A RELIABILITY STUDY OF MINIATURE FUSES

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Summary

Previous investigations on lifetimes are based on curve fitting to experimental results, existing standards also do not provide enough information for lifetime expectancy. The paper presents physical models for lifetime predictions for miniature fuses. Effects of cyclic currents on lifetimes has been studied for current conducting times from several milliseconds to one hour. Excellent agreements have been found between predictions and lifetime observations.

1. Introduction

During normal load situations, the current through fuses may be grouped conveniently under two headings: continuous current and pulsed (cyclic) current.

- A continuous load current is defined as the current under the stationary condition carried by fuses at the normal load.
- A cyclic current is specified as a repeated pulsed current with a certain on time and off time. The waveform of pulsed current is the same in each period. Cyclic currents take place in the circuits of power electronics, for example, rectifier circuits. Motor starting current, inrush magnetising current of no load transformers, inrush current on charging capacitor or capacitor banks can also be considered as pulsed currents.

Ageing can occur in both loading conditions, various attempts [*Arai, 1984; Stevenson 1976; Wilkins 1991; Williams 1981*] have been made to provide solutions for the problem of fuse ageing. Possibly the first paper correlating cycles to failures with current parameters appeared to be in 1969 [*Golden, 1969*]. In resistance welding applications, fuses should be derated to protect thyristors. Cycles to failure for fuses were presented in a graph as a linear function of the ratio of rated melting I^2t to the actual I^2t passed through the fuse during the current conducting time. Taking the fuse element temperature excursion as a parameter was also addressed as an alternative.

In the previous investigations, resistance changes, movement and cracks of fuse elements have been noticed. For both cyclic currents and constant currents, fuse lifetimes have experimentally been found to decrease as the amplitude of current increases. In the above methods, the estimation relies on the curve fitting of experimental data in lifetime tests, extrapolation was not on the physical ground. Therefore reliable applications of fuses highly depend on experience.

At the moment, concerning ageing effects, IEC publication 127 : miniature fuses specifies two types of tests related with lifetime expectancy. The first one is the endurance test stated in IEC publication 127-1 sub-clause 9.4 and the second is the pulse test specified in IEC publication 127-1 sub-clause 9.6. Endurance tests require fuses to withstand 100 cycles. In contrast to endurance tests, pulse tests are performed to gain information of ability to withstand current surges normally experienced in service. These tests require 1000 times of current pulses.

For most applications, fuses have to withstand more than 10^6 current pulses, 1000 current pulses are far too less to meet users requirements. Lacking of guidance from existing standards, manufacturers have to accumulate experience to deal with these practical problems, a good service is normally realised by a try and error method. Therefore to understand ageing mechanisms of fuses and to perform reliability studies are of a practical value for industries.

Because the previous studies are based on the curve fitting to experimental results of lifetimes, parameters used in methods either do not have clear physical meanings or do not defined from the fundamental process. The existing standards also do not provide enough information of fuse ageing and lifetime expectancy. In attempting to answer questions related with reliability, the ageing mechanism of miniature fuses during short time pulse currents and long current periods will be investigated in this study.

This paper attempts to provide a clear view for fuse ageing and to develop physical models for the lifetime predictions for fuses in general applications. The work is concerned with cyclic thermal fatigue for both short current pulses and long current periods.

To demonstrate our theory, a typical time delay fuse (218.800) [*Meng, 1994*] will be used as an example in the descriptions. From the fundamental understanding, physical models will be used to predict lifetimes for short current pulses and to resolve the problem of creep during long current periods. However, it should also be reminded that applications of our theory will not be limited to this type of fuses. Results of reliability investigation on miniature fuses lead to this paper.

2. Lifetime prediction for short current pulses

2.1 Physical models

Before the lifetime of fuse is determined, main contributions to the element damage should be defined. When fuses are subjected to current pulses, temperature rise brings about thermal strain due to thermal expansion. The strain produces stress due to the constrains of fuse elements. This mechanical strain may be divided into an elastic strain and a plastic strain.

Because of thermal buckling [*Meng, 1994*], for the temperature rise above the critical limit, the mechanical strain will reduce accordingly. During thermal buckling, only a part of the thermal strain is contributed to the mechanical strain to produce the stress. Thermal strain induced in the fuse element due to a current pulse is proportional to the temperature rise and given by

$$\Delta\varepsilon_{th} = \beta T$$

The mechanical strain is simply to take the form

$$\Delta\varepsilon_T = \delta\,\Delta\varepsilon_{th}$$

where δ is the deflection factor. This factor is derived [*Meng, 1994*] as

$$\delta = \frac{1}{2} + \frac{2\pi^2}{L_f^2}\frac{I_m}{A}\frac{1}{\beta T}$$

where

- β temperature coefficient for the thermal expansion
- T temperature difference
- L_f length of the fuse element
- A cross sectional area
- I_m area moment of inertia about neutral axis

Because of current pulses, the cyclic thermal stress is applied to the fuse. The thermal stress fatigue is only of cyclic nature, as long as the time period for each current pulse is short enough. Because of insufficient diameter, for the wire to accommodate the plastic deformation, cracks were propagated in a more or less brittle fashion [*Pao, 1992*]. Based on the relationship between the stress and the strain in the elastic range ($\Delta\varepsilon_e = \Delta\varepsilon_T$), the number of current pulses N which fuses can withstand may be predicted [*Smith, 1962*; *Hertzberg, 1989*] according to

$$\frac{\Delta\varepsilon_e}{2}E = \sigma_a = \sigma_{f'}N^b \qquad (1)$$

where

- $\Delta\varepsilon_e/2$ elastic strain amplitude ($\Delta\varepsilon_e = \Delta\varepsilon_T$)
- E modulus of elasticity ($61*10^3$ MP_a)
- σ_a stress amplitude
- σ'_f fatigue stress coefficient (115 MP_a)
- N number of current pulses to blowing
- b fatigue strength exponent -0.08 ($-0.07 < b < -0.15$)

2.2 Comparisons with experimental results

To demonstrate the model proposed (equation 1), comparisons will be presented by using both predictions based on measurements of displacements and predictions purely from simulations.

- Predictions based on measurements of displacements

From displacement measurements, mechanical strains were determined [*Meng, 1994*]. The mechanical strain was equal to the difference between the thermal strain contributed by the temperature rise and the apparent strain determined by the high speed films. The number of current pulses N which fuses withstand is found out from physical models.

Figure 1 presents comparisons of predictions and observations, where the number of current pulses are expressed against the relative I^2t value of pulsed current. The curve gives the predicted values of lifetimes based on the elastic strain relationship. Mark "o" indicates the observations for rectangular current pulses and mark "x" depicts the results for sinuous current pulses. In the graph, I^2t_{min} is the minimum I^2t value corresponding to current - time characteristics at the same time as the conducting time for a current pulse.

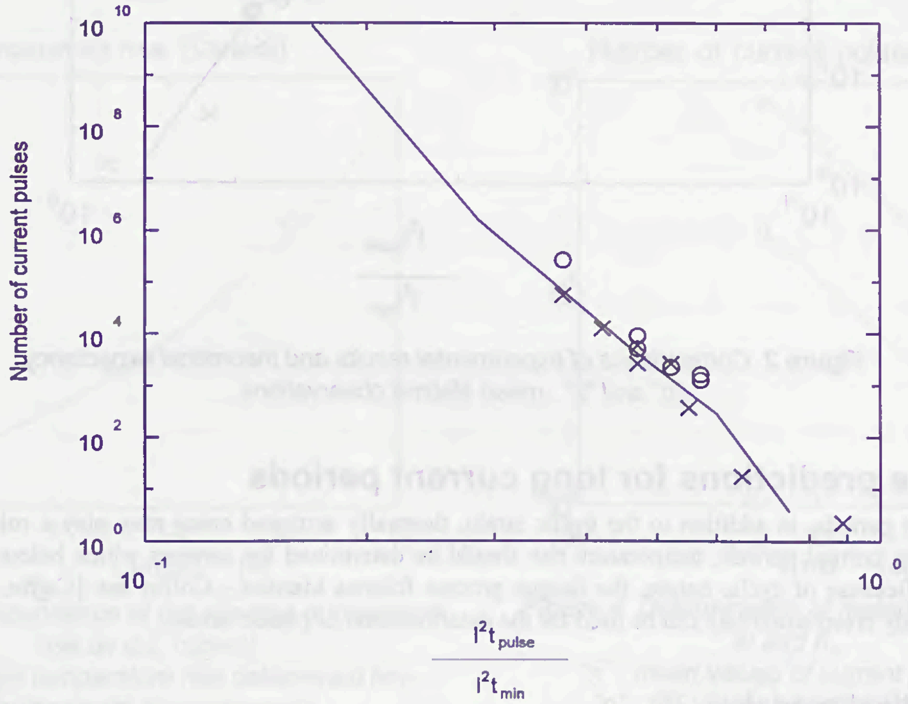

***Figure 1** Comparisons of predictions based on strain measurements (line) with experimental results of lifetimes*
"x" : sinuous current pulses
"o" : rectangular current pulses

♦ Theoretical predictions

In addition to the prediction of lifetimes based on strain measurements, lifetimes were also determined purely from theory by using PSPICE thermal modelling. By introducing the material properties, the number of current pulses which fuses withstand can be computed and tabulated in table 1.

***Table 1** Calculated lifetimes under the pulsed currents*

I^2t_{pulse} A^2s	0.38	0.50	0.63	0.78	0.95	1.04
$\frac{I^2t_{pulse}}{I^2t_{min}}$	0.29	0.38	0.48	0.60	0.73	0.80
Tsim °C	83	114	156	208	276	318
N	$4.7*10^7$	$8.9*10^5$	$1.8*10^4$	487	14	2.4

where T_{sim} is the calculated temperature rise from the thermal modelling.

Figure 2 illustrates comparisons of observed lifetimes with predictions in table 1. The solid line presents the lifetime which is calculated by using the temperature rise obtained from the PSPICE thermal modelling.

Both figure 1 and figure 2 show that the number of current pulses which fuses withstand increases as the I^2t value decreases. Predictions are well fitted with lifetime observations.

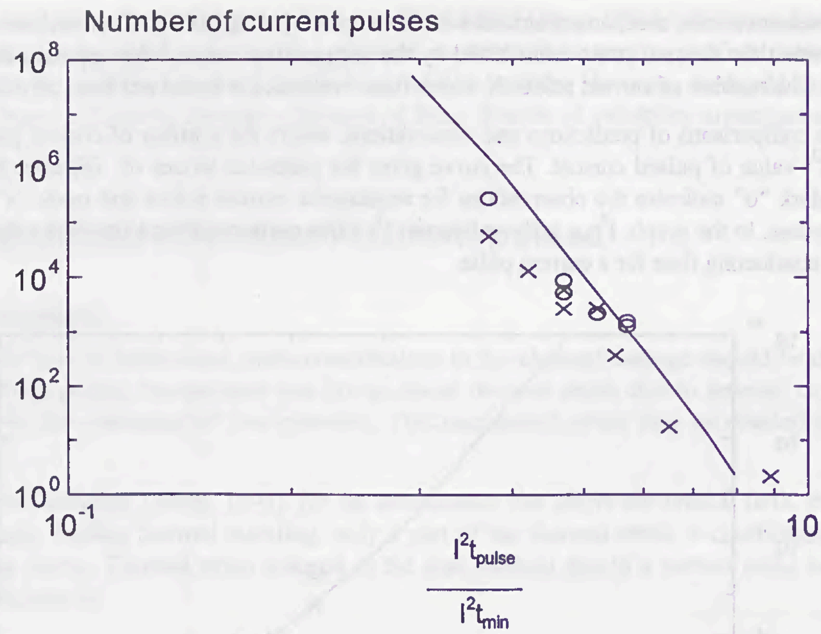

Figure 2 Comparisons of experimental results and theoretical expectancy "o" and "x" : mean lifetime observations

3. Lifetime predictions for long current periods

For long current periods, in addition to the cyclic strain, thermally activated creep may play a role. To estimate lifetimes for long current periods, temperature rise should be determined for currents which below the minimum fusing current. Because of cyclic nature, the fatigue process follows Manson - Coffin law [*Coffin, 1954*]. In this process, the steady creep strain rate can be used for the determination of plastic strains.

3.1 Theoretical models

Temperature rise for long current periods can be determined both by simulations and experiments. When electric currents are applied to fuses, thermal buckling takes place. Both currents and displacements may be measured. Because the maximum displacement has a well defined relationship with the average temperature rise, the relation between the temperature rise and the current is found. Figure 3 shows results of average temperature rises obtained from measurements together with a theoretic approximation. The average temperature rise T is a function of d.c. current I and it is expressed as

$$T = 10^{3/2}\, I^{a1}$$

where a1 = 3.

The creep rate is related to stress, temperature and time in general. Various relationships based on experiments have been proposed in the past. One of the common used relationships is the power law creep. It states that at intermediate to high stresses and at temperature above 0.5 T_m (the absolute melting temperature) the thermally activated creep process is dominated by the activation energy for self - diffusion[*Hertzberg, 1989*]. Because of temperature dependence on current, the creep rate is rewritten as

$$\dot{\varepsilon}_s \propto \sigma^{a2} \propto T^{a2} \propto I^{a1*a2}$$

where a_2 is a constant (4 < a2 < 5). Accordingly, a trial value a2 = 4.5 is suggested.

For the determination of creep, the relationship with time is essential. Concerning time influence, during each period, the contribution of the creep rate to the plastic strain $\Delta\varepsilon_p$ may be defined by

$$\Delta\varepsilon_p \propto \dot{\varepsilon}_s\, t^{m+1}$$

$$\Delta\varepsilon_p = A_0\, I^{a1*a2}\, t^{m+1}$$

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_{f'} N^c$$

The number of current pulses to blowing N is determined by

$$N = \left[\frac{A_0\, I^{a1^*a2}\, t^{1+m}}{2\varepsilon'_f}\right]^{1/c} = K_0\, I^{a1^*a2/c}\, t^{(1+m)/c} \qquad (2)$$

where t is the on time; c, a1, a2, K_0 and m are constants. According to Manson - Coffin law, in this work, c = -0.5 is suggested.

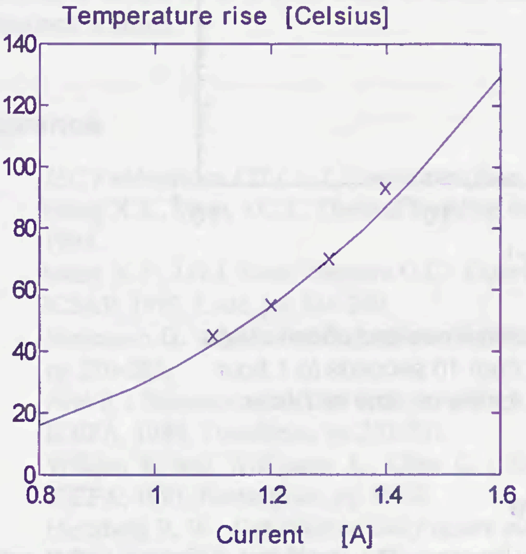

Figure 3 *Dependence of the average temperature rise on d.c. current*
"x" : average temperature rise determined from displacement measurements

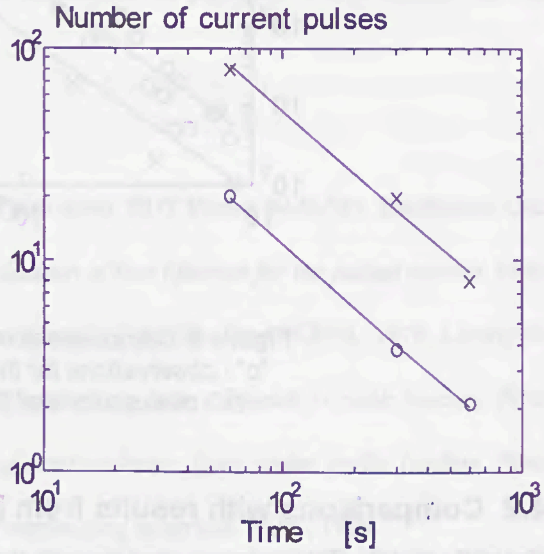

Figure 4 *Determination of material constants m and K_0*
"x" : mean values of current pulses
"o" : 5% values of current pulses

For current pulses with the same current value and different on times, two series experiments in minimum can determine the slope (1+m) of the number of current pulses with on time. The values of m and K_0 are determined from experimental data shown in figure 4 to be -0.5 and $3.6*10^8$. The 5% value of K_0 is $7.8 *10^7$ which is corresponding to the 5% value of the number of current pulses.

3.2 Comparisons with observations

By using values of a1, a2 and m, exponents for current *I* and time *t* can be obtained to be -27 and -1. Figure 5 shows comparisons of the predictions of the number of current pulses as a function (equation 2) of time and current and experimental results (a1 = 3, a2 = 4.5, m = -1/2, c = -0.5).

4. General Discussion

4.1 Difference between short and long current periods

In the section 2 and 3, extensive studies have been performed for short current pulses and long current periods. Now it is time to give a general explanation and remarks for these definitions.

As it has been indicated that the creep rate has a strong relation with time, therefore, a limit is expected to be significant for the dominance of creep. The exact indication is not known yet and probably not necessary, because of the complex of problems and the deviations from other parameters. However, examination of current - time characteristics shows that for the time above 10 seconds, the prearcing time is not precisely defined because of thermally activated creep (including oxidation).

Therefore, for the time delay fuses under the discussion, the time of 10 seconds is taken as a criteria to distinguish the short and long time current pulses. For continuous currents, the model presented for long current periods can be extended.

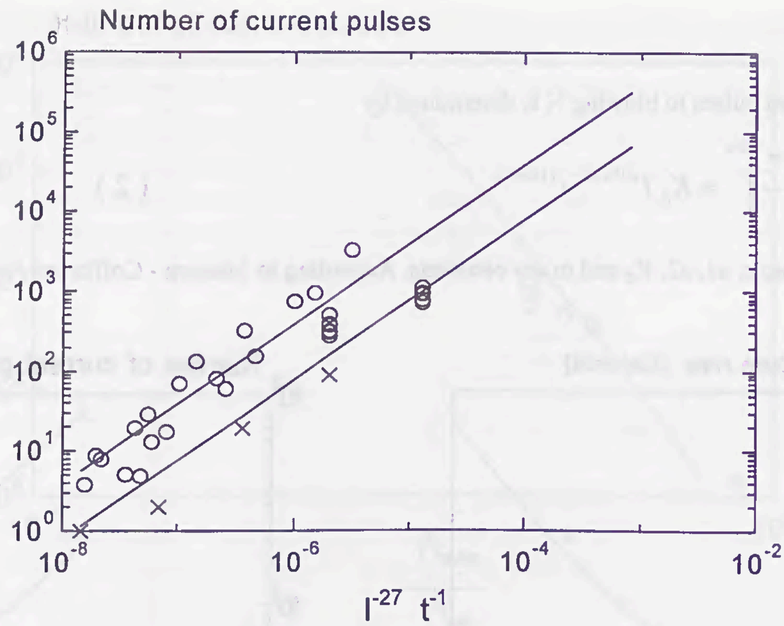

Figure 5 Comparisons of predicted lifetimes and observations
"o" : observations for the on time from 10 seconds to 1 hour
"x": observations of 5% values for the on time of 1 hour

4.2 Comparisons with results from literature

Generally, results above were comparable with the results in literature. The significant difference is that previous researchers considered that the fatigue of fuse element was mainly controlled by the plastic range [Arai, 1983; Costa, 1991; Wilkins 1991]. For short current pulses, elastic strain plays an important role, while for long current periods, plastic strain may control the fuse lifetime.

Moreover, in the former research [Arai, 1983], the shape effect of fuse elements was considered as a factor K. The rule was that K=1 for straight element; K>1 for local deformation; K<1 for bent element. From the photographic measurements, it indicates that the compression force induced by the thermal expansion may cause the buckling of fuse element, a part of thermal strain will converted to the apparent strain, therefore, the factor K should be less than 1 even for the straight fuse element.

Results from long current periods can also be compared with the curve fitted function in the reference [Stevenson, 1976]. On a double log scale, the literature curve slope was 0.045, the slope here found is 0.037 from physical models (1/27) presented in the section 3.

If the temperature rises were normalised by the melting temperature, lifetime limits were found to be in agreement with the results given in the reference [Williams, 1981]. Where the temperature thresholds were directly related with the melting temperature of the fuse element, applications were restricted, because only the thermal properties were considered.

In IEC publications, a very limited number (1000 pulses in IEC 127) of pulsed current is applied to the fuse to examine the quality of fuses. On the one hand, the magnitude of pulsed current will be too low to give a indication of pulse withstand ability of fuses; on the other hand, from this investigation it is clear that fuses may withstand some thousands of pulsed currents, but they may still fail after a long run in service. Therefore, the requirement in IEC is not enough to guarantee the long term behaviour of fuses, more specific values of lifetime should be carried out as a guidance of selectivity.

5. Conclusions

In this work, physical models for lifetime predictions have been established for short current pulse and long current periods. Because no limitations are imposed for any specific constructions, they should be valid for any practical fuses, unless some material constants have to be different.

Predictions for a typical time delay fuses have been demonstrated and compared with experimental observations and an excellent agreement has been found.

The work is developed purely on the physical basis and results obtained so far therefore provide a significant understanding of fuse ageing problems compared with previous investigations. Concerning physical models developed, it should be of a great value to assist the evaluation of commercial products, new developments and applications of fuses.

Reference

[1] *IEC Publications 127 (1- 7) : miniature fuses.*

[2] Meng X.Z., Sloot, J.G.J.: *Thermal buckling behaviour of fuse wires.* EUT Report 94-E-283. Eindhoven, Oct. 1994.

[3] Meng X.Z., J.G.J. Sloot, Damstra G.C.: *Experimental evaluation of fuse lifetimes for the pulsed current.* Proc. ICSAP. 1993, Lodz, pp. 236-240.

[4] Stevenson G. : *Cyclic loading of fuses for the protection of semi-conductors.* Proc. ICEFA, 1976, Liverpool, pp.276-283.

[5] Arai S. : *Determinations and cycles to failure of H.V. current-limiting fuses subjected to cyclic loading.* Proc. ICEFA, 1984, Trondheim, pp.252-261.

[6] Wilkins R. and Wilkinson A., Cline C. : *Endurance of semiconductor fuses under cyclic loading.* Proc. ICEFA, 1991, Nottingham, pp.43-48.

[7] Hertzberg R. W.: *Deformation and fracture mechanics of engineering materials.* Wiley, 1989.

[8] Coffin L.F.Jr.: *A study of the effects of cyclic thermal stresses on a ductile metal.* ASME, Vol. 76, 1954, pp. 931.

[9] Williams E.H., Battel S.J.: *Incremental failure mechanism in subminiature hermetically sealed fuses.* ISTFA 1981 symp. pp. 26-38.

[10] Smith R.W., Hirschberg M.H. and Manson S.S.: *Fatigue behaviour of materials under strain cycling in low and intermediate life range.* NASA, technical note D-1574. 1962.

[11] Golden F.B.: *Rattings & applications of power thyristors for resistance welding.* IEEE Conf. Rec. of 4th Annual meeting of industry and general applications group, pp. 507-515, 1969.

[12] Pao Y.H.: *A fracture mechanics approach to thermal fatigue life prediction of solder joints.* pp. 559-570, IEEE Trans. Vol. CHMT-15, No.4, Aug. 1992.