A THEORETICAL APPROXIMATION OF THE TIME-CURRENT CHARACTERISTIC OF MINIATURE FUSES

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Abstract

It is known from experiments that a linear relationship exists on log-log scale between the minimum fusing current and the diameter of round metal wires, as used in miniature fuses. This can be explained by using a rather simple energy-balance. Extending the energy-balance with Nusselt-numbers, it is possible to predict the slope of the relationship from calculations only. Since for such wires the I^2t-value is known quantity, the limits of the time-current characteristic can be calculated.

1. Introduction

Normally, time-current (It)-characteristics for miniature fuses are presented on a log-log scale as shown in Fig. 1. Such an It-characteristic can be approximated by two asymptotic straight lines, one vertical line representing the minimum fusing current I_s and one line under a well-known slope representing the I^2t-value [1]. These lines are also shown in Fig. 1. (lines 1 and 2 respectively).

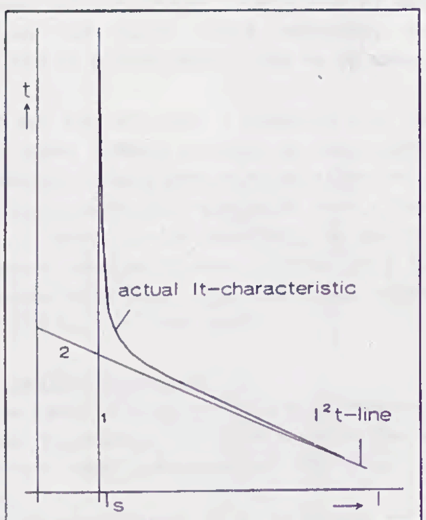

Figure 1: Approximation of the time-current characteristic.

In most cases line 2 can be calculated with rather good accuracy for a given fuse design, using Meyer's formula [2]. If the value of I_s can also be calculated, then this means that the limits of the It-characteristic of a given fuse can be found from calculation only. For a first design of a miniature fuse such an information is mostly sufficient, as far as the It-characteristic is concerned.

In the following section it is shown how the value of I_s can be determined for fuse designs as usual for 5 x 20 mm and 6.3 x 32 mm fuses.

2. Determining I_s

In most cases the fuse-wire in a miniature cartridge fuse can be considered as a long wire, that means that the temperature of the wire at its hottest point (the middle of the wire) is not influenced by the heat transfer to the ends of the wire. Along the wire the well-known temperature distribution as shown qualitatively in fig. 2. occurs. In this figure it is also shown at what length L_t of the fuse wire a transition takes place from a "long wire" to a "short wire", as long as a wire with constant cross-section over its length is considered.

The minimum fusing current I_s is determined by the melting temperature $T = T_s$ in the middle of the wire under steady state conditions. In this case a simple energy equation per unit volume is valid, viz:

$$J_s^2 . \varrho_0 . (1+\beta . (T_s-T_0)) = G . (T_s-T_0) \qquad (2)$$

where

J_s = the current density.

ϱ_0 = the specific resistance at T_0.

β = the temperature coefficient of the specific resistance

G = the heat transfer in radial direction per unit volume and per degree C.

T_0 = ambient temperature.

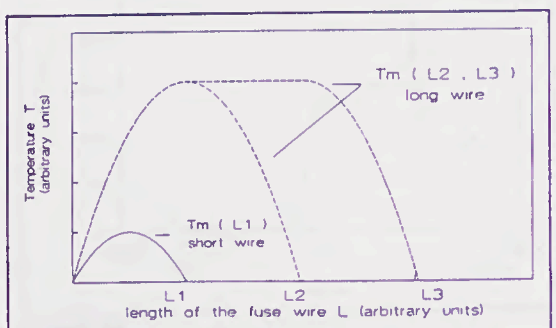

Figure 2: Temp. distribution along a wire carrying the same current I, depending on the length L of the wire.

Introducing $I_s = \frac{1}{4}\pi d^2 . J_s$, where d is the diameter of the fuse-wire, considered to be cylindrical for the sake of symplicity, we then get:

$$I_s^2 = \frac{\pi^2}{16} d^4 . \frac{G . (T_s-T_0)}{\varrho_0 \, (1+\beta . (T_s-T_0))} \qquad (3)$$

or:

$$I_s^2 = G . K_1 . d^4 \qquad (3a)$$

where K_1 is a constant, only dependant on physical parameters of the fuse-wire material.
Note that also for the case of a short conductor, it can be shown [3] that $I_s^2 = K_2.d^4$ with K_2 a constant different from the product $G.K_1$.

It is a well known fact that if we plot the value of I_s of miniature-fuses as a function of the wire-diameter on a log-log scale, a straight line results as illustrated in Fig. 3. This relationship between I_s and d has already been described by Preece as early as 1884 [4] for straight long wires in air, and is sometimes referred to as Preece's law.

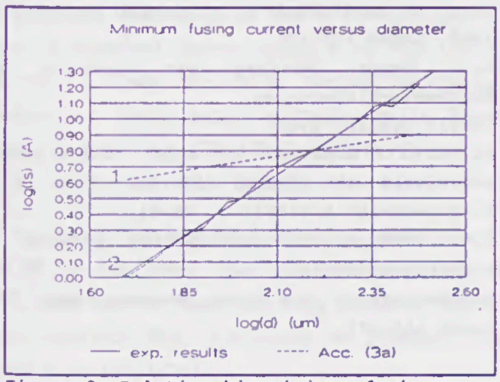

Figure 3: Relationship minimum fusing current I_s and wire diameter d.

If we plot in the same figure the relationship between I_s and d as predicted by eq. (3a) (line 1 in fig.3), then it is clear that the slope of this line differs from the slope as predicted by Preece's law (line 2 in fig. 3). Furthermore Fig. 3 shows a remarkable fit of Preece's law to the experimental results obtained from fuses with Sn-plated Cu-wires.

Obviously the factor G can not be a constant, but does depend on d. If, however, log I_s is linearly related with log d, as proven by experiment, then log G should also have a linear relationship with log d. This means that some power α of d must exist, for which is valid:

$$G.d^{\alpha} = \text{constant} \qquad (3b)$$

From a comparison with experimental data and the relationship given by eq. (3a), it can be derived that $\alpha = 1$ is valid. That means that the product G.d is a constant as a function of d.
If we introduce $G_d = G.d$ in eq. (3a), then it follows:

$$I_s^2 = K_1.G_d.d^3 \qquad (4)$$

in which G_d is a constant. Equation (4) is exactly the relationship as described by Preece.

Numerous experiments revealed that G_d is indeed a constant for one specific metal. Different metals and alloys show different values of G_d. The only metal we found in our experiments which does not follow eq. (4), at least for smaller diameters, is Nickel. The deviations from eq. (4) shown by Nickel are believed to be the result of a second order phase-change, which occurs at 357°C.
Furthermore it was found that the value of G_d depends on the surroundings of the wire (sand filler, air a.s.o), but is not so much influenced by the dimensions or the design of the fuse, as long as the fuse-wire can be considered to be "long".
Knowing values for G_d for different metals and alloys and for different fuse-wire surroundings, I_s can be calculated from eq. (4).

3. <u>Some remarks with respect to Preece's law</u>

A somewhat larger model is needed in order to obtain a relationship between the various values of G_d for different metals. With such a model it can be made plausible that $G_d = G.d$ is indeed a constant.

In the above equation (2), G is the heat-transfer in radial direction, per unit of volume and per degree Celsius.
For round wires in air, the radial heat-transfer is given by:

$$Q = h_c.(T_s - T_0).\pi.d.l \qquad (5)$$

with

$$h_c = \frac{Nu_d.K}{d}$$

and:

Q	=	radial heat transfer	[W]
d	=	diameter of wire	[m]
l	=	length of wire	[m]
Nu_d	=	Nusselt number related to d	
K	=	thermal conductivity of air	[W/(m°C)]
T_0	=	ambient temperature	[°C]

We then find:

$$(\tfrac{1}{4}\pi d^2).l.G.(T_s - T_0) = \frac{Nu_d.K}{d}(T_s - T_0).\pi.d.l$$

or:

$$G = \frac{4.Nu_d.K}{d^2} \qquad (6)$$

Since for non-moving air, the Nusselt-number Nu_d is usually given as:

$$Nu_d = A.(Gr_d.Pr)^B \qquad (7)$$

where:

A, B	=	constants
Gr_d	=	Grashof number related to d
Pr	=	Prandtl number

Because the Grashof-number is proportional with

$(T_s - T_0)$ and with d^3, eq. (6) can be rewritten into:

$$G.d^{(2-3B)} = \text{constant} \, . \, (T_s - T_0)^B$$

Since in literature for B values are found to be around 0.25 to 0.33, we get in case of B = 0.33 the same relationship as observed by Preece:

$$(2-3.B) = 1 \longrightarrow G.d = \text{constant}.(T_s - T_0)^{0.33} \qquad (8)$$

Note that the constant in eq. (8) incorporates the physical properties of air, and is as a result temperature dependant.

Equation (8) makes it plausible that for different fuse-wire materials with different values of T_s, different values of G_d are found.
Furthermore it follows from the above, that the following relationship between the constants G_{d1} and G_{d2} of two different metals in the same straight wire fuse-design must exist:

$$\frac{G_{d1}}{G_{d2}} = \frac{K(T_{s1}-T_0).(Pr(T_{s1}-T_0).(T_{s1}-T_0))^B}{K(T_{s2}-T_0).(Pr(T_{s2}-T_0).(T_{s2}-T_0))^B} \qquad (9)$$

Experimental results obtained sofar, show that eq. (9) can be used as a rough estimate.

4. Conclusion

For round long wires of various metals in air, a rather good fit can be obtained for the relationship between the minimum fusing current and the diameter, using Preece's law.
Since also the I^2t-value is a well-known quantity, the limits of the time-current characteristic as shown in Fig. 1. can be calculated quite well.

Literature:

[1] L. Vermij, A. Mattheij: Time current characteristics of miniature fuses.
Proc. of the ICEFA 3rd International Conference, 1987, pages 122-126.

[2] G.J. Meyer: Beitrag zur Kenntnis der Abschmelz-Sicherungen.
Thesis Berlin, 1906.

[3] L. Vermij: Behaviour of short fuse-elements associated with thermal effects.
Holectechniek 5 (1975) 3, 76-81.

[4] W.H. Preece: On the heating effects of electric currents.
Proceedings of the Royal Society, Apr. 1884 pages 464-471.