

Dissolution of fuse element notches by SnCu solder and the temperature rise of fuse element

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Abstract

The dissolution of fuse element material in SnCu1 melt was investigated experimentally at the conditions as close to those of fuse link as possible. Test strips of E-Cu were dipped into large volume of molten SnCu1 kept at various specified temperatures in order to measure the reduction of their thickness due to the dissolution of Cu strip into SnCu1 melt. Thickness was measured by metallographic methods. Then the dissolution parameters were evaluated with the approximation of semi-infinite one-dimensional problem, where mass flux density of Cu into the SnCu1 melt determines the diffusion of Cu due to concentration difference through the solid inter-metallic layer of constant thickness. For this solute-solvent system a dissolution coefficient K is evaluated concerning the Arrhenius law for its temperature dependence. The actual temperature, at which M-effect takes place in fuse element, was assessed by computer simulation of its thermal steady state at the over-current of fuse blow. The dissolution process is considered to evolve over the consecutive steps of stationary conditions till the final rupture of the notch, so the initial thermal state is calculated when solder just melts and the final pre-rupture state where the notch is just dissolved. The relative magnitude of coefficient K was assessed along the segments adjacent to the rupturing site for the purpose to give us an insight into the phenomenon of abnormal M-effect.

Keywords: dissolution of Cu strip in SnCu solder, dipping experiment, diffusion in solid, dissolution parameters, dissolution rate K , temperature of fuse element, calculation of temperature rise.

1 Introduction

Operation of fuse link under over-current load shall follow time-current characteristic, which is confined between the limiting values according to the relevant product standard [1]. The actual characteristic for the given type of fuse correlates to the phenomena leading to the rupture of fuse element by melting as well as to those at blow by high-current arc. At moderate over-currents the melting of fuse element (wire, strip) takes place provided by M-effect alloy, which is often a special type of solder deposited at the preferential rupturing sites. The melted M-effect alloy steadily dissolves the notches on the perforation of fuse element strip and the time at which the entire thickness of the notch is dissolved under the specified over-current determines the tripping characteristic of the fuse at the pre-arcing conditions. Therefore the evaluation of parameters of the dissolution process enables the prediction of time-current curve. The investigation of dissolution results in better understanding of the M-effect as well as the reasons for an eventual deviations from the regular operation of fuse link, which can lead to excessively high surface temperatures of its cartridge and consequently to the thermal degradation of adjacent parts [2].

2 Physical backgrounds to the evaluation of dissolution parameters

The dissolution of solid component into the liquid solvent is considered to take place by the diffusion through a thin solid interface layer of thickness δ . The mass loss (dm) of material occupying a volume V , which is closed by a surface S , due to the penetration into a liquid solution through the area of surface S in the time interval (dt) is given by general relations for mass flux Φ_m (1)

$$\Phi_m = - \frac{dm}{dt}$$

$$\oint_S j_m dS = - \frac{\partial}{\partial t} \int_V \rho_m dV \quad (1)$$

where the mass flux density j_m on the surface S of solid material in the volume V having mass density ρ_m flows into a liquid solution. Mass flux is driven by the diffusion, which is determined by the diffusion coefficient D appropriate for a given solute/solvent pair, under the gradient of solute concentration ($\text{grad } c$). Gradient stated in equation (2) is

considered nonzero only inside the border layer of thickness δ :

$$j_m = -D \text{grad } c$$

$$j_m = -D \frac{(c_{\text{solution}} - c_{\text{solid}})}{\delta} \quad (2)$$

The concentration of solute material in the solution c_{solution} is considered constant over its volume, while c_{solid} is the concentration of solute contained in the solid volume V . The reformulation of (1) for the plain parallel geometry in semi-infinite space results in (3),

$$j_m \Delta S = \frac{\partial}{\partial t} (\rho_m \Delta S dx)$$

$$j_m = \rho_m \frac{\partial x}{\partial t} \quad (3)$$

where the layer of uniform thickness dx is dissolved from an element of area ΔS on surface S in time interval dt . By combining equations (2) and (3) the expression (4) is derived for the evaluation of the thickness x of the dissolved solid surface layer:

$$\frac{\partial x}{\partial t} = K \frac{(c_{\text{solution}} - c_{\text{solid}})}{\rho_{\text{solid}}}, \quad K = \frac{D}{\delta} \quad (4)$$

The coefficient K is a dissolution coefficient determined experimentally. On the other hand the analog mathematical derivation of equations (1) and (2) leads to the well known Nernst-Brunner equation (5):

$$\frac{\partial c_{\text{solution}}}{\partial t} = -K \frac{S}{V} (c_{\text{solid}} - c_{\text{solution}}) \quad (5)$$

frequently used as the theoretical background for the evaluation of dissolution parameters of solid copper into Sn-based solder in printed circuit boards [3, 4]. The temperature dependence of the diffusion coefficient D is generally given by Arrhenius law [5] formulated by (6)

$$D = D_0 \exp\left(-\frac{\theta}{T}\right) \quad (6)$$

where T is absolute temperature, θ is a characteristic temperature derived from the activation energy W_a and D_0 is a pre-exponential

factor. Due to the analogy between coefficients D and K the equation (6) is applicable also in equation (5).

3 Experimental determination of dissolution parameters

3.1 Experimental procedure

The experimental procedure was analogous to those reported in [6]. A soldering bath with thermostatic regulation was filled with few kilograms of SnCu 1 for a dipping experiment. Test samples of E-Cu strip (thickness 0,20 mm, width 20 mm, length approx. 5 cm,) were dipped into solder at the predetermined temperature for the specified time. After that a metallographic cross section of test samples were made in order to measure the thickness of the rest of intact Cu-material in strip. The difference between the original thickness of copper strip and the thickness of Cu remained unchanged after dipping is considered equivalent to the thickness dissolved into SnCu1 in time t and equal to x in eq. (4).

3.2 Analysis of test samples

The metallographic cross-sections of test samples were investigated in the metallographic microscope. A typical structure of interface between solid Cu strip and re-solidified solder is shown in Fig. 1:

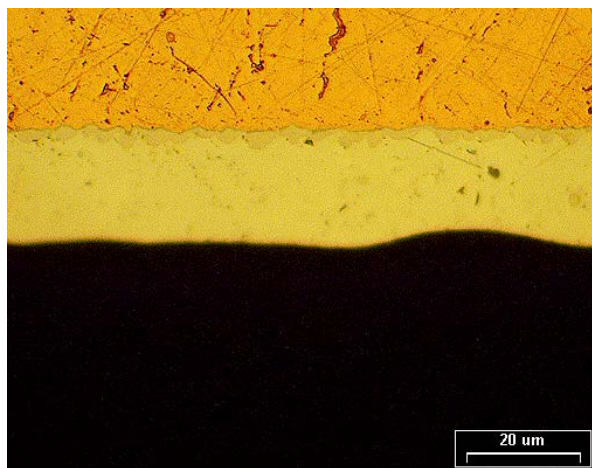


Fig. 1: Cross-section of test Cu strip – re-solidified solder layer on copper base with inter-metallic layer in-between.

A border layer consists of two inter-metallic alloys of variable thickness. Near the unalloyed Cu the inter-metallic phase ϵ of relatively uniform thickness composed of Cu_3Sn [3,6,7] was formed while near the solder melt the inter-metallic phase η of Cu_2Sn_3 [3,6,7], which exhibits a scallop structure. The re-solidified solder coating shows uniform metallographic structure over the whole volume. However, the test conditions should reflect the conditions of M-effect taking place in a fuse element as possible. Therefore the melting process in fuses was investigated in parallel as well: the alloy structure and the border layers observed on the on test samples are analog to those appeared at M-effect in melting fuses, shown in Fig. 2:

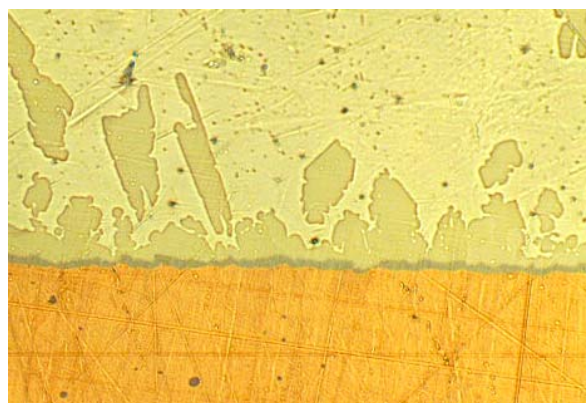


Fig. 2: Inter-metallic layer on the soldered segment of fuse element after blow.

Concerning the structure of re-solidified melt, which is mixed with more or less uniformly distributed crystals of phase η , the applied approximation for the equations (4) and (5) is confirmed as essentially realistic: mean concentration gradient is close to zero outside the interface layer δ comprising phases ϵ and η . Moreover, the thickness δ of layer δ is irrelevant in the calculation of dissolution parameters as the dissolution coefficient K calculated from measured results does not depend explicitly on it. Regarding Fig.2 the value of c_{solution} in (4) and (5) represents the uniform concentration of Cu in the melt irrespective to shown metallurgic structure of re-solidified solder. The concentration c_{solution} of Cu in the melt is given as the mass of Cu per volume of melt (kg/m^3) and by analogy the concentration of Cu in solid strip (c_{solid}) is identical to mass density of solid Cu strip (ρ_{solid}).

3.3 The method of evaluation

The thickness of the intact material of Cu-strip after dipping test was measured microscopically on the cross-section of test samples. The difference between original thickness and the measured value determines double thickness ($2x$) of the dissolved layer. The attained accuracy of measured x illustrates the situation shown by the outlook of a resulting test sample in Fig. 3 as an extreme case of sample used for thickness measurements.



Fig. 3: Test sample strip after dipping illustrates the non uniform dissolution of test strip over its surface.

For the evaluation of dissolution parameters the equation (4) was used. According to the approximation by infinitely large solder volume the right side of (4) is considered independent of time t . After the integration over the dipping time t and concerning the analog expressions for D and K by equation (6) the relation between the dissolved thickness of Cu strip $x/\mu\text{m}$ in the molten solder versus time t/s regarding the temperature of SnCu-melt T/K is given by equation (7):

$$x = K_0 \exp\left(-\frac{\Theta}{T}\right) \left(1 - \frac{c_{\text{solution}}}{\rho_{\text{solid}}}\right) \cdot t$$

$$x = K^* \cdot t \cdot \exp\left(-\frac{\Theta}{T}\right) \quad (7)$$

where K_0 is a pre-exponential constant independent of t and T . The pre-exponential constant K^* for the specified initial mass concentration of Cu in solvent SnCu1 (nominally 1 wt% of Cu) can be in principle evaluated from measurements by (7), but in the elapse of dipping tests the Cu content in SnCu1 test has increased to almost 3 wt%, which has also contributed to the inaccuracy of evaluation.

3.4 The evaluation of K^* and Θ

The dissolution parameters were evaluated from the equation (8), which is derived from (7),

$$\ln x - \ln t = \ln K^* - \frac{\Theta}{T} \quad (8)$$

where pairs of values $x_i(t_i; T_i)$ obtained by particular i -th measurement at corresponding set temperature T_i are arranged into an X Y plot. Variables X and Y and the relevant coefficients a and b are determined by (9):

$$Y \equiv \ln x - \ln t, \quad X \equiv \frac{1}{T},$$

$$a \equiv \ln K^*, \quad b \equiv \Theta, \quad (9)$$

Fig. 4 shows XY plot with X_i, Y_i pairs regarding the definitions in (9), on which the best-fit linear function $Y = a + bX$ has been obtained by linear regression.

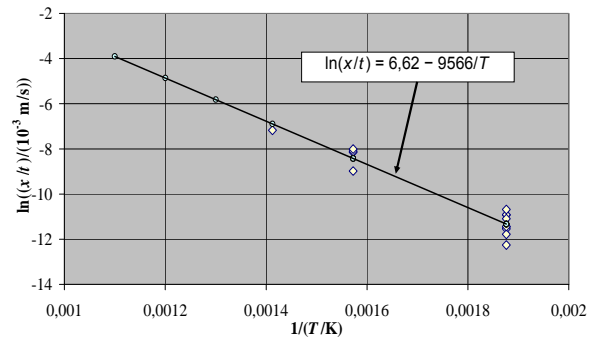


Fig. 4: Plot of measured x obtained at corresponding temperature T and time t fitted by linear regression function.

As the result coefficients Θ and K^* for the dissolution of solid E-Cu into SnCu1 solder were obtained as follows:

$$\Theta = 9566 \text{ K}, \quad K^* = 0,752 \text{ m/s}$$

In the literature describing the growth of inter-metallic layer on Cu-conductors of PCBs covered by Sn-base solder [6]. The reported values of Θ are substantially lower than those calculated from the present measurements. Values of the order of melting point magnitude would also be expected.

4 Temperature range at which M-effect takes place in a fuse link

The actual conditions at which the dissolution of fuse element takes place are substantially temperature dependent. Measurements of the temperature along the fuse element are not easy to perform with the appropriate accuracy even in the pre-arcing phase. The temperature rise has been frequently calculated by various simulation methods [8, 9, 10, 11]. The aim of the present study was to indicate phenomena leading to the abnormal M-effect during fuse operation as well. For this purpose the temperature distribution over the most critical segments of the fuse element has been assessed.

4.1 Simulation approach for the calculation of temperature rise

The fuse element under discussion, having a rated current 160 A, is loaded by current of 252 A. It is made of E-Cu strip of thickness 0,20 mm, perforated by 6 rows of round openings distributed over its length which form 6 columns of current contractions across its width. For the purpose of simulation the current path of length 43 mm was considered divided of 9 identical parallel sections of width 2,5 mm, each loaded by 28 A (250 A/9 sections). A series of 6 contractions spread along its length in the position of notches, each modeled by narrow rectangles of width 0,872 mm and length 2,00 mm. The simulation task was therefore reduced to a section of width 2,50 mm loaded by 28 A as a part of infinitely wide fuse element in order to reduce the problem on the one-dimensional, where the conditions varies in the direction of current flow along the fuse element.

The applied calculation method follows the physics of thermal equilibrium in the above mentioned section of fuse element strip with specific electrical conductivity σ , thermal coefficient of electrical resistance α and thermal conductivity λ concerning also thermal conduction through the sand filler to the ceramic cartridge. The connecting terminals and the ceramic cartridge of fuse link are considered to belong to the ambient, which temperature T_a is constant and equal everywhere in this "ambient". The value of thermal conductivity of sand filler λ_s was found in the literature [9]. The thermal equilibrium is described by a type differential equation (10), which is valid for each particular segment and notch of the modeled section.

$$\lambda \frac{d^2 \theta}{dx^2} + k \theta + a = 0 \quad (10)$$

In equation (10) coefficient λ determines thermal conductivity of Cu-strip, coefficient k relates to the difference between the dissipated power and thermal flux to the cartridge, while the coefficient a relates to the generated heat wherever at x . In general $k > 0$, $k = 0$ and $k < 0$ is possible regarding conditions for the particular segment or notch. The calculation of temperature rise ϑ along the fuse element (x) was performed following solutions of equation (10). They are formulated in (11) except for $k = 0$:

$k < 0$:

$$\theta = C_1 \cosh\left(\sqrt{\frac{|k|}{\lambda}} x\right) + C_2 \sinh\left(\sqrt{\frac{|k|}{\lambda}} x\right) + \frac{a}{|k|}$$

$k > 0$:

$$\theta = C_1 \cos\left(\sqrt{\frac{|k|}{\lambda}} x\right) + C_2 \sin\left(\sqrt{\frac{|k|}{\lambda}} x\right) - \frac{a}{|k|} \quad (11)$$

Arbitrary constants C_1 and C_2 are determined by the edge conditions for each particular segment or notch, which were derived from the coupling conditions between successive parts of modeled section.

Functions (11) were applied not only in the case of solid Cu-strip of uniform thickness but also for a double layer of solder of arbitrary thickness on Cu-strip. Moreover, they were applied also for the double layer of SnCu-melt/Cu-strip. In the case of dual layer an equivalent electrical and thermal conductivity was calculated for such material combination. Due to the lack of material data for SnCu1 the data for Sn is used for approximation. As the data for melted Sn and SnCu alloys are also not available the approximations stated for melted metals were taken from the literature [12].

4.2 Results of temperature-rise simulation

The calculation of temperature T along the fuse element is, regarding expressions in (11), based on the temperature rise θ , which is superposed on the constant ambient temperature T_a of ceramic cartridge and terminals. T_a depends on the cooling

effect of the actual ambient around the fuse link. For the simulation purpose the T_a value is chosen such that at least the melting point of SnCu1 is achieved at the value of load current taken for simulation which is equal to those used in actual operation tests of fuse links. To achieve the melting of solder on the soldered segment of fuse element was considered prerequisite for the initiation of M-effect process. Following steps of M-effect proceeds over the consecutive states of thermal equilibrium at which the dissolution of Cu steadily reduces the

thickness of solid Cu-strip of the notch at the unchanged T_a value till its rupture.

In the result $T(x)$ plot of temperature distributions $T/^\circ\text{C}$ along the fuse element are shown in Fig.5 for the initial and final phases of M-effect: first, at the moment the solder is just melted, and second, when the notch completely dissolves throughout its thickness. In both cases the external conditions remains unchanged.

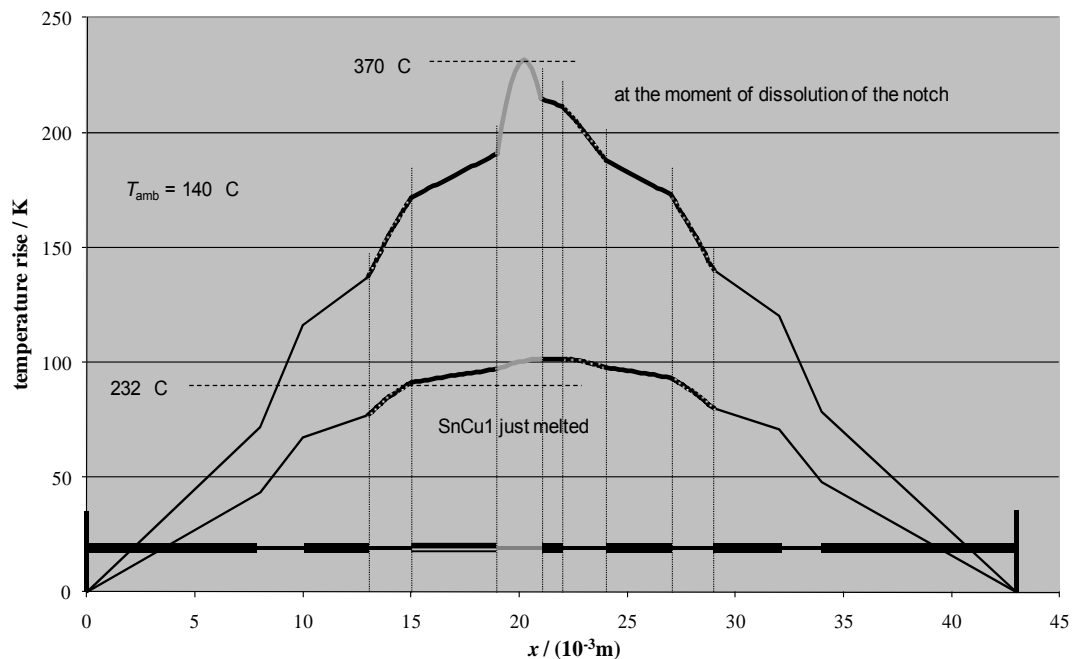


Fig.5: Distribution of temperature rise along fuse element 0,2 mm in the beginning and at the end of M-process. Bars above the horizontal axis represent the distribution of segments and nodes along the fuse element

4.3 The dissolution rate for segments near to the soldered notch

The tendency of molten solder to spread beyond its area of deposition could significantly influence the operating characteristic of fuse. In fact the temperatures of segments nearby to those deposited by solder is far above the melting point of SnCu1, the dissolution process can occupy much broader area than expected, when solder melt reaches these places. The potential intensity of dissolution in the hottest areas of fuse element was assessed for such cases by the ratio of dissolution coefficient $K^*(x)$ relative to K^*_{232} at the melting point of Sn. The results are shown graphically in Fig.6.

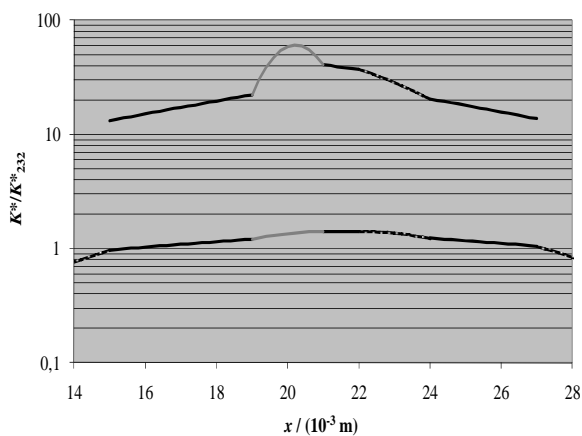


Fig.6: Relative value of dissolution coefficient K^* regarding K^* at the melting point of Sn along fuse element strip 0,2 mm.

From the graph of Fig. 6 it is evident that the dissolution rate for segments near the rupturing site by M-effect would be of the same order of magnitude and they represents potential sites where alloying of Cu strip by melted solder can take place in the case they would be wetted by the solder.

4.4 Formation of high resistive high-temperature solid SnCu-alloy

The operation of melting fuse at pre-arcing conditions is based on the formation of low-temperature melt due to the dissolution of fuse element strip by M-effect alloy providing that heating by the over-current attains the melting point of this alloy, which enables the dissolution of fuse element. The over-current should maintain the resulting alloy melted till break. It is possible due to low melting point of the alloy resulting from the

dissolution process. In the case of Cu strip deposited by Sn-base solder the melting temperature depends on the chemical composition of SnCu alloy as it is evident from the binary diagram of SnCu state [7]. The lowest melting temperature corresponds to the eutectic SnCu0,7 and it increases by the amount of Cu. Therefore the insufficient amount of solder deposit can lead to the formation of alloy with too high melting temperature, which cannot be attained by the specified over-current. The fuse element is likely to turn into heating element causing excessive heating of fuse cartridge and the operation of fuse link does not comply with the stated time-current characteristics. The various possible ways of evolution of M-effect are illustrated graphically in Fig. 7, shown by arrows. The rupture of fuse element is represented by two left-side arrows, leading to the formation of SnCu melt in the area of temperatures obtained by simulation. The right-side arrow represents the formation of solid SnCu alloy which does not result in breaking.

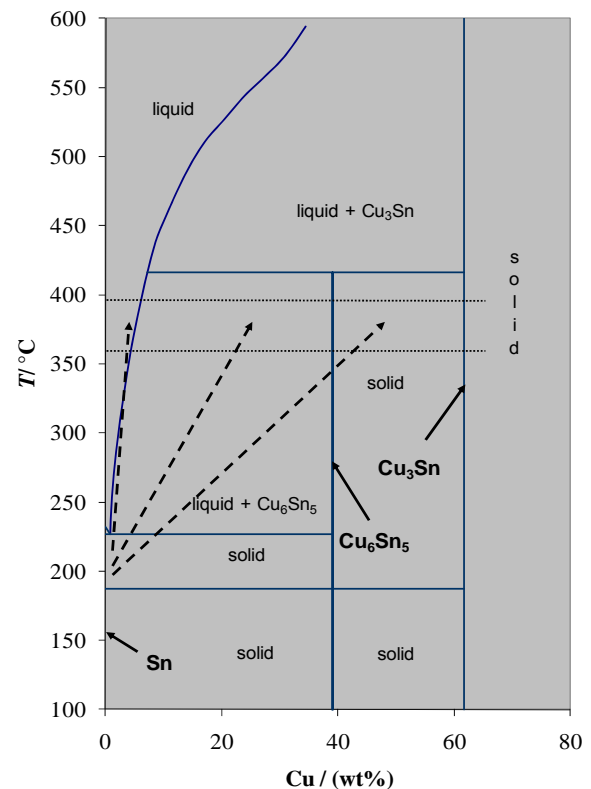


Fig.7: Various possible development of M-effect in the case of fuse element strip 0,2 mm shown in binary SnCu diagram.

5 Discussion

The dissolution parameters of solid Cu into molten SnCu1 were evaluated from measurements in order to investigate the dissolution of fuse element made of Cu strip by SnCu1 solder. As the result values of dissolution coefficient K and exponential parameter θ were obtained. The performed measurements and applied evaluation procedure were similar to those described in the literature. Some results obtained by measurements differ significantly from those referred elsewhere probably due to the dissimilar subject of investigation: the referred literature mainly deals with the growth of the inter-metallic layer on the soldered Cu conductive paths of printed circuit boards.

The data concerning the temperature distribution over the fuse element is prerequisite for the study of M-effect. A temperature measurement of fuse elements inside the fuse link is a complex procedure and the obtained results of limited accuracy. Therefore in parallel to the dissolution experiments the simulation of temperature distribution over the segments and notches of perforated fuse element strip due to heating by over-current was performed by semi-analytical calculation methods. Regardless of the lack of required material data and applied approximations the results obtained by the described simulation correlates to the available measured data. They are considered to be qualitatively applicable for further studies of M-effect.

6 Conclusions

The obtained values of the dissolution parameters along with the estimated temperature distribution over the fuse element evaluated for a given moment of dissolution time by semi-stationary approximation enable the complete time-relating simulation of dissolution process by involving the dissolution rate, which was evaluated as well. The purpose of such simulation is presumable explanation of the abnormal M-effect. In this paper the initial and the final state of dissolution are presented. It is pointed out that not only the specially designed rupture site of fuse element but also neighboring segments are sites of high temperature where the formation of SnCu alloy can take place in the case of excessive solder migration. But due to the limited amount of solder deposit on Cu strip the process can result in the formation of

SnCu alloy with higher content of Cu and consequently with considerably higher melting temperature. In this case a **solid** SnCu alloy presumably appears instead of low-temperature SnCu **melt** (see Fig. 7). High electric resistance of solid SnCu alloy turns fuse element into heating element.

There is no clear evidence whether the wetting of surface of fuse element by solder due to diffusion substantially contributes to the spreading of the dissolution area. An unwanted surface migration of melted solder over the of fuse element leading to the formation of solid SnCu alloy during M-process can presumably be driven also by surface tension of liquid solder meniscus which covers the perforated sites of fuse element strip. This effect has not been investigated yet.

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2011

**9th INTERNATIONAL CONFERENCE
ON ELECTRICAL FUSES AND THEIR APPLICATIONS**

The background of the cover is an abstract, futuristic illustration. It features a central, glowing cylindrical object, likely a fuse, with a complex, multi-layered structure. The object is rendered in shades of yellow, orange, and red, with a bright, white, glowing core. The background is filled with a grid of light blue and white lines, creating a sense of depth and technical precision. The overall aesthetic is clean, modern, and scientific.

**THERMAL ANALYSIS AND TEMPERATURE
CALCULATION FOR THE NV MELTING FUSE**

Anton Hamler, Sašo Grill, Jelena Popović Cukovic