

FUSING AND AGEING BEHAVIOUR OF FUSE ELEMENTS WITH "M"-EFFECT AT MEDIUM- AND LONG-TIME OVERLOAD

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ABSTRACT

This paper reports on investigations of the "M"-effect of fuse elements with various base metal/solder combinations in the range of very-long-time overload and medium-time overload. Two factors are influencing the shape of the time/current characteristics:

- The current where the time/current characteristic approaches the asymptotic shape is equal to the current where the solder reaches the solidus point temperature. A comparison with calculated current values shows good agreement with the measurements.
- In the medium-time range the different fuse elements perform according to the solder's dissolution capability for the base metal. There is no correlation with the solidus point temperature.

In further tests the dissolution behaviour was studied independently of the load current. Various fuse element/solder combinations were annealed in a furnace and the remaining base metal thickness at different times and temperatures was measured. The results show two ranges of dissolution which are in good accordance with both ranges of the time/current characteristics. Furthermore the dissolution capability can be described and calculated with the knowledge of diffusion laws and phase diagrams of the base metal/solder systems.

1. INTRODUCTION

In "M"-effect fuses the dissolution of the base metal (Cu, Ag) by a deposit of soft solder is utilized to adjust the time/current characteristics in the overload range. On the other hand this irreversible effect may be the cause of undesirable ageing.

IEC recommendations /1/ and VDE specifications /2/ require for standard fuses that the shapes of the time/current character-

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istics lie between definite time/current values in the overload and short circuit range. The rated current is defined according to these values. The maximum test time for fuses up to 160 A rated current is 1 or 2 hours. No further regulations are made concerning longer times.

In order to obtain more information about the range of very long time overload (between one hour and several days) and of medium time overload (below one hour) investigations of the "M"-effect were made with various base metal/solder combinations at overcurrent load. Different solder materials with different solidus point temperatures between 124° C and 327° C were tested.

At overcurrent load tests the dissolution behaviour is not independent of the load current, because the effective remaining cross section, the resistance, the temperature and thus the dissolution speed mutually influence and enhance each other.

In order to study the dissolution behaviour independently of the load current various fuse element/solder combinations were annealed at different temperatures in a furnace. The dissolution of the base metal in dependence of time and temperature was studied, measuring the remaining base metal thickness by micrographs. The results are compared with diffusion theories and they contribute to explain the ageing behaviour as well as the shape of the time/current characteristics, which had been found by the overload current tests.

2. TEST METHODS

2.1 Test Arrangement Fig. 1 shows the principle of the test circuit. The high-current transformer T2 is connected to the AC power supply (220 V/50 Hz) over contactor K1, variable-ratio transformer T1, contactor K2 and the antiparallel thyristors V1, V2. The secondary circuit of the high-current transformer supplies the series connection of the shunts R1, R2, current transformer T3 and the fuse model E.

The tests were carried out in a current range between 80 A and 130 A, with currents kept constant within ± 1 A by a control circuit. The fuse model E is designed to hold replaceable test fuse elements. Fig. 2 shows the basic dimensions of the fuse elements. One edge of the solder deposit is located in the centre of the element, i.e. at the site of the highest temperature $\vartheta_{\max}$. The terminals of the fuse model are watercooled. Their temperature is kept constant at 18° C - 19° C to ensure reproducible random conditions. All tests were carried out with air as surrounding medium around the fuse elements.

The main measuring equipment consists of:

- a. a time counter, which records the fusing time in steps of 20 ms.
- b. an infra-red radiation pyrometer, which allows contactless temperature measurement on the fuse element surface.

- c. an x-t-recorder for the fuse element voltage and the temperature of the solder deposit.

2.2 Characteristic Data of Investigated Materials

Two base

metals were used for the fuse elements:

- Cu
- Ag

Several solder alloys with low, medium and high eutectic temperatures and melting temperature range respectively were chosen:

- Bi/Pb	55,5/44,5	wt. %	124° C
- Bi/Sn	57/43	wt. %	134° C
- Sn/Cd/Zn	70/25/5	wt. %	160° C
- Sn/Cd	80/20	wt. %	177° C - 192° C
- Sn/Pb	60/40	wt. %	183° C
- Sn			232° C
- Pb			327° C

(Data: manufacturers' data and /3/)

2.3 Fusing Tests

These tests were carried out in the circuit of fig. 1 with the material combinations of chapter 2.2. For each current and material approximately 5 single trials were carried out. The time t_s until fusing is plotted as an average.

2.4 Dissolution Behaviour Tests

The following base metal/solder combinations were exposed to different temperatures in a furnace (base metal + solder):

- Cu + Sn
- Cu + Sn/Pb 60/40
- Ag + Sn
- Ag + Sn/Cd 80/20

The temperature values and the annealing times for the tested fuse elements were:

- 150° C	0 - 20 days
- 200° C	0 - 10 days
- 250° C	0 - 50 hours
- 350° C	0 - 320 minutes
- 480° C	0 - 60 minutes

After each test the fuse elements were cooled down quickly.

Afterwards micrographs were made and the remaining base metal thickness $\bar{d}$ was measured. The dissolution depth $\bar{x}$ is then given by the following equation:

$$\bar{x} = \frac{d_l + d_r}{2} - \bar{d} \quad (1)$$

(see also fig. 3)

3. RESULTS

3.1 Fusing Characteristics at Medium- and Long-Time Overload

Fig. 4 shows the measured time/current characteristics. The time range covered lies between 10 minutes and 7 days. The solid lines connect the measured time/current values. The dashed lines lie outside the range of measurement and represent the shape of curves to be expected by theoretical considerations.

Material symbols with arrows mark the asymptotic current values gained theoretically by assuming that the solidus point (melting point) temperature is just reached there. Arrow symbols within the figure mark current values, where the fuse elements were tested without fusing. In these cases the solder also never became liquid.

It was expected that evident material changes occur only when the solder is liquid. This was confirmed for at least 4 material combinations (Ag + Sn, Cu + Sn, Cu + Sn/Pb 60/40, Cu + Sn/Cd/Zn 70/25/5). For these materials at very long times and for the same base metal (Cu) the asymptotic current values are arranged in the sequence of the solidus temperatures T_s , e.g.: Cu + Sn/Cd/Zn 70/25/5 ($T_s = 160^\circ \text{C}$) at 85 A, Cu + Sn/Pb 60/40 ($T_s = 183^\circ \text{C}$) at 90 A, Cu + Sn ($T_s = 232^\circ \text{C}$) at 95 A.

As mentioned before these current values can be determined by calculation. For this calculation an equation derived by /4/ is used, which describes the dependence between current I and temperature $\vartheta_{\max}$ in the centre:

$$I = \sqrt{\frac{\lambda \cdot \kappa_e}{\alpha_e}} \cdot \frac{2 \cdot b \cdot d}{l} \cdot \arccos \left(\frac{1}{\vartheta_{\max} \cdot \alpha_e + 1} \right) \quad (2)$$

- | | |
|---|---|
| I - current | b - width of fuse element |
| λ - heat conductivity | d - thickness of fuse element |
| κ_e - electrical conductivity | l - length of fuse element |
| α_e - temperature coefficient of electrical conductivity | $\vartheta_{\max}$ - maximum temperature at $l/2$ |

The conditions for the validity of equation (2) are:

- Heat conduction occurs only within the base metal of the fuse element to the terminals. This is often valid in air.
- Negligible electric current and heat flow occurs through the solder deposit. This condition is nearly fulfilled because the electrical and thermal conductivities of the solder are much smaller than those of the base metal.

If the solidus temperature T_s is taken for $\vartheta_{\max}$ and the materials data are inserted, the equation gives the desired current values.

Fig. 5 shows the calculated values, which are compared with the measured currents at which the solders became liquid. The results show good agreement of calculations and measurements.

The comparison of Cu + Sn and Ag + Sn fuse elements shows that the asymptotic course of the Ag + Sn characteristics lies at a higher current (100 A) than that of Cu + Sn (95 A). This effect could be expected because of the better heat conductivity of silver. With higher currents, however, the greater dissolution capability for silver quickly leads to smaller fusing times of Ag + Sn fuse elements in comparison with Cu+Sn.

In view of time/current behaviour and ageing this leads to the following conclusions: From known literature /5/ it could be expected that the diffusion speed is practically negligible in the solid state, and becomes effective only when the solder is liquid. The measurements as well as the calculation basing on this assumption show that the asymptote of the time/current characteristics actually coincides with the current where the solder becomes liquid. At a higher current range the dissolution capability predominates the fusing behaviour.

The influence of solidus temperature and dissolution capability must not coincide. Therefore the consequence is that crossovers between different time/current characteristics do exist.

In practical application the rated current of a fuse is defined at long fusing times according to two values /1, 2/:

- a. the conventional non-fusing current $I_{nf} = 1,3 \cdot I_N$
- b. the conventional fusing current $I_f = 1,6 \cdot I_N$

The characteristics have to run between these angle points. The conventional fusing time is e.g. one hour for fuses up to 63 A rated current.

In order to compare the characteristics of different base metal/solder combinations it is essential to refer all characteristics to the same rated current. Therefore all characteristics have to be modified with known methods like changes of cross-section and/or length.

Fig. 6 shows the results of such an adaptation. All characteristics were fit by multiplying the currents of fig. 4 with a constant in order to run through the point with the conventional time 1 hour and 91,35 A (which is $1,45 \cdot I_N$ of a fuse with $I_N = 63$ A rated current).

It can be recognized that at this point most of the base metal/solder combinations have not reached the asymptotic shape and show fusing after some hours at even lower overcurrents.

This means that at low long-time overloads ageing starts the earlier the more the asymptote lies at lower overcurrents. Especially the fuse elements with solders, which have low solidus temperatures, are expected to be more subject to

ageing, e.g. Cu + Sn/Pb 60/40 is more subject to ageing than Cu + Sn and Ag + Sn. At medium-time overload the specific dissolution behaviour of the materials dominate the time/current behaviour.

3.2 Results Of Dissolution Behaviour Tests Already the newly manufactured fuse elements showed a certain depth of dissolution, referred to as starting dissolution depth. The single starting values of Cu + Sn fuse elements scattered between 0 and 9 μm , those of Cu + Sn/Pb 60/40 fuse elements between 0 and 7 μm . These values are typical for the dissolution by the manufacturing process (soldering). They are plotted at $t = 0$ in the following diagrams.

As results of the annealing tests with Cu+Sn and Cu+Sn/Pb 60/40 fuse elements fig. 7 shows the dissolution depth $\bar{x}$ (see also fig. 3) in dependence of time t with temperature T as parameter.

Generally the dissolution depth increases with higher temperature. In the beginning a fast dissolution occurs, followed by a certain stagnation or saturation after some time.

As long as the test temperatures were lower than the solders' solidus temperatures no progress of the dissolution was detectable. All measured $\bar{x}$ values lied within the starting range even after 20 days of annealing time.

But at $T = 200^\circ\text{C}$ the Sn/Pb 60/40 solder is already liquid whereas the Sn solder is still solid. Cu + Sn/Pb 60/40 shows already an increasing dissolution depth with the time whereas that of Cu + Sn remains still in the starting range. At temperatures above 250°C when both solders are liquid the dissolution depth of Cu + Sn is always greater than that of Cu + Sn/Pb 60/40. Then the curves of the dissolution depth also characterize the fusing behaviour under current load. In fig. 4 above 95 A - the current where both solders are liquid - Cu + Sn shows always a quicker dissolution i.e. the fusing time is smaller than that of Cu + Sn/Pb 60/40. The dissolution capability then rules the fusing behaviour.

The measurements of the annealing tests confirm that both ranges of dissolution are in good accordance with the two ranges of the time/current characteristics.

Theoretically the dissolution capability could be described with the knowledge of diffusion laws and phase diagrams of the base metal/solder systems.

With the special example of Cu + Sn this means:
Diffusion mainly occurs from Cu to Sn /5/.

At temperatures below the solidus temperature this leads to the growth of intermetallic layers at the interface between base metal and solder. The growth rate is so small that it can be neglected in the considered time range.

At temperatures above the solidus point the diffusion speed of copper into tin becomes higher by orders of magnitude /6/. The reverse direction tin into copper is negligible.

Now two effects are responsible for the value of the dissolution depth:

- a. The growth of intermetallic layers at the interface.
Three intermetallic layers exist in the investigated temperature range /3, 5, 6/, see also fig. 8:

1. δ -phase (Cu₄₁ Sn₁₁)
2. ϵ -phase (Cu₃ Sn)
3. η - or η' -phase (Cu₆ Sn₅)

They were identified in micrographs in the above sequence between the copper base and tin.

- b. The dissolution of copper in the liquid solder.
Because the diffusion speed is proportional to the concentration gradient, the dissolution starts with a steep increase at $t = 0$. After some time the concentration of copper in tin approaches a temperature-dependent saturation value which corresponds to the liquidus line in the phase diagram fig. 8, e.g. 1,35 % by weight at 250° C, 4,33 % at 350° C, 13,42 % at 480° C (points marked with circles in fig. 8). When this saturation value is reached no further copper is dissolved by the liquid solder.

Under the assumption that the base metal is dissolved in the liquid tin until saturation and no additional intermetallic layers are formed, and that the dissolution occurs uniformly under the original area of the solder, a theoretical maximum dissolution depth for $t \rightarrow \infty$ can be calculated. The final dissolution depth x_{∞} is only dependent on the saturation concentration $C_s(T)$, the densities ρ_{Sn} and ρ_{Cu} and the height d_{Sn} of the solder deposit. Equation (3) gives the correlation:

$$x_{\infty} = \frac{\rho_{Sn}}{\rho_{Cu}} \cdot d_{Sn} \cdot \frac{C_s(T)}{1 - C_s(T)} \quad (3)$$

- x_{∞} - dissolution depth for $t \rightarrow \infty$
 d_{Sn} - height of new solder deposit
 ρ_{Sn} - density of tin
 ρ_{Cu} - density of copper
 $C_s(T)$ - saturation concentration by weight (depending on temperature) for copper in liquid tin according to liquidus lines.

The horizontal lines 1 in fig. 7 show the values of the maximum dissolution depth according to equation (3). For a more accurate picture also the copper containing intermetallic layers have to be considered. Their thicknesses at the maximum annealing time were measured from micrographs and converted to a copper thickness according to their copper content and added to the value given by equation (3).

The lines 2 show the results.

The measured maximum values and the calculated values show good agreement.

These values were calculated with the solder height of newly manufactured fuse elements. During the annealing time, however, the shape of the solder deposit changes and the area of the interface between deposit and base metal changes e.g. from 4 mm length to about 4,4 mm. If this height reduction to about 90 % of the manufacturing height is taken into account an even much better agreement between calculation and measurement is obtained.

A comparison between the results shows that at higher temperatures (350-480° C) the dissolution of copper in liquid tin until saturation dominates indeed, whereas at lower temperatures the formation of intermetallic layers contributes about 50 % to the total copper consumption.

The lines 3 and 4 in fig. 7 show theoretical results for Cu + Sn/Pb 60/40 fuse elements. In the investigated temperature range the dissolution capability of Pb for Cu is very small. Therefore the lead content of the solder can be considered as a mainly inactive filler, reducing the amount of the active component tin to 60 weight % or 70 volume %. Then the theoretical values of the dissolution depth were calculated by multiplication of the Cu + Sn values from equation (3) with the factor 0,7 according to the solder's tin content by volume.

The measured values confirm this expected tendency, the deviation is, however, greater. A more precise explanation would demand the consideration of the exact system Cu-Sn-Pb.

Further tests were made with fuse elements, where silver was the base metal. The solder materials were Sn and Sn/Cd 80/20. Fig. 9 shows the results.

The starting dissolution depth of Ag fuse elements is greater than that of Cu fuse elements. At higher temperatures the dissolution of the base metal is much stronger with Ag fuse elements. Especially the Ag + Sn fuse elements show sometimes a big scatter of the dissolution depth.

In the temperature range of 250° C to 480° C Ag + Sn always shows a greater dissolution depth in comparison with Ag + Sn/Cd 80/20.

At a temperature $T = 250^{\circ}\text{C}$ the agreement between measured and calculated (see equation (3)) values for both Ag fuse elements is quite good. But at higher temperatures (350°C and 480°C) both solders tend to spread widely across the surface of the base metal. This causes an unpredictable and not very constant reduction of the height of the solder deposit. It leads to inaccuracies in the precalculation of the maximum dissolution depth by using the solder deposit height of newly manufactured fuse elements.

If the solder spreading is suppressed, the calculation is practicable again.

Altogether the saturation effect may also have great influence on the fusing behaviour at low overload currents and long fusing times. In order to achieve fusing in this range, the base metal beneath the solder deposit must be dissolved through the whole thickness. For safe operation the height of the solder deposit should not remain under a certain minimum height which, under the simplified assumptions of equation (3), reads

$$d_{\text{solder}} \geq d_{\text{base}} \cdot \frac{s_{\text{base}}}{s_{\text{solder}}} \cdot \frac{1 - C_s(T)}{C_s(T)} \quad (4)$$

Otherwise an undesirable stabilization at high temperature levels is possible.

4. SUMMARY

The dissolution behaviour of base metal and solder is the important factor in the overload current range concerning the fusing and ageing behaviour.

Two temperature ranges must be distinguished:

- The temperature of the solder deposit is below the solidus point temperature. The dissolution of base metal is very slow and practically negligible.
- The temperature is greater than the solidus temperature. Then more evident dissolution occurs by growth of inter-metallic layers and dissolution of the base metal in the liquid solder up to saturation. The last effect predominates at higher temperatures.

With respect to ageing the results show that fuse elements with solder deposits, which have low solidus temperatures, are more subject to ageing at long-time overload than those, which have higher solidus temperatures.

With respect to fusing characteristics the results show that the asymptotic current values could be estimated by supposing that the solder deposit becomes liquid at these currents. At greater overload currents the fusing behaviour is ruled by the dissolution behaviour. The interpretation of measured dissolution curves at different temperatures shows that characteris-

tic dissolution data can be derived theoretically from the phase diagram of the solder/base metal system. The opposite requirements of good ageing behaviour and desired fusing behaviour have to lead to acceptable compromises concerning the base metal/solder combination.

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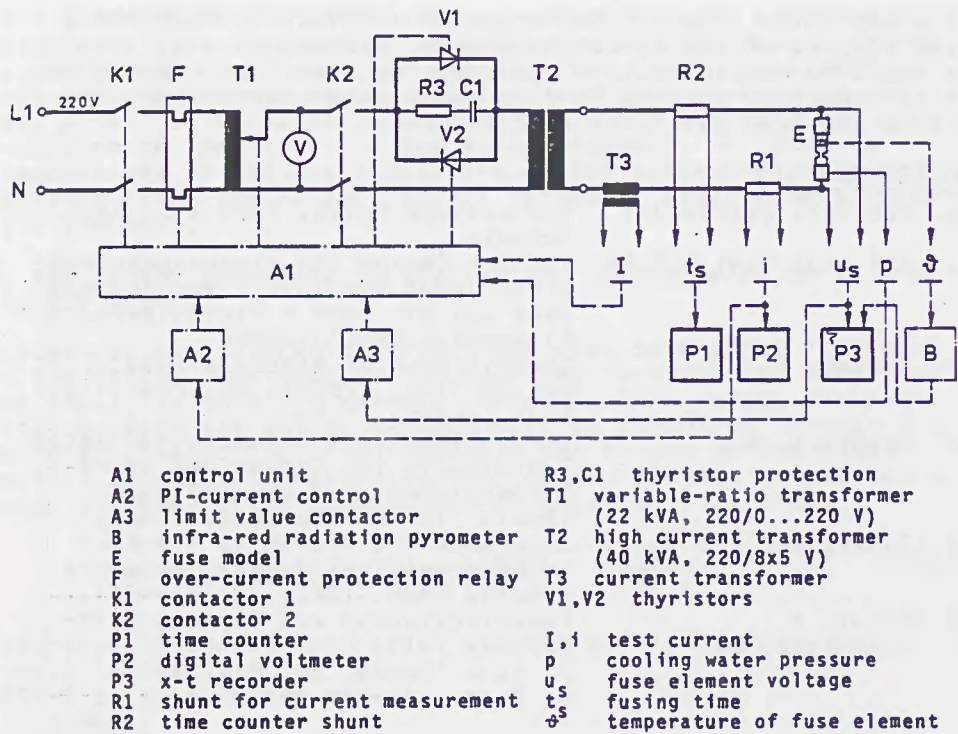
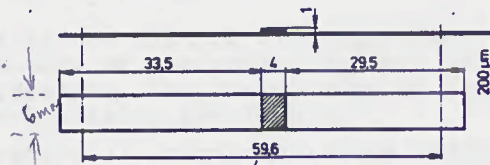


Fig.1 Test circuit



(length between watercooled terminals)

Fig.2 Dimensions of fuse elements

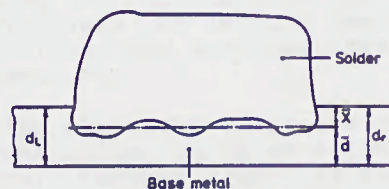


Fig.3 Principle of evaluation of micrographs

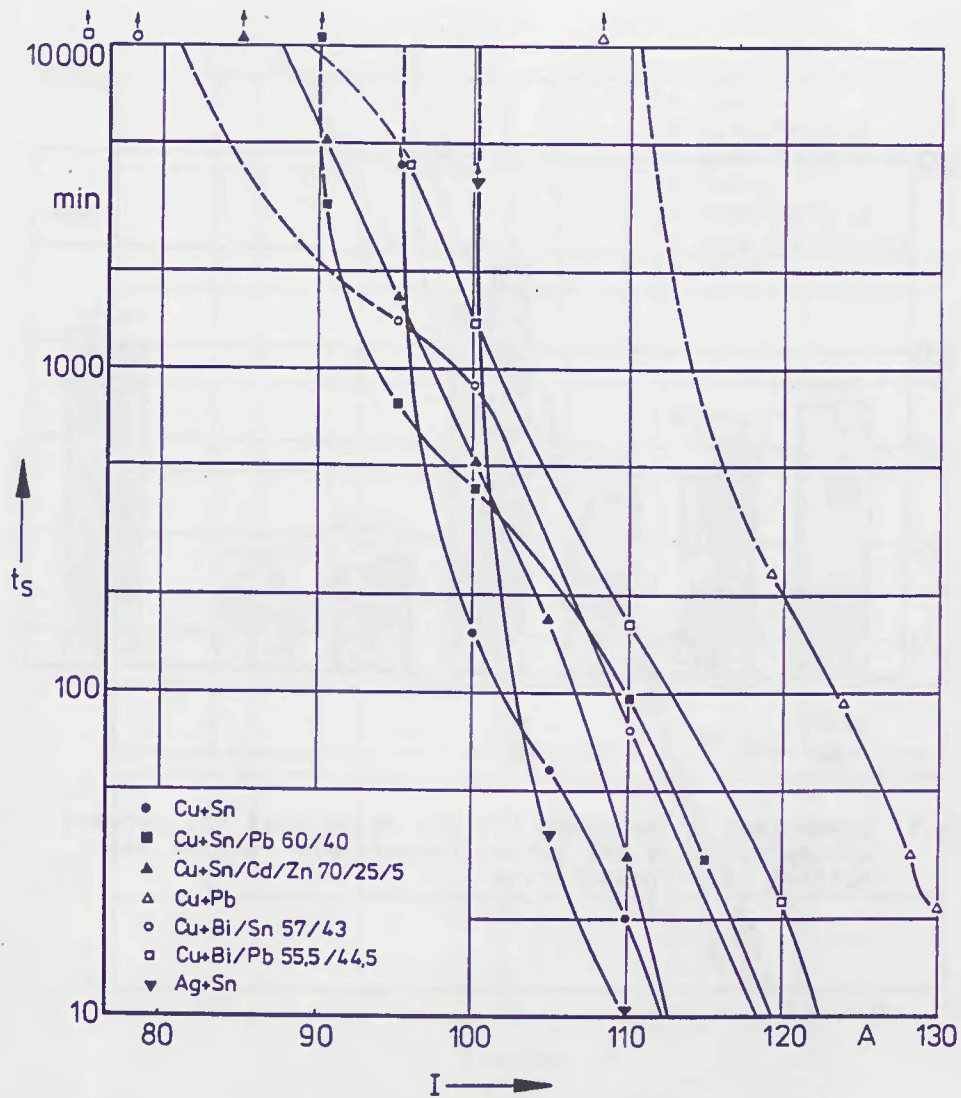


Fig.4 Time/current characteristics at medium- and long-time overload

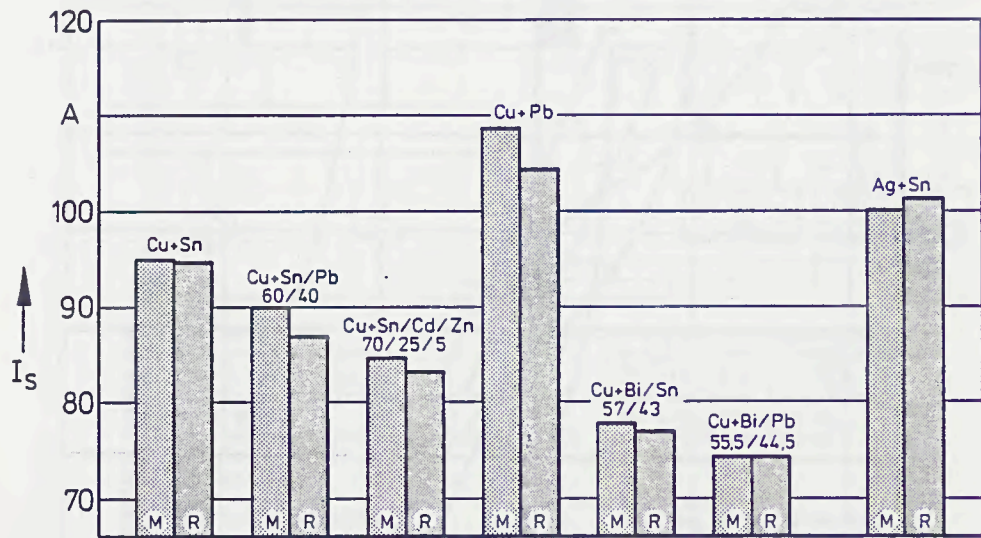


Fig.5 Comparison of measured (M) and calculated (R) current values at which the solder temperature reaches the solidus point temperature

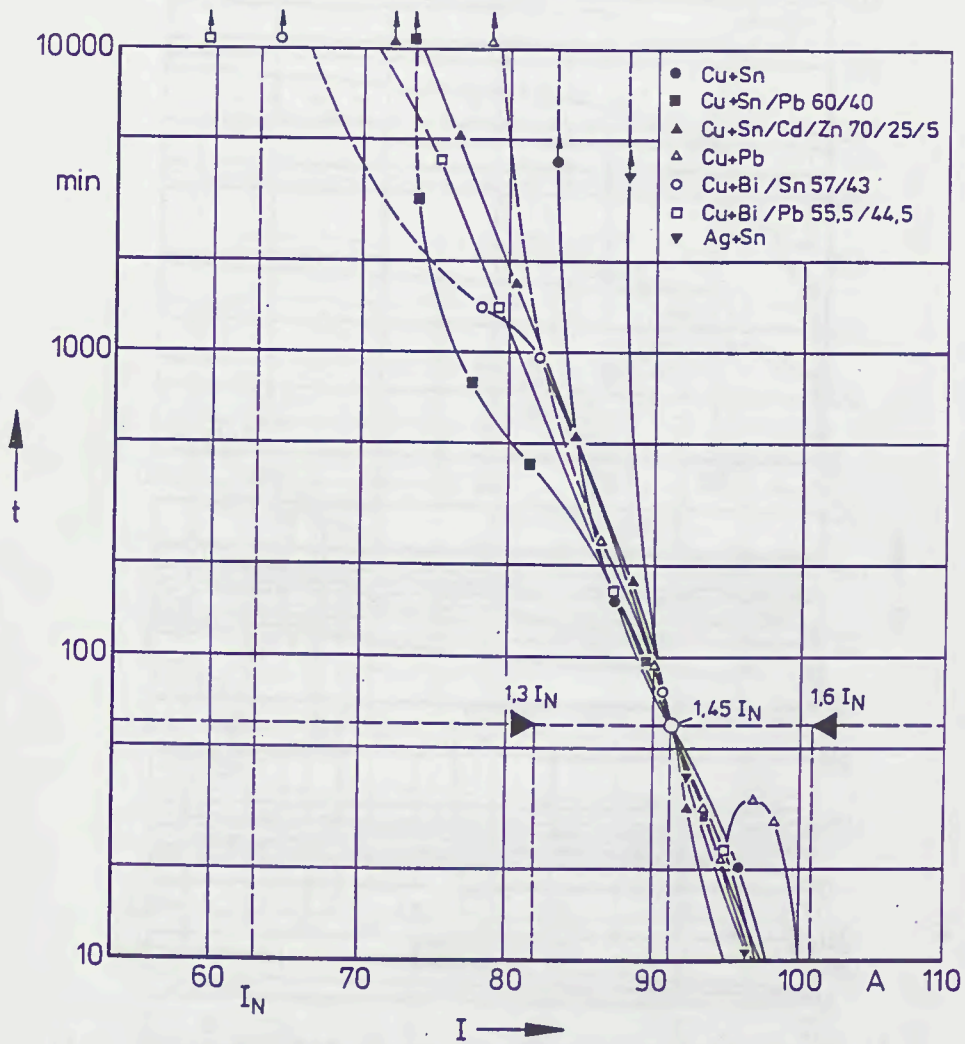


Fig.6 Time/current characteristics with adaptation to the point 60 minutes/ 91 A

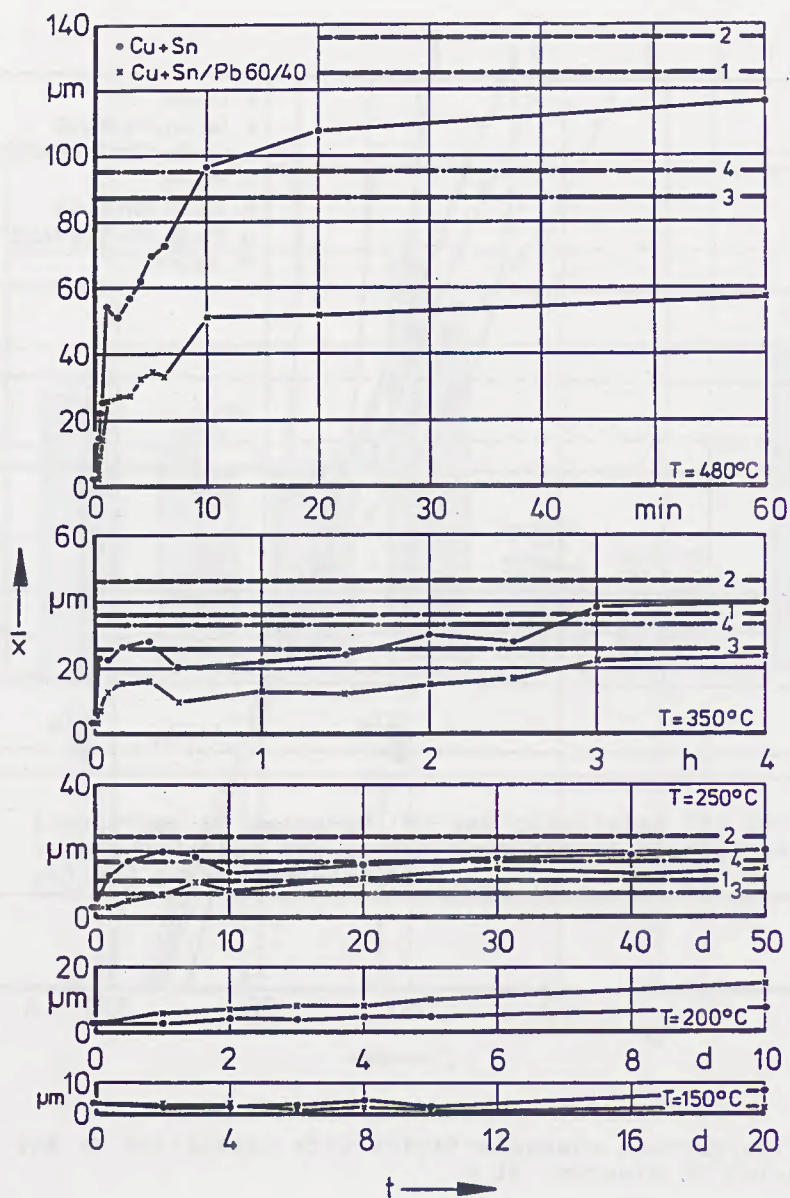


Fig.7 Dissolution depth $\bar{x}$ in dependence of time t with temperature T as parameter for Cu fuse elements
 (Theoretical values for $t \rightarrow \infty$:
 lines 1,3 - without intermetallic layers
 lines 2,4 - with intermetallic layers)

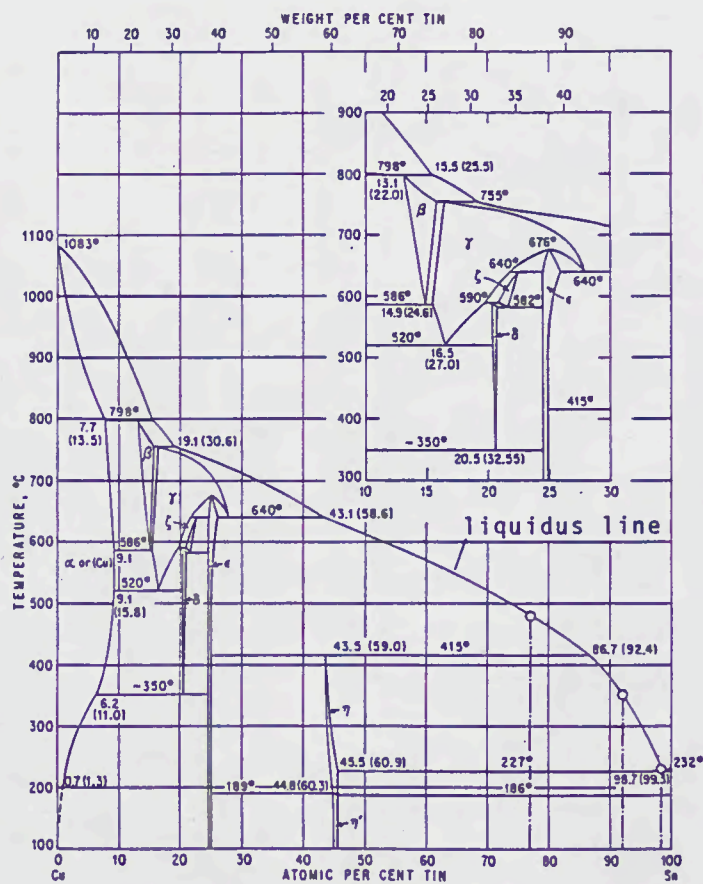


Fig.8 Phase diagram of the Cu-Sn system (from Hansen /3/)

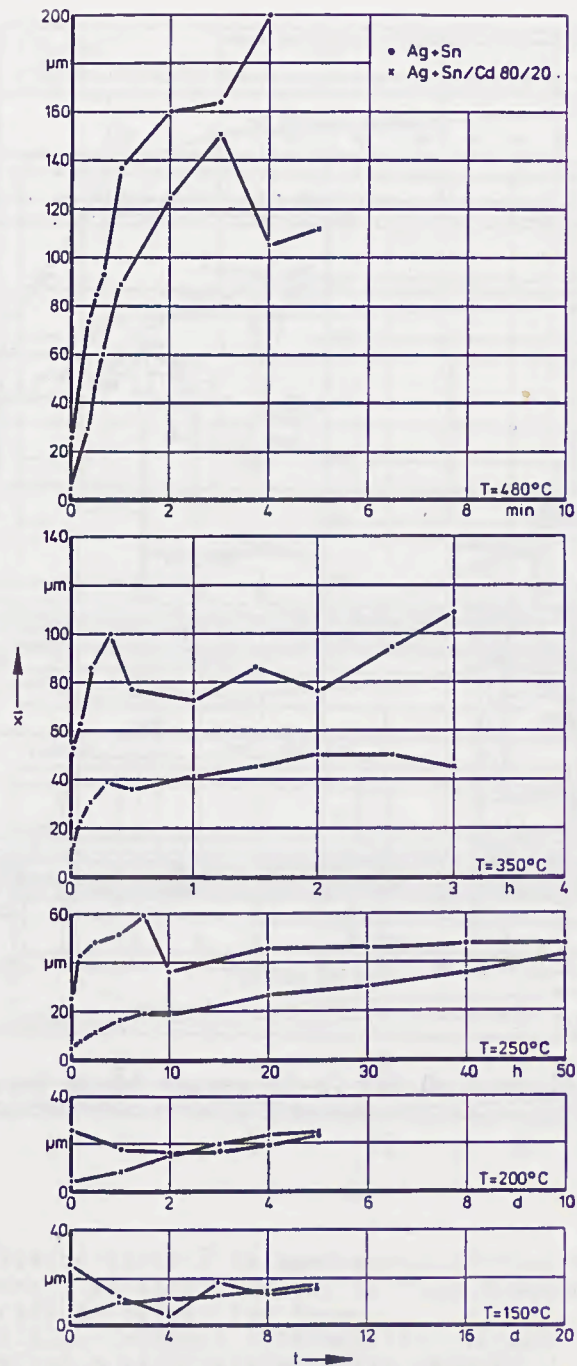


Fig.9 Dissolution depth $\bar{x}$ in dependence of time t with temperature T as parameter for Ag fuse elements

