Temperature Simulation of Pb-Free Sn-9Zn Elements for a Low Voltage Fuse

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The distribution of the temperature was estimated by combination of electrical and thermal calculations on the basis of Ohm’s and Fourier’s laws in the fuse element-connector-electric wire system in order to design Pb-free Sn-9Zn fuse elements used in electric power line. The temperature distributions in fuses were obtained on the basis of the amount of Joule’s heat generation and heat transfer depending on the ratio of the length and diameter of fuse elements. Main requirements for AC-low voltage fuses were satisfied on the promising fuse element with the size designed on the basis of the heat generation and transfer calculations. The promising size was the diameter of 2.5 mm and length of 10 mm in the smaller diameter part of two step cylindrical fuse elements. In contrast, the electrical potential and temperature distributions can be also estimated by this calculation method, regardless of a kind and shape of the fuse elements, connectors and electric wires.

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Keywords: temperature simulation, lead-free tin-zinc alloy, fuse element, environmentally friendly materials, voltage distribution, substitute material

1. Introduction

Lead and Pb containing alloys and compounds are considered environmental hazards because of lead’s toxicity.¹) There are no clear scientific data or studies that clearly describe the mechanism by which lead from disposed electrical and electronic products enter the ground water stream, or the animal or human food chain. The only available data that appears to be relevant come from unrelated studies that have described the breakdown of PbO to PbCO₂ in the presence of Cl⁻ and CO₂.²) The Pb is considered as hazardous to the environment in the electrical and electronic industry. In Japan, the legislation prohibiting Pb from being sent to land fills and other waste disposal sites is already in place. In US, three legislations in limiting the use of Pb have been introduced in both the Senate and the House Representatives.³) Although these bills have not been passed yet, it is likely that some form of bills will be passed in the future. The European Union has officially designated 1 July 2006 as the date when the Directive on the Restriction of Hazardous Substance in Electrical and Electronic Equipment will require “the use of lead, mercury, cadmium, hexavalent chromium and halogenated flame retardants” be phase out.⁴) This requirement applies to the manufacturing of both domestic and export products. Electrical and electronic products now have two choices: either attaining 100% recycling of Pb, or using Pb-free solder and fusible alloys.

Due to the above world-wide legislative requirements, it is important to develop viable alternative Pb-free alloys for AC-fuse elements used in electric power line. The Sn-39 mass%Pb alloy has been used as an AC-low voltage fuse element in electric power line.⁵,⁶) The main requirements for alternative fusible alloys are:

1. Low melting point: The melting points should be comparable to practical Sn-Pb system alloys.
2. Availability: There should be adequate supplies or reserves available of candidate metals.
3. Ability of manufacture: The production of raw materials should not be difficult.

The Sn-9Zn alloy has been investigated in our previous study as an alternative Pb-free alloy for low-voltage fuse elements, except for the points of its performance in a break at high value, 3000 A, of electric current, weather proof and wettability on copper.⁵,⁶) It is important in the design of fuse elements that their temperature distributions are exactly known in some conditions evaluating the main requirements for the AC-low voltage fuse. The purpose of this paper is to investigate the distribution of the temperature by combination of both electrical and thermal calculations using the two step cylindrical fuse element-connector-electric wire system, and propose the promising size of a Sn-9Zn fuse element. For the fuse elements designed on the basis of the results of calculations, their performance is experimentally evaluated in respect to main requirements for a fuse element.

2. Experimental Procedures

2.1 Sn-9Zn alloy and requirements for a fuse

The schematic illustration showing the assembly of some parts including of the Sn-9Zn fuse element in a fuse box proposed in this study is shown in Fig. 1. The fuse box consisted of a Sn-9Zn fuse element, copper connector, copper sleeve, cover, case and vinyl coated electric wire with a diameter of 3.2 mm. The practically used Sn-39Pb fuse element showed a straight cylindrical shape. For AC-low voltage fuses used in electric power line, mainly three requirements listed in Table 1 have been satisfied on the Sn-39Pb fuse elements.⁵,⁶) The Sn-9Zn fuse elements also have to satisfy these requirements. The performance of Sn-9Zn in respect to the period showing the (1) melt down or (2) unmelt down at fixed values of the electric current and (3) amount of increase in temperature at the fixed positions were experimentally evaluated according to the conditions listed in Table 1. The temperatures were measured by thermocouples at four fixed positions shown in Fig. 1. The fixed positions were the metallic surfaces of sleeves, M1 and M3, surface of a case, M2, and metallic surface of an electric copper wire, M4. The thermocouples were K-type and had 0.32 mm
diameter. They were spot-welded with metallic surfaces, M1, M3, M4 shown in Fig. 1, and contacted with the case surface, M2, using a tape made of aluminum. The electric current of 64, 72, 99 and 210 A under the voltage of 220 V was discharged on the fuse element-connector-electric wire system shown in Fig. 1, according to experimental conditions listed in Table 1.

Pure Sn with the purity of 99.9% and pure Zn with the purity 99.9% were weighed according to the nominal composition of the eutectic Sn-9Zn alloy. They were melted in a graphite crucible in air. Its melt was cast into the cold split-die made of carbon steel. Two step cylindrical shape having a constriction in the center region was selected for the heat concentration at the center of the fuse elements. Two step cylindrical fuse elements consisting of the small and large diameter parts were turned in a lathe, from Sn-9Zn ingots with a diameter of 15 mm and a length of 115 mm. Total length of fuse elements was 30 mm as shown in Figs. 1 and 2(a). The large diameter part has a diameter of 5 mm and length of 5 to 11 mm. In contrast, the small diameter part has a diameter of 2.5 and 3.0 mm and length of 8 to 20 mm. The both edges of the large diameter part with a diameter of 5 mm of the Sn-9Zn fuse element were soldered to copper connectors using a Sn-9Zn wire.

![Fig. 1](image1.png) **Fig. 1** The construction of a fuse box. M1, M2, M3 and M4 are positions for the measurement in temperature by thermocouples. Units are given in millimeters.

![Fig. 2](image2.png) **Fig. 2** The schematic illustrations showing (a) the size of the copper wire, copper connector and Sn-Zn fuse element in the fuse element-connector-electric wire system for simulation and (b) calculated isopotential contours in the y-z plane at 433 K under the constant current flow of 99 A for the fuse element with a diameter of 2.5 mm and a length of 8 mm in its smaller diameter part. Units are given in (a) millimeters and (b) volts.

<table>
<thead>
<tr>
<th>Requirement for a fuse</th>
<th>Experimental conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Period showing melt down of a fuse element under a fixed value of electric current</td>
<td>Melt down of a fuse element less than 600 s at a constant current discharge of 99 A. 99 A corresponds to 180% of a rated current.</td>
</tr>
<tr>
<td>(2) Period showing un-melt down of a fuse element under a fixed value of electric current</td>
<td>After a constant current discharge of 72 A via a fuse for 1 ks, un-melt down of a fuse element for 3 s at a constant current discharge of 210 A. 72 A corresponds to 130% of a rated current.</td>
</tr>
<tr>
<td>(3) Amount of increase in temperature on fixed positions under a fixed value of electric current</td>
<td>Increase in temperature less than 40 and 50 K on the surface of the polycarbonate case, M2, and sleeve, M1 and M3(^{+1}), respectively, at a constant current discharge of 64 A.</td>
</tr>
</tbody>
</table>

Note: \(^{+1}\): M1, M2 and M3 denote the fixed positions measured temperature by thermocouples, as shown in Fig. 1.
2.2 Model for electrical and thermal calculations

The assembly of the Sn-9Zn fuse element, copper connector and electric copper wire, and the size of each object used in this calculation are shown in Fig. 2(a). A three-dimensional Cartesian coordinate system was used in the fuse element-connector-electric wire system. The governing equations are based on Ohm’s and Fourier’s laws for electrical and thermal analyses, which can be written as following equations (1) and (2), respectively,

\[
\rho_c c_e \frac{\partial E}{\partial t} = \frac{\partial^2 E}{\partial x^2} + \frac{\partial^2 E}{\partial y^2} + \frac{\partial^2 E}{\partial z^2} = 0
\]

where \(\rho_c, c_e, E\) and \(t\) represented the specific resistivity, capacitance, voltage and time, respectively.

\[
\rho_p \frac{\partial T}{\partial t} = \lambda \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + Q
\]

where \(\rho_p, c_p, \lambda, T\) and \(Q\) represented the density, specific heat, heat conductivity, temperature and amount of heat generation per 1 s, respectively. \(Q\) is obtained from the \(\rho_c, \) electrical conductivity, and current density calculated from the potential difference along \(x, y, z\) directions. Therefore, \(Q\) can be written as following eq. (3),

\[
Q = \rho_c \left( \frac{1}{\rho_c} \sqrt{\left( \frac{\partial E}{\partial x} \right)^2 + \left( \frac{\partial E}{\partial y} \right)^2 + \left( \frac{\partial E}{\partial z} \right)^2} \right)^2
\]

The finite difference method, FDM, was used to solve the above equations for voltage and temperature as a function of time and position.

The governing equation for boundary mesh points was represented by equation (4) at the fuse element, connector and electric wire/air interfaces,

\[
\rho_p v_{ol} \frac{\partial T}{\partial t} = \lambda \sum_{i=1}^{6} S_i \frac{T_i - T}{l_i} + \sum_{i=1}^{3} h A_j (T_c - T_j) + Q
\]

where \(v_{ol}\) was the volume of the element, \(l_i\) was the distance between the mesh point representing the element and its neighboring mesh point in each direction, \(T_i\) was the temperature of the neighboring mesh point in \(i\) direction, \(A_j\) was the areas facing the boundary, \(T_c - T_j\) was temperature difference of between noted mesh points and air through the interface, \(h\) was heat transfer coefficient at the interfaces.

2.3 Measurement of physical properties

Density measurement using a high density liquid was performed by Archimedes’ method. Differential thermal analysis, DTA, was carried out on the Sn-9Zn alloy. DTA measurement of samples with the mass of 0.46 g was conducted at a constant heating and cooling rates of 5 K/min in a low purity argon stream. The \(\rho_c\) was simultaneously measured from room temperature to about 470 K by the standard four probe d.c. method in air using a computer-controlled equipment. The temperature gradient along the length, 17 mm, of the sample for the measurement of \(\rho_c\) was about 5 K. The \(c_p\) was measured from room temperature to about 470 K using samples with the diameter of 9 mm and thickness of 1.7 mm, by the laser flash method. The \(\lambda\) was measured from 325 to 434 K using samples with the diameter of 11 mm and length of 50 mm, under the steady-state of the heat conduction in air. The value of \(\lambda\) was obtained using the relation represented in equation (5),

\[
\lambda \frac{\Delta T_i \pi D^2}{L} = EI
\]

where, the product of \(E\) and \(I\) represented the amount of Joule’s heat discharged to a cartridge heater with a capability of 200 V and 200 W, \(D\) and \(\Delta T_i\) represented the diameter of samples and the temperature difference caused between the points keeping a fixed length, \(L_i\): approximately 5 mm, respectively. The temperature was measured by the K type thermocouples with the diameter of 0.1 mm.

3. Results and Discussion

3.1 Sn-9Zn alloy

The microstructure of the Sn-9Zn alloy showed a typical Sn-Zn eutectic structure with the light contrast Sn and the dark contrast Zn phase in normal eutectic cells formed alternately, as shown in Fig. 3. There was also an irregular region consisting of the darker needle-like phase, misaligned primary Zn, and the light contrast primary Sn surrounding the primary Zn, which meant crystallization of Sn in the depleted region of Zn due to the formation of the primary Zn phase by atomic diffusion under the non-equilibrium state. The chemical composition of the Sn-9Zn alloy is listed in Table 2. It is also found that primary Zn was crystallized because the Sn-9Zn alloy had a little larger Zn content, compared with the eutectic alloy.

Figure 4 shows DTA curves obtained from the Sn-9Zn alloy. In the DTA heating curves of Sn-9Zn, one endothermic peak of 11 mm and length of 50 mm, under the steady-state of the heat conduction in air. The value of \(\lambda\) was obtained using the relation represented in equation (5),

\[
\lambda \frac{\Delta T_i \pi D^2}{L} = EI
\]

where, the product of \(E\) and \(I\) represented the amount of Joule’s heat discharged to a cartridge heater with a capability of 200 V and 200 W, \(D\) and \(\Delta T_i\) represented the diameter of samples and the temperature difference caused between the points keeping a fixed length, \(L_i\): approximately 5 mm, respectively. The temperature was measured by the K type thermocouples with the diameter of 0.1 mm.

### Table 2: Chemical composition (mass%) of the Sn-9Zn alloy cast in this experiment.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Sn</th>
<th>Zn</th>
<th>Pb</th>
<th>As</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-9Zn</td>
<td>90.89</td>
<td>9.05</td>
<td>0.048</td>
<td>0.007</td>
<td>0.003</td>
</tr>
</tbody>
</table>
peak, $P_0$, appeared at 474 K. Meanwhile, in the cooling curve of Sn-9Zn, one peak, $P_1$, appeared at 471 K. These peaks corresponded to the eutectic reaction. The eutectic point was 471–474 K, which agreed with that, 472 K, in the constitutional diagram of the Sn-Zn system. In contrast, the melting temperature of 454 K was reported for the practically used Sn-39Pb alloy. The melting temperature of Sn-9Zn alloy was 20 K higher than that of the practical alloy. It is considered on the basis of the melting point that the size in fuse elements made of Sn-9Zn alloy must be changed satisfying main requirements for an AC-low voltage fuse, compared with the practically used Sn-39Pb alloy.

3.2 The physical properties used in potential and temperature calculations

The specific resistivity of the Sn-9Zn alloy was measured at various temperatures of the range of 293–460 K. Figure 5(a) shows the temperature dependence of $\rho_e$. As can be seen, $\rho_e$ increased monotonously with increasing temperature.

The thermal conductivity of the Sn-9Zn alloy was measured at various temperatures of the range of 325–425 K. Fig. 5(b) shows the temperature dependence of $\lambda$. As can be seen, $\lambda$ decreased monotonously with increasing temperature.

The specific heat of the Sn-9Zn alloy was measured at various temperatures of the range of 300–453 K. Fig. 5(c) shows the temperature dependence of $c_p$. As can be seen, the constant value in $c_p$ was shown in the temperature range of 300 to 350 K. However, the $c_p$ increased above that temperature range.

It is found below the melting point of the Sn-9Zn alloy that the values of $\rho_e$, $\lambda$ and $c_p$ can be generally represented using equations listed in Fig. 5 and Table 3 as the function of the temperature.

3.3 The potential and temperature calculations

3.3.1 The constant current discharge of 99 A

Table 3 shows the parameters used for the electrical and thermal calculations. The voltage and temperature were calculated using Eqs. (1) and (2), respectively. The electric current of 99 A was discharged from the edge surface of the copper electric wire to another one, as shown in Fig. 2(a). The current density on the edge surface of the electric wire was 12.3 $A/mm^2$ at room temperature. For instance, the measured value in the total electrical resistance was 706 $\mu\Omega$

Table 3 The physical properties and other parameters used in potential and temperature calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda$</td>
<td>$-0.09028 \times Temp + 101.79$ W m$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>$\rho_e$</td>
<td>0.0454 $\times$ Temp $-1.6141$ $\mu\Omega$ cm$^{-1}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>7.275 at 293 K Mg/m$^3$</td>
</tr>
<tr>
<td>$c_p$</td>
<td>$4 \times 10^{-10} \times$ Temp$^3 + 6 \times 10^{-7}$ Temp$^2 - 0.0005 \times$ Temp $+ 0.3194$ kJ kg$^{-1}$ K$^{-1}$</td>
</tr>
<tr>
<td>Electric current</td>
<td>64, 72, 99, 210 A</td>
</tr>
<tr>
<td>Time step</td>
<td>0.0001 s</td>
</tr>
</tbody>
</table>

throughout the fuse element-connector-electric wire system having the diameter of 2.5 mm and length of 10 mm in the smaller diameter part.

The change in temperature at the center of fuse elements with respect to current discharge time at a constant current discharge of 99 A is shown in Fig. 6 for the fuse element-connector-electric wire system having various sizes of the diameter of 2.5 or 3.0 mm and length of 8 to 20 mm in the smaller diameter parts of fuse elements. The temperature increased to the melting point as the time increased, for fuse elements with the length of 10 to 20 mm and diameter of 2.5 mm in their smaller diameter parts. The temperature in the fuse element with a length of 8 mm and diameter of 2.5 mm increased to the melting temperature after 617 s. In this paper, for convenience, it is assumed that the melt down of fuse elements was caused at their melting temperatures.
Fig. 6 The relation between the temperature and time obtained from the calculations under the constant current flow of 99 A at the center in Sn-9Zn fuse elements having the various sizes. *d and l represent the diameter and length in their smaller diameter parts, respectively.

of 617 s could not satisfy the time limit, less than 600 s, for its melt down under this condition. In contrast, the rate of increase in the temperature decreased and the saturated value of the temperature under this condition was shown below the melting temperature, as the current discharge time increased for all fuse elements with a diameter of 3.0 mm in their smaller diameter parts. It is found that the temperature at the center in fuse elements can be controlled by change of length and diameter in their each diameter part, and the length of 10 to 20 mm and the diameter of 2.5 mm are promising for passing this experiment condition.

The potential and temperature distributions were obtained in the whole of the fuse element-connector-electric wire system. Fig. 2(b) shows the calculated isopotential contours in the y-z section at 433 K. The potential distribution showed symmetry with respect to y or z axes. The potential was almost unchanged in the y-direction. A little deviation from the constant potential distribution in the y-direction was created in the part, “A” in Fig. 2(b), showing the isopotential contours of 0.049 and 0.019 V, in the larger diameter part on the Sn-9Zn fuse element. There was a large depression in potential of 0.03 V throughout small diameter part with a diameter of 2.5 mm and length of 8 mm, compared with that of 0.044 V throughout the Sn-9Zn fuse element with a length of 30 mm and that of 0.068 V throughout the fuse element-connector-electric wire system. It is considered from the shape and value of isopotential contours that the high values in the current density and electrical resistance are achieved by the occurrence of heterogeneity part, “A” in Fig. 2(b), of the potential in both y- and z-directions due to the different diameters in two step cylindrical shapes, compared with straight cylindrical shapes for the practically used fuse elements.

Figure 7 shows the calculated isothermal contours in the y-z section obtained in various fuse elements with the diameter of 2.5 or 3.0 mm and length of 8 or 20 mm in their smaller diameter parts. The temperature distribution showed symmetry with respect to y or z axes, regardless of sizes of fuse elements. The temperature was almost unchanged in the y-direction. The temperatures were measured by thermocouples at four positions, M1, M2, M3 and M4 in Fig. 1, for the fuse element-connector-electric wire system, and the values of the measured temperatures at M1 on the metallic surface of the electric wire were indicated within the parentheses in Fig. 7. The value of calculated temperature was also close to that of measured temperature at M1 in the electric wire. The largest heat source or the maximum value of the calculated temperature throughout the fuse element-connector-electric wire system was shown at the center in the smaller diameter part of fuse elements, and the shape of its distribution was unchanged depending on sizes of compacts. The heterogeneity in temperature or a little deviation from the constant distribution in the y-direction could be developed by the two step cylindrical shape of fuse elements. The heat flow was caused from the center to the both edges or outer rim in the fuse elements with a length of 30 mm and from the copper connector to the electric wire. The temperature differences were 7 and 32 K throughout smaller diameter parts, and 13 and 10 K throughout the larger diameter parts for the fuse elements with a length of 8 and 20 mm in their smaller diameter of 2.5 mm, respectively. In contrast, the temperature differences were 32 and 10 K throughout smaller diameter parts, and 10 and 5 K throughout larger diameter parts for the fuse elements with a smaller diameter of 2.5 and 3.0 mm and a length of 20 mm, respectively. The temperature distribution corresponded to the potential distribution shown in Fig. 2(b). It is concluded on the basis of the calculations of the potential.
and temperature that the temperature was changed depending on the ratio of length and diameter in smaller and larger diameter parts because of the difference in the amount of Joule’s heat generation and heat transfer by heat conduction. Furthermore, regardless of a kind and shape of the fuse elements, connectors and electric wires, their potential and temperature distributions could be also estimated by this calculation method. In this calculation, the governing equation for boundary mesh points was represented by eq. (4) at the fuse element, connector and electric wire/air interfaces. The heat transfer coefficient in eq. (4) means the sum of ones for the natural convection and heat radiation. The heat radiation can be neglected in this temperature range. In contrast, the heat transfer by the natural convection was included in the calculation by using its coefficient, \( h_c \), denoted by eq. (6),\(^9\)

\[
  h_c = 1.32(\Delta T/D)^{1/4}
\]

where \( \Delta T \) was temperature difference of between noted mesh points and air through the interface, \( D \) was diameter of each element.

**3.3.2 The constant current discharge of 72 A and 210 A**

The change in calculated temperature at the center of fuse elements with respect to current discharge time at a constant current discharge of 72 and 210 A is shown in Fig. 8 for the fuse element-connector-electric wire system having fuse elements with the diameter of 2.5 or 3.0 mm and length of 10 or 12 mm in their smaller diameter parts. The saturated values in the temperature were shown after the current discharge time of 300 s at 72 A, although the constant current was discharged via a fuse for 1 ks in the practical experiment as listed in Table 1. The constant current of 210 A was discharged via the fuse element-connector-electric wire system after the current discharge of 72 A for 360 s, in the potential and thermal calculations. The constant values in the temperature after 360 s were obtained from the calculations for three fuse elements. These values at the center were depended on the size of their smaller diameter parts. The rate of increase in the temperature decreased and the temperature reached at the saturated value as current discharge time increased. The temperature at the center of fuse elements reached at the melting temperature after the current discharge time depending on their sizes at 210 A. The temperature was changed depending on time depending on their sizes at 210 A after the current discharge of 72 A for 360 s, as shown in Fig. 8(b). It is also found under this condition of the current discharge that temperature increased at the center of the two step cylindrical fuse elements when the length was increased and diameter was decreased in their smaller diameter parts, respectively. The temperature can be also controlled at the center in fuse elements because the amount of the heat-generation and -transfer is controlled by change of ratio of their length and diameter. It is concluded on the basis of thermal calculations that the size with a length of 10 mm and a diameter of 2.5 mm in the smaller diameter part was promising for passing both requirements consisting of (1) the un-melt down of a fuse element for 3 s at 210 A after current discharge of 72 A and (2) its melt down less than 600 s at 99 A.

**3.4 Practical performance-evaluation under the current discharge**

The practical experimental results are listed in Table 4 for the fuse element-connector-electric wire system having the five kinds of fuse elements with the diameter of 2.5 or 3.0 mm and the length of 8 to 12 mm in their smaller diameter parts. The results obtained from the both experiments consisting of the constant current discharge of (1) 99 A and (2) 210 A after current discharge of 72 A, agreed with those obtained from their calculation results shown in Figs. 6 and 8. The melt down was caused in the center part of fuse elements under two experimental conditions mentioned above. Figure 9 shows the melt down at the center of the fuse element with the diameter of 3 mm and the length of 12 mm, as one example. This fuse was current discharged at 210 A for 8.5 s after the discharge of 72 A for 1 ks, as listed in Table 4. The melt down at the center in the fuse element shown in Fig. 9 agrees with the maximum temperature shown at the center parts in the calculation as shown in Fig. 7.

The change in temperature at four positions with respect to current discharge time at 64 A is shown in Fig. 10 for the fuse element with a diameter of 3.0 mm and length of 8 mm in its smaller diameter part, as one example. The four temperature-measuring positions, M1, M2, M3 and M4, correspond to those shown in Fig. 1. The temperatures at M1, M3 and M4 increased to approximately 500 s and became almost constant after 500 s. Both points, M1 and M3, on the metallic surface of sleeves showed the increase in temperature of 23 to 24 K and M2 on the surface of the case showed that of 6 K, after the current discharge of 2000 s, which satisfy the requirement of the increase in temperature less than 50 K and 40 K, respectively, at a
constant current of 64 A. All fuses satisfied this requirement as listed in Table 4. There was little temperature difference of 1 K between M1 and M3, which corresponded to the results of temperature calculations showing symmetry with respect to y-axis, as shown in Fig. 7.

It is concluded that the promising size of Sn-9Zn elements for an AC low-voltage fuse could be designed on the basis of the potential and thermal calculations and its diameter and length were 2.5 and 10 mm, respectively, in the smaller diameter part of two step cylindrical shape.

### 4. Conclusions

The temperature distribution in fuse elements with two step cylindrical shape was estimated on the basis of the amount of Joule’s heat generation and heat transfer depending on the ratio of their length and diameter for the fuse element-connector-electric wire system. As the promising size of fuse elements, the diameter of 2.5 mm and a length of 10 mm in the smaller diameter part of two step cylindrical fuse elements were selected on the basis of the results of potential and thermal calculation. Main requirements which were experimentally evaluated for an AC-low voltage fuse element used in electric power line, were satisfied on the Sn-9Zn fuse element having the promising size. The potential and temperature distributions can be also estimated on the basis of Ohm’s and Fourier’s laws, regardless of a kind and shape of the fuse elements, connectors and electric wires.

| Table 4 Some experimental results obtained from the evaluation of fuse-performance for two step cylindrical fuse elements having various sizes. |
|---|---|---|---|---|---|
| | $d=2.5$ mm | $d=3.0$ mm |
| | $l=8$ mm | $l=10$ mm | $l=12$ mm | $l=8$ mm | $l=12$ mm |
| Melt down of a fuse element less than 600 s at 99 A | 785 s | > 1800 s | 277 s | > 1800 s | 176 s | > 1800 s |
| Judgment: | Reject | Reject | Judgment: | Reject | Judgment: | Reject |
| After current flow via a fuse at 72 A for 1 ks, | 3.6 s | 2.3 s | 17.0 s | 8.5 s |
| un-melt down of a fuse element for 3 s at 210 A | Judgment: | Judgment: | Judgment: | Judgment: |
| | Judgment: | Pass | Pass | Pass |
| Increase in temperature | | | | |
| less than 40 and 50 K on M2 and M1 or M3, | | | | |
| respectively, at 64 A | | | | |
| | M2:8 K | M2:9 K | M2:6 K | M2:9 K |
| | M3:26 K | M3:30 K | M3:24 K | M3:31 K |
| | Pass | Reject | Pass | Pass |
| | Pass | Pass | Pass | Pass |

Note: *1: M1, M2 and M3 denote the fixed positions measured temperature by thermocouples, as shown in Fig. 1.*

*2, 3: $d$ and $l$ denote the diameter and length in the smaller diameter parts of fuse elements, respectively, as shown in Fig. 2(a).*

*4: Test termination without melt down of fuse elements.

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**Fig. 9** A photograph showing the melt down at the center of the fuse element discharged the current of 210 A for 8.5 s after the current discharge of 72 A for 1 ks in the fuse element-connector-electric wire system. The diameter and length are 3.0 and 12 mm, respectively, in the smaller diameter part. Units are given in millimeters.

**Fig. 10** The relation between the time and temperature at four positions, M1, M2, M3 and M4, shown in Fig. 1, obtained from the experiment at the constant current discharge of 64 A for evaluation of performance on the fuse element with the diameter of 3.0 mm and length of 8 mm in its smaller part.
REFERENCES