments, the copper wire maybe be broken before or near the peak current by adding the electro-magnetic force. Here is a timelag from applying the electro-magnetic force to the broken time.

In the experiments copper wires of 83.3% were broken at lower electrode (the B point of maximal shear stress), 8.3% were broken at upper electrode. And 8.4% were broken at both electrodes.

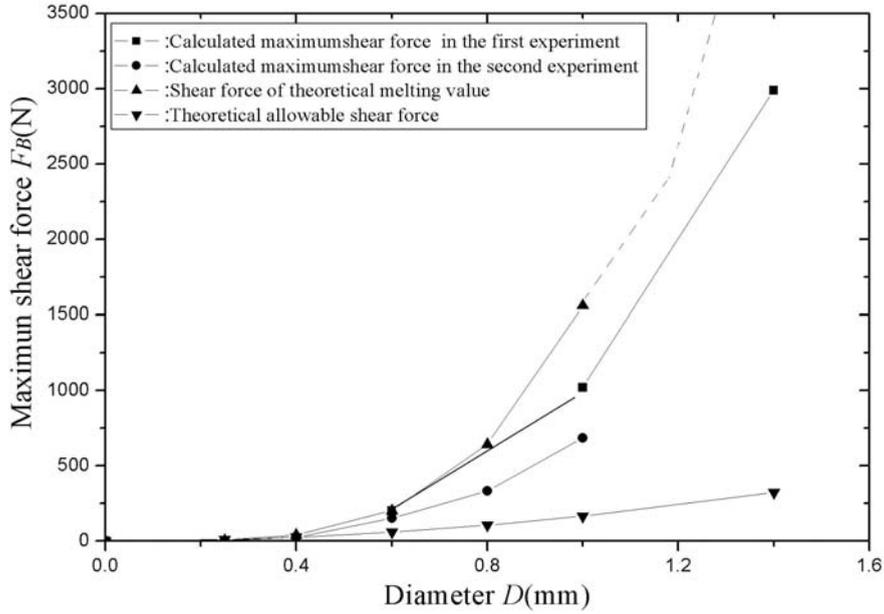


Fig. 12 The calculated maximum shear stress of sheared copper wires

5.3 Skin effect

Skin effect is the phenomenon where the apparent electric resistance near the surface of a wire decreases as the frequency increases. The area through which the charge carriers flow is referred as the skin depth δ .

$$\delta = \sqrt{2/(\omega\mu\sigma)} \quad (12)$$

where, $\omega = 2\pi f$: angular frequency, σ : electric conductivity, μ : permeability.

In the experiments, the impulse current is similar to the sine wave. Wave front is regarded as 1/4 cycles. So the equivalent frequency is $f = 16.7 \text{kHz}$ which is obtained from one-period time $t_p \approx 60 \mu\text{s}$. Then $\delta_{(20^\circ\text{C})} = 5.13 \times 10^{-4} \text{m} = 0.513 \text{mm}$ is calculated by using $\sigma_{(20^\circ\text{C})} = 5.82 \times 10^7 \text{S/m}$

and $\mu = 4\pi \times 10^{-7}$ H/m in the normal temperature. When the depth of skin effect is taken into consideration, the value δ is equivalently 100% to copper wire of 1 mm Φ and 73% to copper wire of 1.4 mm Φ , so most of the cross-section is occupied. If the temperature in δ is regarded as uniformity, the electrifying section becomes a ring-shape area S_c with the width δ as

$$S_c = \pi \{R^2 - (R - \delta)^2\} = 2\pi\delta(R - \delta/2) = \pi\delta(D - \delta) \quad (13)$$

where R : wire radius(D/2). When the skin effect is considered, the surface temperature of 1.4 mm Φ rises from 493°C to 621°C. For the copper wires of 1.4 mm Φ the skin effect causes the surface temperature higher, which accelerates the broken process.

5.4 Pinch effect

When high current flows through a wire, the wire is squeezed inward. If the material is too weak to sustain the pressure, the material will be pinched off. So the broken process will be accelerated by pinch effect in the liquid-like state.

5.5 Effect of temperature on the strength

The published data on the reduction of the strength hold for various durations at different temperature. However in these experiments the duration time is too short to calculate the reduction of the strength.

6 Conclusions

The phenomena when straight copper wires are broken by lightning current were examined experimentally and theoretically, and the following results are obtained:

- (1) The broken mechanism is mainly considered as a result of Joule heating and electro-magnetic force.
- (2) The Joule heating is a principal reason to break thin copper wires such as 0.25 mm Φ . For the copper wires of 0.4 mm Φ or more, because the electro-magnetic force increases, the copper wires are mechanically broken by shear stress before it is completely melted.
- (3) The temperature of broken copper wires is estimated to be about 400~1,000°C and decreases with the increase of diameter.
- (4) The shear stress generated by electro-magnetic force increases with peak current and decreases with the diameter. Totally the shear force increases with the diameter.
- (5) The broken current peak value of the wire is mainly decided by the material, electrode configuration, and the diameter.

Acknowledgment

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Appendix 1

The current density J is defined as

$$J = i(t)/S \tag{A1}$$

$$\text{hence } \int_{t_1}^{t_2} J^2 dt = \frac{1}{S^2} \int_{t_1}^{t_2} [i(t)]^2 dt \tag{A2}$$

Substituting equation(3) for $[i(t)]^2$

$$\int_{t_1}^{t_2} J^2 dt = \frac{C_0 \gamma}{\rho_0} \int_{t_1}^{t_2} \frac{(1 + \beta T + \eta T^2)}{(1 + \alpha T + \zeta T^2)} dT \tag{A3}$$

where, γ : Copper mass density [kg/m³]

Calculating the equation(A3), the following curve shows the variation of temperature with $\int_{t_1}^{t_2} J^2 dt$ for $T_1 = 0$.

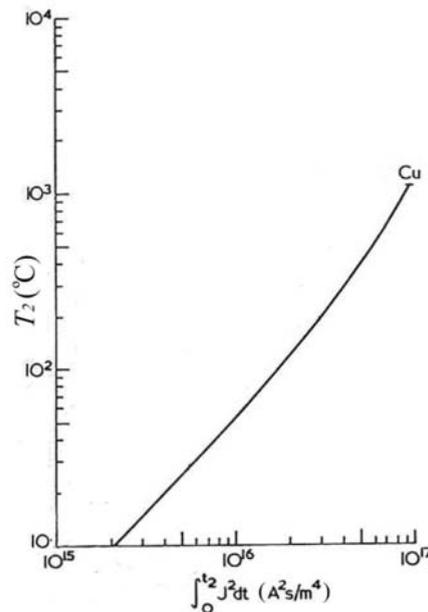


Fig. A1 Relationship curve between T and $\int_0^{t_2} J^2 dt$ with $T_1 = 0$