METALLURGICAL DETERIORATION OF COPPER FUSE ELEMENTS IN HIGH VOLTAGE FUSES

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INTRODUCTION

The properties of an electric fuse should, as far as possible, remain unchanged during the entire fuse life-time. It is essential, therefore, that the fuse element metal should have high resistance to oxidation. Furthermore, if the design is based on the so-called M-effect [1], possible intermetallic reactions in the M-spot should not cause significant changes in the fuse performance.

Silver readily meets these demands. It has high resistance to oxidation, and it has been demonstrated that intermetallic reactions between silver and a tin M-spot do not occur at unacceptable rates [2]. Although other metals like copper, zink and aluminium are widely used in low voltage fuses, most high voltage fuse designs are still based on silver elements. However, rising silver prices and doubts about future availability, have pushed the search for a less precious substitute.

This contribution is concerned with intermetallic reactions between a copper fuse element and a tin M-spot at different temperatures. It contains results from a study of solid state interdiffusion rates, dissolution rates for copper in liquid tin, and a description of the fusing processes in the M-effect region.

EXPERIMENTS AND RESULTS

Solid state reactions. Copper-tin diffusion samples were prepared by fusing a 2.6 x 1.0 x 100 mm piece of Sn onto a 2.6 x 0,135 x 200 mm Cu strip by means of a microtorch. The copper strip had been given a thin ($<1\,\mu m$) silver coating for oxidation protection. Examination of fresh samples by X-ray microanalysis showed that no detectable amounts of intermetallic compounds had formed at the interface during the fusing process.

A number of diffusion samples were heat treated in an oven at four different temperatures ranging from 147°C to 222°C for time spans up to 2800 hrs. The temperature variation in the oven was less than $\pm 2°$C.

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After heat treatment the diffusion samples were cut in sections at right angles to the interface and polished to 0.1 μm finish with diamond paste. Subsequent quantitative X-ray microanalyses showed that a duplex compound layer, with atomic tin consentrations 24.6% and 45.5% respectively, had developed at the interface. This is in accordance with the Cu-Sn phase diagram shown in fig. 1, which predicts formation of the ε (Cu_3Sn) and the η' (Cu_6Sn_5) phases. No variations in concentration were detected neither in the metals nor in the compounds. The growth rates of the compounds are shown in figs. 2 and 3.

To check a possible influence of the silver coating, similar diffusion samples were made from uncoated copper strips, and heat treated at 215°C. The growth rates for the intermetallic compounds are shown in fig. 4.

Liquid state reactions. For temperatures exceeding the melting point of tin, 232°C, the diffusion processes simply leads to a dissolution of solid copper into the tin liquid. Dissolution rates were experimentally determined by immersing copper strips into tin melts of different temperatures and copper consentrations. The amount of copper that had been dissolved in a certain period of time, was obtained from the remaining thickness of the copper strip. The temperature of the tin melt was stable when the melt was kept close to its liquidous point, while it decreased by as much as 1.5°C per second for the highest temperatures.

Measured dissolution rates are shown in fig. 5. The amount of copper dissolved from one side of the copper strip has been plotted versus square root of the immersion time.

Analyses of the immersed copper strips show that a thin layer of Cu_3Sn developes at the solid/liquid interface, probably through diffusion of tin into copper.

Most likely copper is dissolved by a continuous growth of the Cu_3Sn layer at the copper side, and a simultaneous dissolution of the compound at the tin side. The thickness of the Cu_3Sn layer was less than 1 μm in all the immersion experiments.

Fusing in the M-effect region. To study the M-effect more closely, a number of fuses with copper fuse elements 2.6 x 0.135 x 520 mm were made. The copper element contained 32 equally spaced constrictions, and had a 2.6 x 1.0 x 5.0 mm tin M-spot placed between two constrictions in the middle of the element. The temperature could be measured by two chromel-alumel thermocouples that were pinched into the M-spot as indicated in fig. 6.

Fusing experiments with low voltage currents ranging from 25 A to 66 A were carried out. For these currents the fusing is caused by the M-effect, and the fusing times range from nearly 3 hrs. down to approximately 17 sec. Careful studies of the M-spot region after current interruption revealed two different patterns of fusing:

A. The tin M-spot is more or less confined to its original shape and place even after melting, and the copper underneath the tin melt is gradually dissolved until the fusing is completed. Normally the fusing occurs at the edge of the M-spot.

B. Melted tin flows along the copper strip to a neighbouring constriction, where the narrow copper neck is dissolved into the melt.

Typical M-spot temperature curves for a fusing pattern of type "A", are shown in fig. 6. The temperature increases rather rapidly to the melting point of tin where it slows down considerably due to the melting energy. When the tin is melted, the temperature rise is more or less constant until the temperature starts to escalate just prior to fusing.

In a second series of fusing experiments the current was shunted at different stages in the fusing process between the melting time for tin (t_m) and the total fusing time (t_f). Also in this series the fusing followed pattern "A". Analyses of the M-spot region showed that the copper underneath the tin liquid is gradually dissolved. The dissolution rate is generally higher at the edge of the M-spot. At t_1 the dissolution has reached a stage where the current path through solid copper is completely broken, and the current has to flow through the melt. Clearly this causes a run-away effect in the temperature.

It should be noticed that current interruption does not occur when the solid copper strip is broken. Indeed, experiments terminated just prior to fusing showed that the current can flow through the melt even when the copper is completely dissolved 1 to 2 mm to the sides of the M-spot. This proves that final fusing does not occur until the tin-copper melt has reached a temperature at which it has sufficiently low viscosity to flow into the voids between the quartz grains.

DISCUSSION

The annealing experiments have shown that the intermetallic compounds Cu_3Sn and Cu_6Sn_5 develope at the copper-tin interface in an M-spot. The measured thicknesses vary considerably along the interface and even more so between identically heat treated samples. This is due to the fact that the diffusion processes are influenced by a number of statistical parameters like cleanness of the interface, voids in the metals, stress consentrations, etc.

Despite the large spread in the results, figs. 2 to 4 demonstrate that the growth has a parabolic time dependency, at least for long annealing times. It can also be seen that the initial growth rate of Cu_6Sn_5 is considerably higher than the long term growth rate. Cu_3Sn starts to grow after a certain delay time which increases with decreasing temperature. Similar observations were made by Kay and Mackay [3] in a study of tin coatings on copper. The explanation for this is to be found in the phase diagram. Copper is insoluble in solid tin. Diffusion of copper into tin, therefore, immediately leads to the formation of the tin-rich compound Cu_6Sn_5. Tin, on the other hand, is slightly soluble in copper even at low temperatures (1.3 weight % at 200°C). Hence, diffusion of tin into copper does not lead to formation of Cu_3Sn until the consentration has reached the solubility limit. The time needed to reach this limit naturally increases with decreasing temperature. When the Cu_3Sn compound starts to grow, one would expect the Cu_6Sn_5 growth rate to be reduced since the availability of copper for further growth is

reduced. This is in accordance with our results.

Comparison of figs. 2 and 3 with fig. 4 indicates that the thin silver coating has a very limited effect on the growth of copper-tin compounds. It seems that the growth rate of Cu_3Sn is somewhat higher for the uncoated copper strip. This could, however, equally well be due to differences in residual stresses in the two types of copper strips [3].

Fig. 7 is an Arrhenius plot of the quadratic growth rates obtained from figs. 2 and 3. The experimental values for Cu_3Sn falls reasonably well on a straight line. This is not true for Cu_6Sn_5. A possible explanation might be the ordering transformation that occurs for this compound at 186°C. The results are, however, to limited to confirm this.

The measured growth rates for Cu_3Sn are in reasonable agreement with those reported by Onishi and Fujibuchi [4], while there are considerable discrepansies for Cu_6Sn_5, our results showing a much stronger temperature dependency. No satisfactory explanation has been found for this difference.

The time spans needed to complete the transformation of a 50 µm thick copper fuse element to high resistance intermetallic compounds are listed in table 1.

Temp. [°C]	147	182	222
Transf.time	14 years	2.5 years	24 days

Table 1. Transformation times for 50 µm copper.

This demonstrates that to prevent the copper element underneath the M-spot from being transformed into high resistance compounds, the long term service temperature should not exceed approximately 150°C. Short term temperature rise, due to for instance motor starts or inrush currents, does not cause unacceptable deterioration even if the temperature approaches the melting point of tin (232°C). It should be noted that the transformation times for copper are considerably longer than for silver [2].

Dissolution rates for solid copper in liquid tin have proved to be strongly temperature and consentration dependent, as clearly demonstrated in fig. 8. For pure tin melts the dissolution rate follows an Arrhenius type of equation, while it decreases more rapidly with temperature for melted alloys. Again it appears that the corresponding process between silver and tin is markedly faster [5].

From these results one would expect the M-effect for copper to be slower than for silver, as indeed it is. In our experiments the fusing times for copper elements were 3 to 5 times larger than those for corresponding silver elements, (2.6 x 0.12 x 520 mm).

The interrupted fusing experiments have shown that the fusing process

follows one of two different patterns. Surprisingly enough it turned out that the total fusing time is independent of the fusing pattern for a given current. Further it was established that the ratio between the melting time for the M-spot (t_m) and the total fusing time (t_f) very nearly is constant, $t_m/t_f \simeq 0.2$, in the M-effect region. One would expect ,therefore, that if a fuse element during service has suffered temperatures taking the fusing process close to current interruption, the actual part of the time-current characteristics will be shifted toward shorter times by a factor of almost 5. Clearly this kind of aging is not acceptable, especially not for motor fuses. Frequently occurring service currents should, therefore, not be allowed to bring the fuse element to the melting point of the M-spot.

CONCLUSIONS

Copper fuse elements containing a tin M-spot are gradually aged even at temperatures below the melting point of tin through formation of high resistance intermetallic compounds. The aging rate is, however, acceptably low.

For temperatures exceeding the melting point of tin the aging rate is strongly accelerated and could lead to undesirable changes in the time-current characteristics.

Copper is superior to silver as far as resistance to intermetallic reactions in the M-spot is concerned.

REFERENCES

[1] Metcalf, A.W (1939), BEAMA J. 44, 109-112.

[2] Daalder, J.E., Kulsetås, J. (1979), Diffusion Phenomena in Sn-Ag Couples Around and Below the Eutectic Temperature. EFI TR NR. 2526.

[3] Kay. P.J., Mackay, C.A. (1976), The Growth of Intermetallic Compounds on Common Basis Materials with Tin-Lead Alloys. Trans. Inst. Metal Finishing, 54, 68-74.

[4] Onishi, M., Fujibuchi, H. (1976), Reaction-Diffusion in the Cu-Sn System. Trans. JIM, 16, 539-547.

[5] Valle, A. (1980), Thesis. The University of Trondheim, Norwegian Institute of Technology, Physics Department, (in Norwegian).

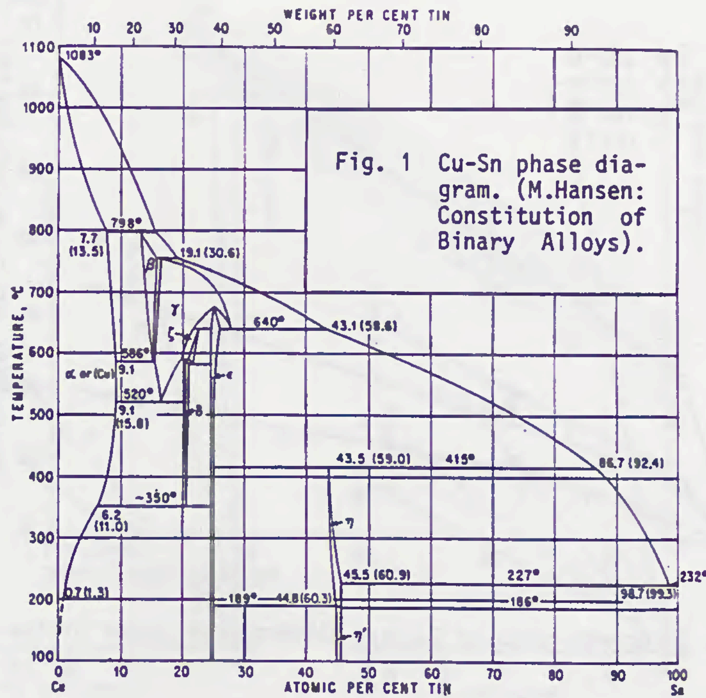

Fig. 1 Cu-Sn phase diagram. (M.Hansen: Constitution of Binary Alloys).

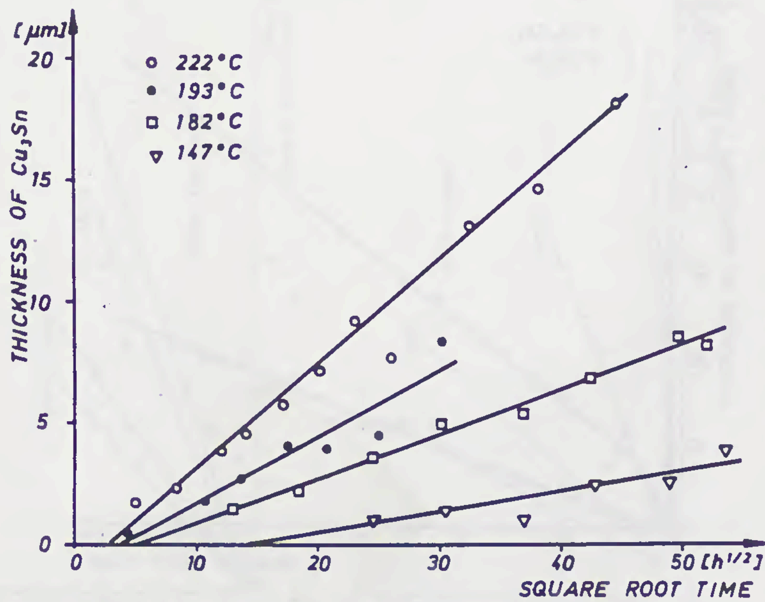

Fig. 2 Growth rates of Cu_3Sn, silverplated copper strips.

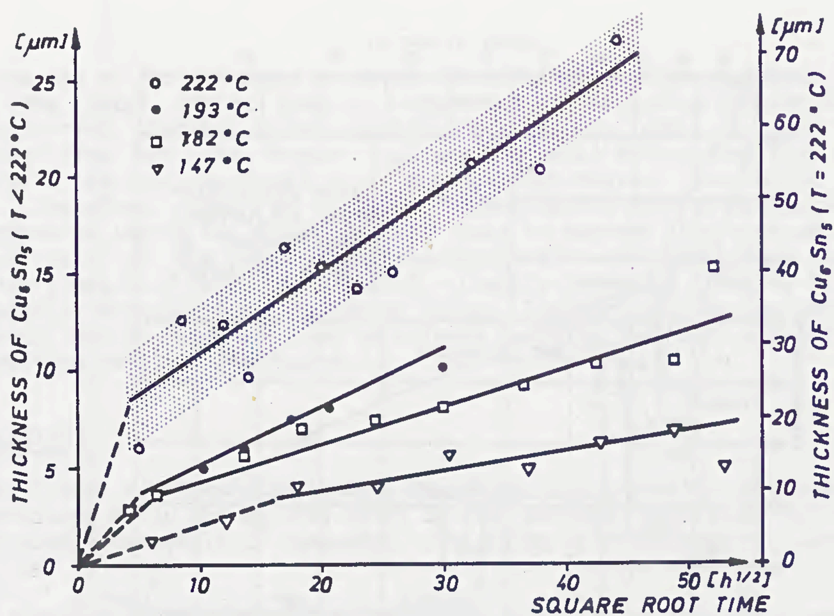

Fig. 3 Growth rates of Cu_6Sn_5, silverplated copper strips.

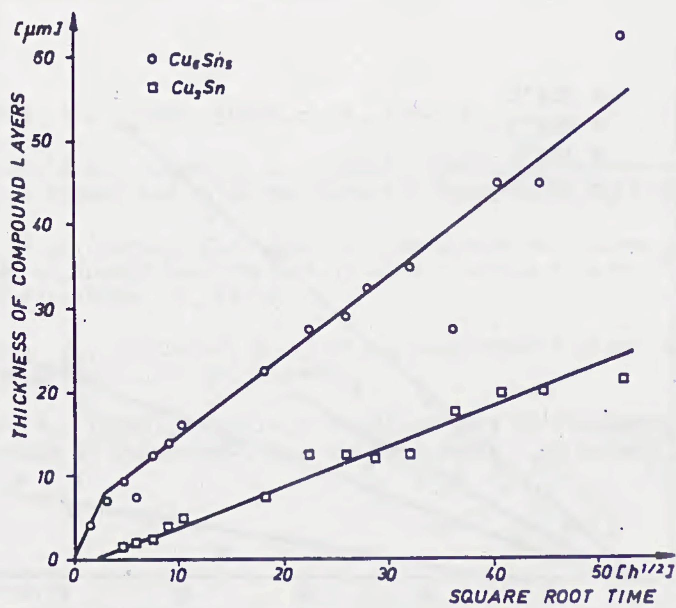

Fig. 4 Growth rates of Cu_3Sn and Cu_6Sn_5 at 215°C, unplated copper strips.

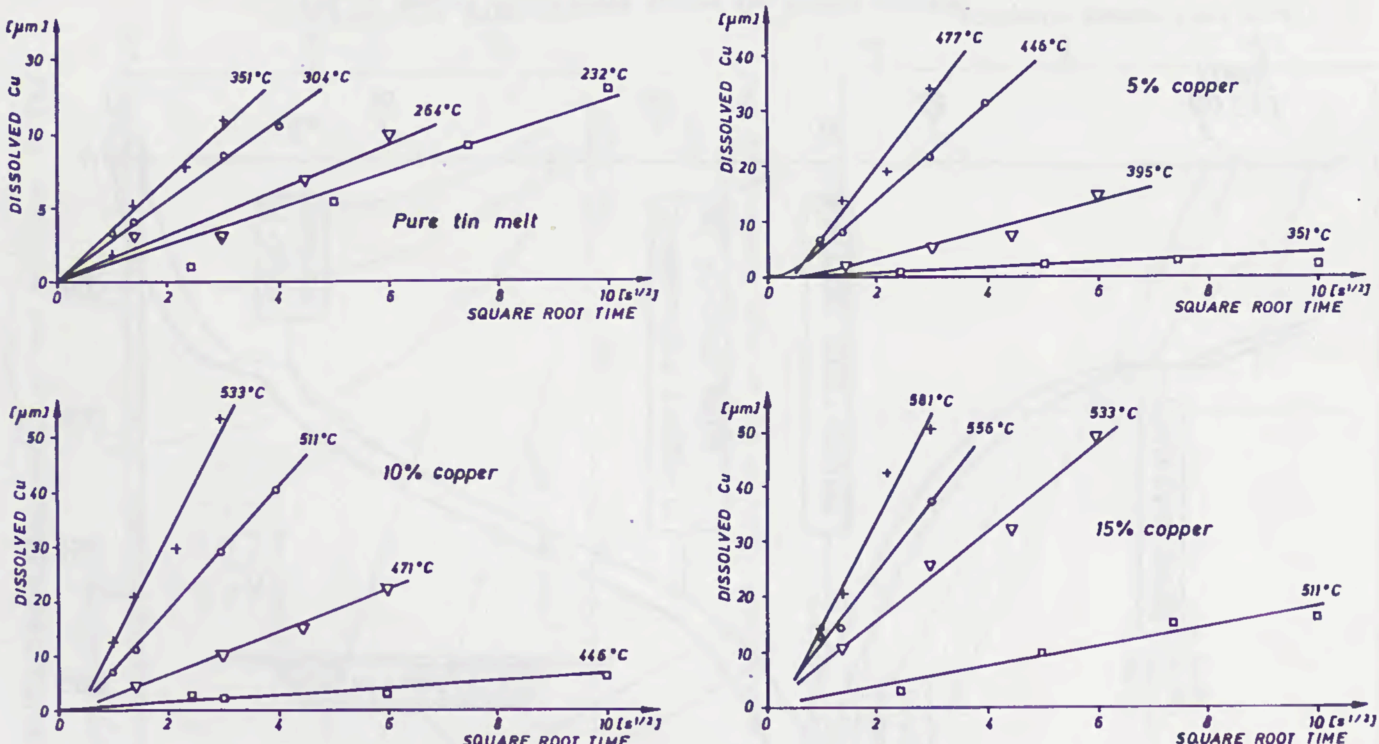

Fig. 5 Dissolution rates for solid copper in liquid tin-copper alloys.

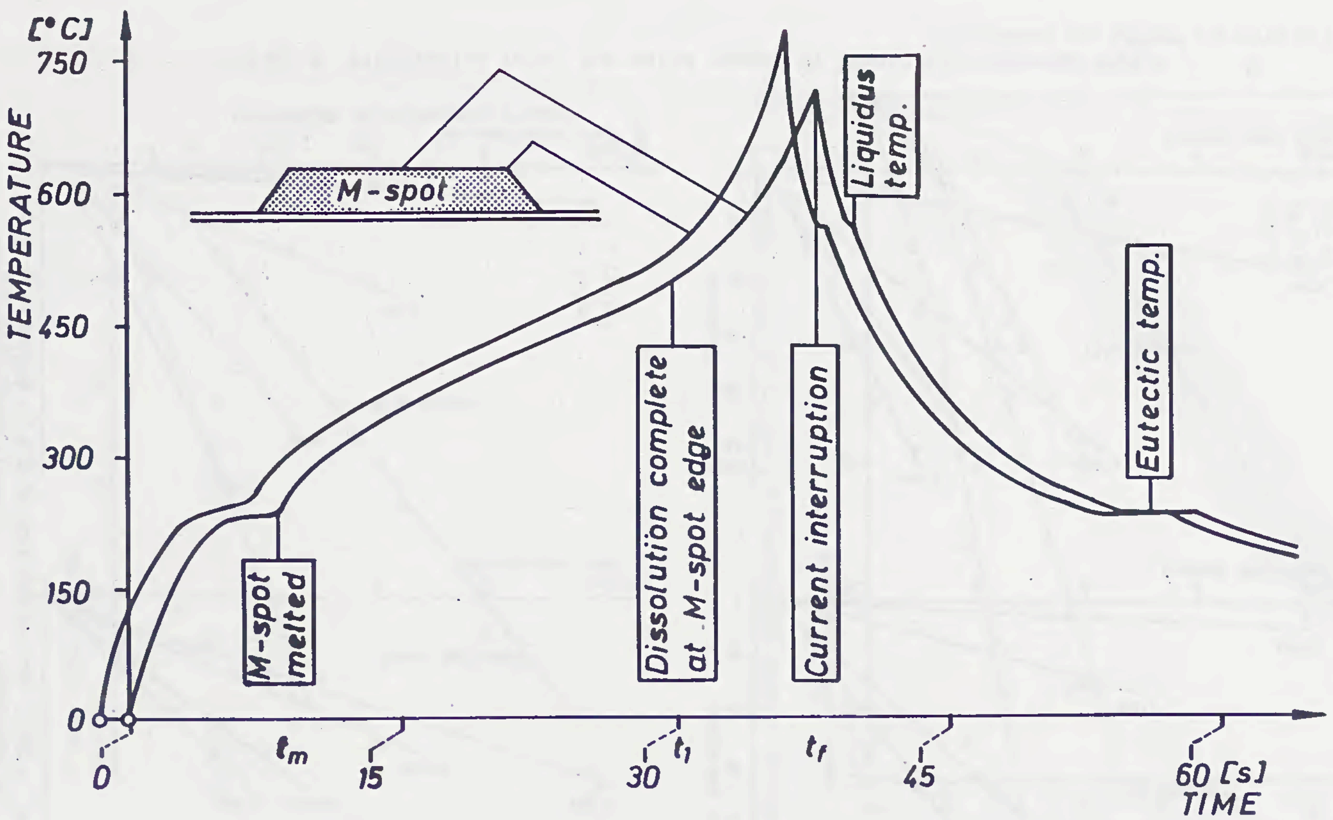

Fig. 6 M-spot temperature during the fusion process.

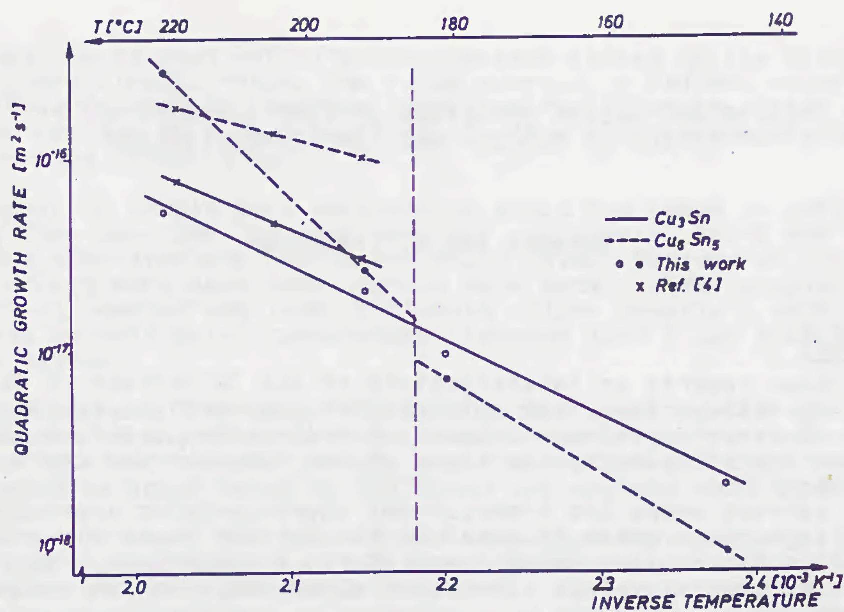

Fig. 7 Arrhenius plot of the quadratic growth rates of intermetallic compounds.

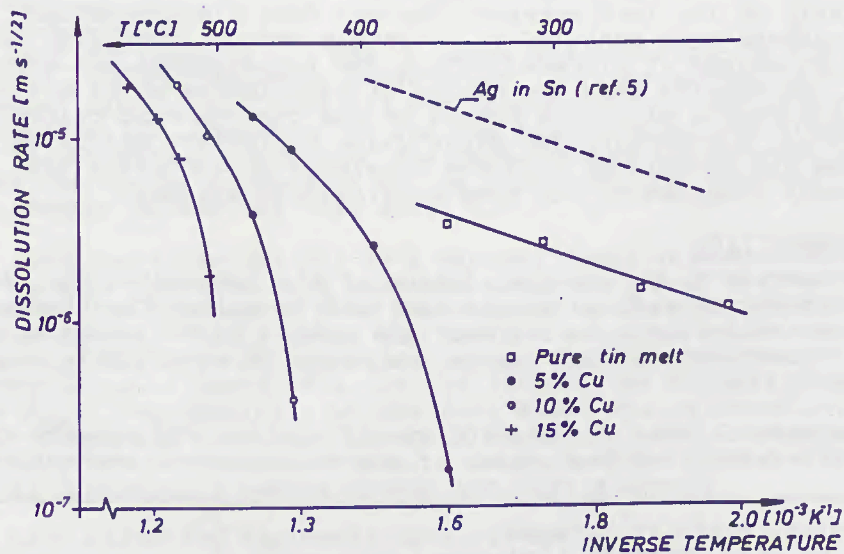

Fig. 8 Arrhenius plot of dissolution rates of copper in liquid tin-copper alloys