BREAKING BY MELTING FUSE AT ANOMALOUS M-EFFECT

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Abstract: At breaking of moderate overcurrent by melting fuse the M-effect is prevalent process. Sometimes heat dissipation at M-effect is so intensive, that the temperature rise on surface of ceramic fuse link attains extremely high value. On the other hand at normal M-effect the temperature rise is quite moderate. In order to investigate the phenomena of *anomalous* M-effect the variation of voltage drop on fuse link terminals during breaking process was measured. After that the optical microscopy of interrupting sites of fuse element, the metallographic and SEM examinations with EDX microprobe analysis were conducted. A comparison with characteristics of *regular* M-effect was performed. The substantial differences in the course of voltage drop and material state were found out between both types. At the *anomalous* type a broad interrupting zone of an alloy with high melting temperature was formed on fuse element, while at *regular* type the interruption sites are located on notches of fuse element, where an alloy with low melting temperature was formed. Initially the both type of M-effect followed the same characteristics, which deviate from each other just before the interruption.

Keywords: fuse element, M-effect, heating up period, melting period, voltage drop, Cu-solder alloy

1. Introduction

When the melting fuse is used for the protection of circuit against overcurrent, the duration of breaking process depends on the current to be broken. This relationship should follow the required time/current characteristics, given by relevant standards [1]. At overcurrent slightly greater than rated current the time to break is in the order of magnitude 1000 s, but when it attains a value of 10 times rated current or more, a fuse blows in a few ms. The fuse element is properly designed in order to meet the required operating characteristics. Regarding current ratings of the fuse it is made either of thin Ag or Cu wire or strip. Strip is perforated (Fig. 1) in order to form special pattern of nodes, where current lines are constricted due to controlled heating of fuse element [2].

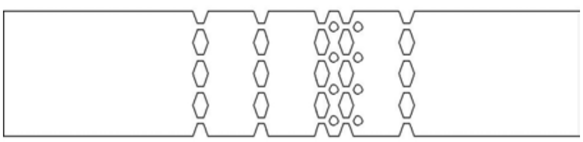

Fig. 1: Node patterns of fuse element

At the inrush of high overcurrent the heat dissipated in fuse element for few ms causes almost adiabatic heating of nodes resulting in melting and boiling. At low overcurrents more moderate process takes place in the time scale of 100 or even 1000 s. Dissipated heat is conducted away from the fuse element through the filling sand toward the outer surface of ceramic cartridge of fuse link as a semi stationary thermal process. In the moment of break it can results in a considerable temperature rise of the fuse link, which should be kept in limits regarding thermal withstand ability of parts in its vicinity.

In order to investigate thermal effects of break on fuse links gL 63A, a standard time/current test was conducted at load current 100 A. During testing the test pieces achieved surface temperature of cartridge below 300°C, but some of them were found to be heated up to the red glow. Therefore the additional measurements and examination of test pieces were accomplished in order to investigate this anomaly.

2. Measuring and analytical methods

Each test piece gL 63A was inserted into standard terminal socket and loaded by test current 100 A from stabilized DC current source. The temporal variation of voltage drop u between terminals was recorded from the onset of load current to the moment of blow of the tested fuse link. Results were sampled with the frequency of 1 s and digitally processed by the grating of 16 mV. They were stored in computer for further analyses.

Some typical results of voltage drop versus time obtained by measurements at the described test conditions were shown graphically on Fig. 2, where each plotted curve corresponds to particular test sample. A typical course of voltage drop curve $u(t)$ is evident for particular test, which starts from the initial low value (some 200 mV), proceeds with slow increase until after certain time it exhibits the final steep increase over 500 mV and even up to 1400 mV at the moment of current interruption.

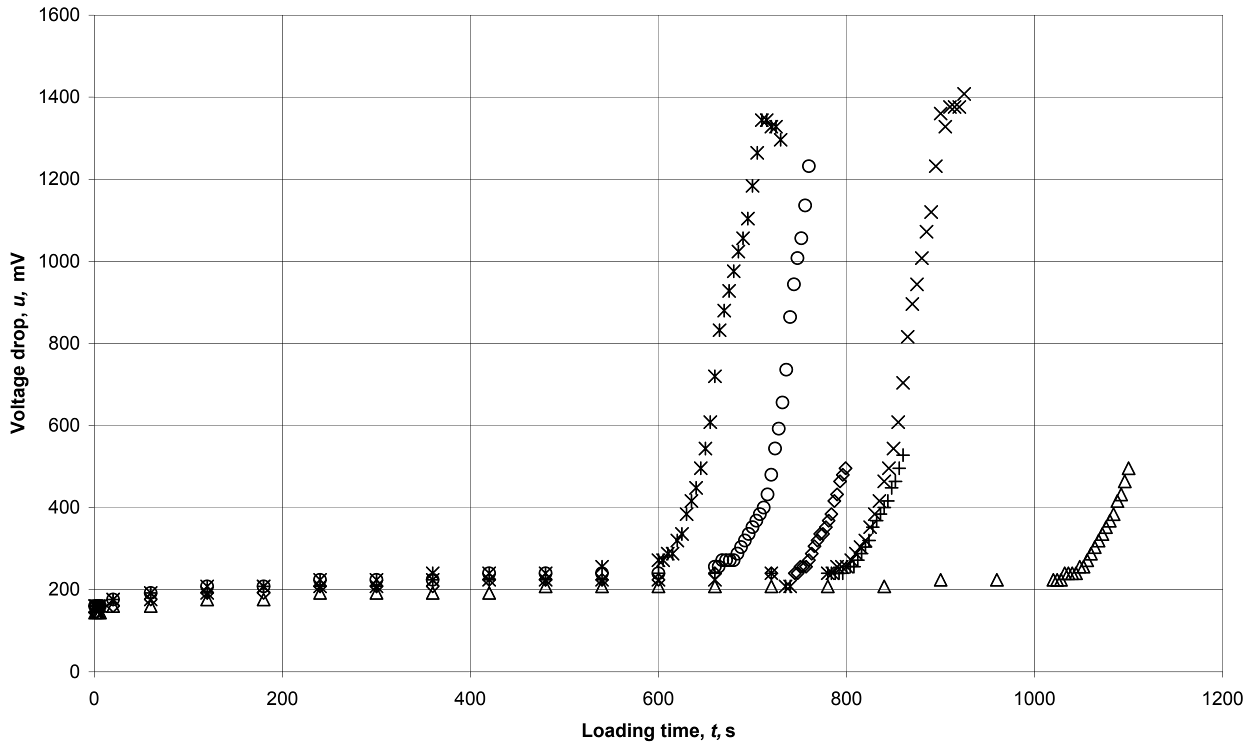

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Fig. 2: Temporal variation of terminal voltage drop under load current measured on several test pieces

Slowly increasing part of each curve shown in Fig. 2 reflects the heating-up of fuse element at constant current. A physical approach to this effect leads to an analytical expression for this part of curve, which can be written in general form as follows:

$$u_{\text{heat}}(t) = A + B\left[1 - \exp\left(-\frac{t}{\tau}\right)\right] \qquad (1)$$

The *heating-up phase* is followed by the period of fast increase of voltage drop, which is attributed to the transitions of the material state of fuse element. Regarding the design of fuse element, where some of the nodes are coated by solder in order to facilitate their melting, the break of overcurrent by fuse element takes place particularly by melting of soldered nodes. Therefore this period is called *melting phase*.

Test results obtained by measurement of the voltage drop versus loading time (see examples in Fig. 2) were correlated with measurements of temperature of fuse links and physical state of fuse element after break in order to explain breaking phenomena. For this purpose optical microscopy was applied at the investigations of fuse element after blow as well as metallographic methods and electron microprobe analysis.

3. Analysis of measured results

Two clearly evident types of voltage drop/time curves can be distinguished: the type with short duration of M-effect having peak value at break at some 500 mV, and the type with longer M-effect and peak value somewhere between 1200 mV and 1400 mV. Therefore the first type is called *regular* and the second type *anomalous* melting phase.

The surface temperature of fuse link measured on each particular test piece during break test was in close correlation with the type of melting phase. At break by *regular* type it never exceeds 300°C, while at *anomalous* type a red glow on cartridge surface was observed, which was assessed to be at least 600°C.

No correlations between parameters which would facilitate anomalous M-effect were found. Therefore an analysis of voltage/time variations in melting period was conducted. Measured voltage drop resulted from the contributions of partial voltage drops on fuse terminals, end caps, terminating ends of fuse element strip and nodes in series. In the melting period the essential variation of voltage drop took place on the nodes of the interrupting sites, so all other contributions to them were disturbing. They were eliminated by extrapolation of heating-up voltage curve and subtraction from actual voltage drop. An example of best fit approximation is shown in Fig. 3.

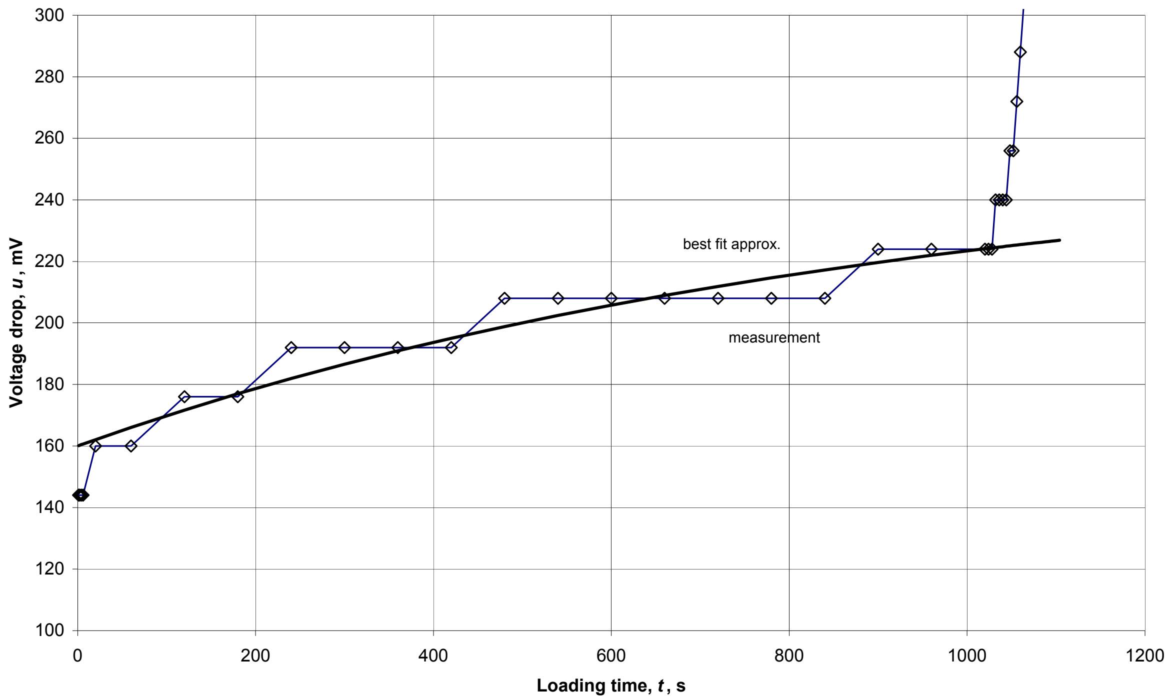

Fig. 3: Best fit approximation of heating up curve and extrapolation into the area of melting voltage drop.

In order to obtain best fit curve the relation (1) was used by fitting parameters *A, B* and τ. The value τ was chosen such that (1) fitted better the results in the interval $t > 10$ s. By subtraction of best fit curve from measured data the voltage drop on melted parts of fuse element, $u_M(t)$, was calculated with certain inaccuracy:

$$u_{\mathrm{M}}(t) = u(t) - u_{\mathrm{heat}}(t) \qquad (2)$$

By applying (2) on measuring results of each tested fuse link a "melting voltage" curves $u_M(t)$ were obtained.

As it was confirmed that the duration of heating-up period does not influence the melting process a shift of time scale was made into the moment of melting onset. In order to compare temporal variation of melting voltage for individual test pieces, a shifted time axis t_M were used in order to follow the development of melting for various test pieces. So the relation of melting voltage/time, $u_M(t_M)$, was applied for further analysis. The origin of t_M - axis determined from the set of measured results corresponding to several test pieces implies certain inaccuracy arising from the estimation of moment, when the transition from heating-up into melting occurred. As the result a set of calculated curves $u_M(t_M)$ which describe the variation of melting voltage starting from the onset of melting was shown in Fig. 4 for several fuse elements under discussion.

Curves of Fig. 4 are plotted on the semi-logarithmic graph due to better presentation. The melting curves for both *regular* and *anomalous* melting phase are shown. Regardless of several sources of inaccuracy a substantial overlap of curves is noticeable. It indicates that similar physical processes presumably took place in tested fuse links. Moreover the curves corresponding to regular (symbols Δ, ◊ and O) and anomalous type (symbols +, × and *) overlap each other. In the moment of interruption u_M attains characteristic peak value U_M at 250 mV < U_M < 280 mV for regular type of M-effect and at 1000 mV < U_M < 1100 mV for anomalous type. Particularly for anomalous type u_M attains its maximum by voltage leveling, which is characteristic for e.g. transitions from solid state into melt, well known as the phenomenon of contact spot [3]. The temperature rise on contact spot is directly proportional to the contact voltage drop. Terms such as "softening voltage" or "melting voltage" are commonly used in contact physics. Although quantitative analogy between fuse element and contact spot can not be drawn, the essential elements are analogous. So it can be presumed that the interruption of fuse element at the anomalous M-effect takes place at substantially higher (melting) temperature than for regular one.

4. Methods of examination

Test pieces were subjected to the examination of its state after break. The residue of blown fuse element was carefully extracted from its cartridge. Prior to examination it was carefully cleaned from the loose grains of sand.

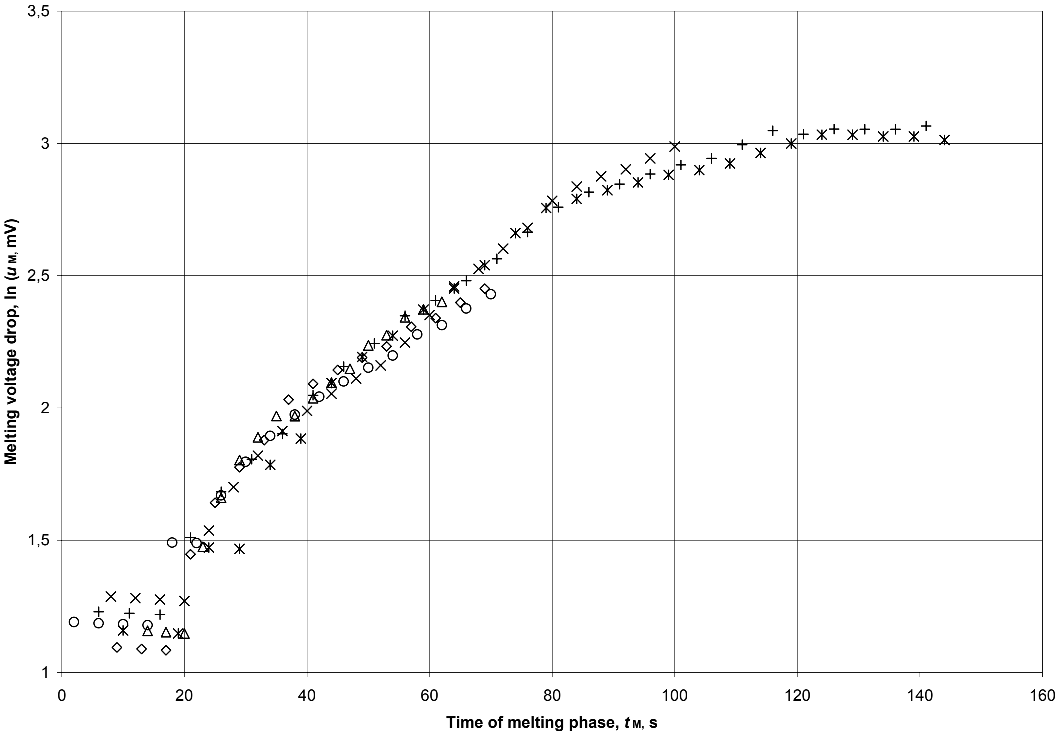

Fig. 4: Curves of melting voltage drop for fuse links having *regular* and *anomalous* type of M-effect.

At first the interrupting sites of blown fuse element were examined by optical stereo microscope at lower magnification. A close correlation between the appearance of blown piece and the type of M-effect taken place was established. While on the one hand the interrupting sites of regularly blown fuse element were located in the small area around notches (as shown in Fig. 5), on the other hand the interrupting sites of fuse element blown by anomalous melting phase were spread along the broad area of perforation and were covered by thick layer of vitrified filling sand (see Fig. 6).

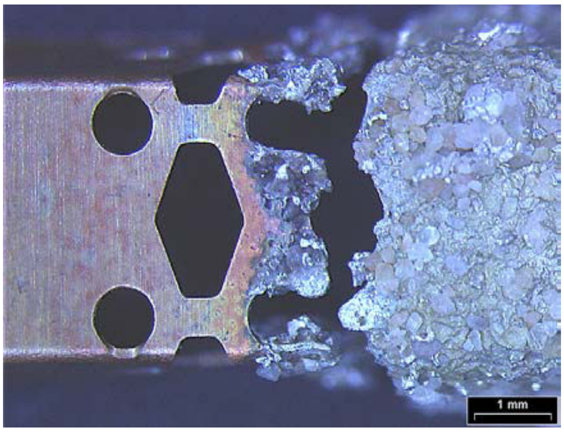

Fig. 5: Interrupting area of regularly blown fuse element with solder layer on the right side.

Interrupting sites shown in Fig. 5 were dissolved by melted solder (seen on the right side of photos with embedded grains of filling sand) which is spread over the adjacent notches.

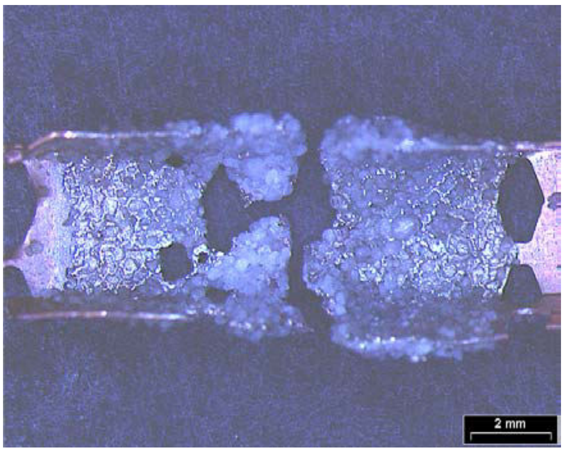

Fig. 6: Interrupting area of fuse element after the break by anomalous M-effect spread along more than two segments of perforation, where melting is indicated.

The metallographic structure of the interrupting site on fuse element, shown in Fig. 5, is illustrated in Fig. 7, where the metallographic cross-section of this part in presented at larger magnification. At the left side to the bottom the remnant of partially dissolved Cu-strip of fuse element is shown, which is covered by a thick layer of solder alloy. Dark irregularly shaped "islands" at the top of photo belongs to the embedded sand grains. The metallographic structure of solder shown in Fig. 7, although uniform across the solder layer, does not show the original structure of solder coating.

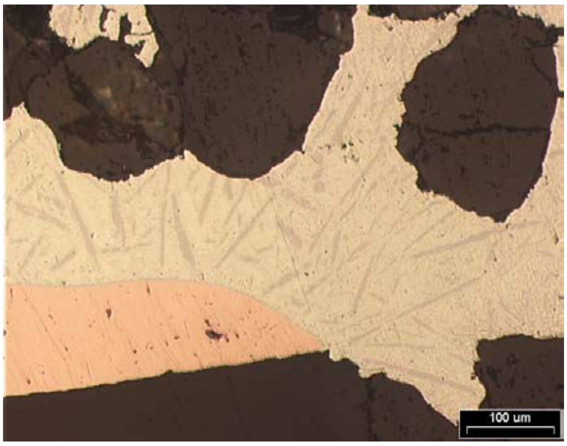

Fig. 7: Cross-section of interrupting site on fuse element for regular type of melting.

Scanning electron microscopy (SEM) was also conducted on several cross-sections similar to that shown in Fig. 7. SEM image of solder layer under discussion obtained by emitted secondary electrons was shown in Fig. 8.

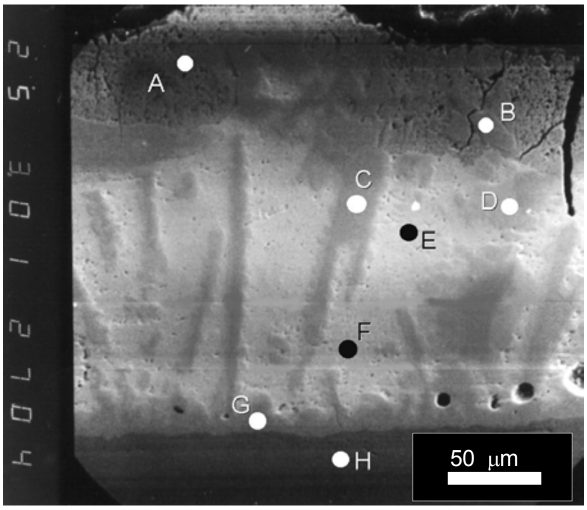

Fig. 8: SEM secondary electron image of cross-section of solder layer after blow of fuse element by regular melting phase.

The deviation of chemical composition is qualitatively indicated from the darkness of particular area proportional to the average atomic number on the observed site [4]. The darkest area at the bottom of Fig. 7 belongs to Cu-strip, while the central area of microphotography obviously corresponds to the alloy of lighter elements. In order to identify chemical composition of particular metallographic phases a microprobe EDX spectroscopy [5] was conducted on the sites of labeled in Fig. 8 by letters from A to H. In the needle-like phase of this alloy (indicated in Fig. 7 and 8) elements Cu and Sn were detected with the amount of Cu > 50 wt % (site C in Fig. 8). The lighter phase, indicated by letters E and F is composed of Cu, Sn and Cd, where the amount of Cu does not exceed 20 wt %. The described alloy structure was found to be characteristic for process of regular M-effect.

The cross-section of fuse element blown by anomalous melting phase, as illustrated in Fig. 6, is shown magnified in Fig. 9.

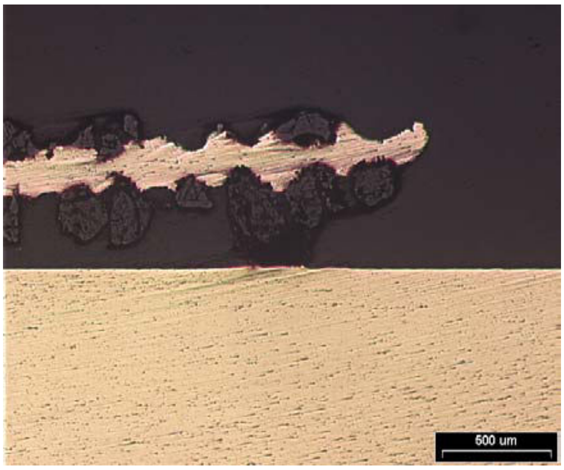

Fig. 9: Cross-section of interrupting area at anomalous type of M-effect.

Microphotography shows the cross-section along the interrupting area of semi-melted fuse element with embedded sand particles on both sides of its strip. At larger magnification it was observed, that in the interrupting zone the metallographic structure of the strip material is more homogenous in contrast to the structure shown in Fig. 7, where regular M-effect was active. The transition region from melting zone into the rest of the intact Cu-strip is shown in Fig. 10.

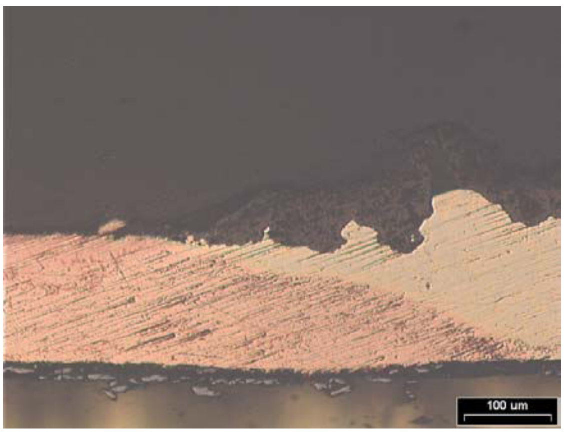

Fig. 10: The transition region between "melting" zone and the rest of fuse element strip.

No remnants of the solder layer can be observed on this cross-section. On the left side of photo the rest of Cu-strip is visible, while on the right side the "melted" part of strip is shown. No more than two metallurgical phases are discernible in the zone of interruption (not distinguishable in Fig. 10) even on the boundary between pure Cu and the alloy of "melted" region.

5. Discussion

The metallographic examinations of interrupting sites or melting zone indicated the formation of the alloy with a variety of metallurgical phases at the *regular* type of melting process and the formation of two-phase alloy at the *anomalous* type. Phases with high content of Sn and Cd were found by EDX analysis on the interrupting sites in the case of *regular* type of M-effect, while in the case of *anomalous* type of M-effect only two metallurgical phases were found in the alloy even at the boundary to Cu. The conditions at which particular phases of alloys are able to exist could be considered to a great extent from a diagrams of metallurgical states for involved elements. In fact a ternary diagram of states would be used in order to discuss the alloy of Cu, Sn and Cd. But in the literature only binary diagrams of states having Cu, Sn and Cd are available [6]. The role of Cd in the formation of alloy Cu-solder seems to be minor concerning microprobe EDXA. So for the qualitative assessment of "melting" process of M-effect of both types the binary Cu-Sn diagram as shown in Fig. 11 is considered sufficient.

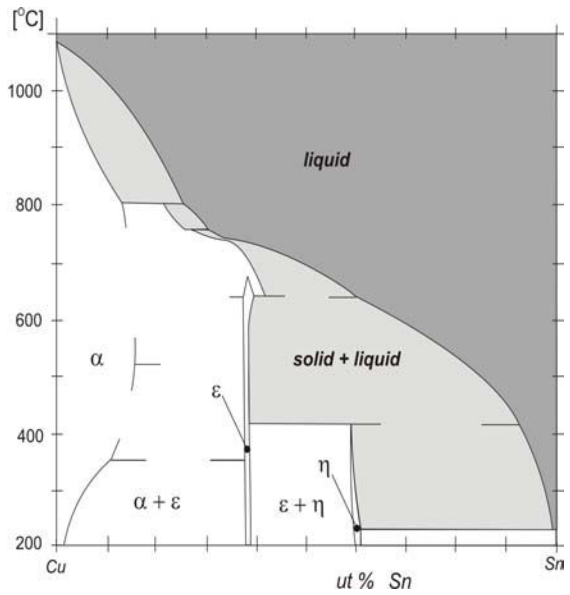

Fig. 11: Binary diagram of states for Cu-Sn alloys

In the diagram various solid metallurgical phases for Cu-Sn alloy can be found depending on the content of Sn (or Cu) given in the weight percent. The boundary of solidification at given Cu-Sn composition as well as the boundary of melt is shown as the curve of temperature versus wt % of alloying component. The region of melt is shown in Fig 11 as dark shadowed area while the region of solid-liquid mixture as light shadowed area. As it can be seen from the diagram the melting temperature of the alloy increases with the increasing content of Cu, as well as the temperature of solidification. Concerning the metallographic structure of the alloy as observed by optical metalography (Fig. 7) and in the SEM image (Fig. 8) in connection with EDX analyses, the needle-like forms presumably belongs to ε phase of Cu-Sn alloy, which is stable below 700°C. Its grains are surrounded by the thin layer likely of η phase, which is stable below 415°C. At the content of Cu up to 37 wt %, only the mixture of α and ε phase exists at low temperature, at which the metallographic preparation and observations of the structure was actually accomplished.

Following the above considerations some estimations of interrupting temperature could be established. During the interruption of fuse element by *regular* M-effect probably some 50% of Cu was dissolved in the melt with solder. The interrupting temperature of the notch presumably reached a value below 600°C but over 415°C, the limit of the existence of η phase. As the process was far from stationarity, the layer of η phase around the grains of ε phase was formed in the cooling period of interruption. In the interrupting zone of *anomalous* M-effect the alloy of only two metallurgical phases, having the highest possible content of Cu, was found. It is presumably the alloy of α and ε phase in approximately equal content, as were indicated by optical metallography. Concerning Cu-Sn binary diagram the Cu strip of the fuse element comprised some 20 wt % of Sn dissolved in in the "melting" zone. The temperature of solidification of such alloy is 798°C, which means that the interruption by *anomalous* M-effect could not be accomplished below 800°C.

The above consideration was confirmed qualitatively by taking into account values of "melting" voltage u_M at the moment of interruption (see plotted curves in Fig. 4 of Section 4). They are concentrated around two characteristic values, so that an apparent distinction between *regular* and *anomalous* M-effect can be established over the interrupting values U_M. Lower values of *regular* type indicate lower breaking temperatures of interrupting site and vice versa for the interrupting zone of *anomalous* type.

6. Conclusions

Due to possible detrimental consequences of *anomalous* M-effect in the application of fuse links for circuit protection the answers on the two principal questions should be given in the conclusion: a) what is the source of effects, which consequences are assigned to the *anomalous* M-effect, and b) how to avoid the possibility of *anomalous* melting effect to appear. Both answers are interesting primarily for the manufacturer of melting fuses in order to ensure high reliability of protection against all kinds of overcurrent.

As already mentioned the detrimental consequence of *anomalous* M-effect is a risk of thermal defects in the vicinity of fuse link due to its extremely high surface temperature rise. It is shown in the preceding Sections, that in the case of *anomalous* M-effect the "melting" period lasts more than 100 s and the temperature of the great region of fuse element presumably exceeds 800°C. Due to the good thermal conductivity of sand filler and ceramic cartridge the surface temperature at these conditions consequently attains "red glow" value. In the contrary at *regular* M-effect the "melting" period is significantly shorter (up to 70 s) and only a very small area of notches attains temperature not greater than some 600°C. So the heat dissipated in the fuse element is significantly smaller and the temperature rise of fuse link cartridge is within the safe limit.

From the temporal variations of melting voltage it is apparent, that regardless of how the melting and dissolution process proceeds, the phenomena taking place in the initial period of *regular* as well as in *anomalous* M-effect are common. The deviation from common course (as it can be indicated from Fig. 4) can be observed just before the termination of *regular* type. Obviously a gradual deviation from the conditions, which lead the phenomena toward the *regular* melting process causes the M-effect to proceed into the *anomalous* one. A competitive effects between the dissolution of notches and spreading of melted solder along the fuse element could be due to the slight deviations of conditions sometimes in favor of *anomalous* M-effect instead of *regular* one and vice versa. But they can be controlled by conditions determined by the design of fuse element.

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