THERMAL FATIGUE DAMAGE OF ULTRA-FAST FUSES

Jean-Louis Gelet(1)

(1) FERRAZ-SHAWMUT
Rue Vaucanson
69720 Saint Bonnet de Mure – France

Tél. : 33 (0) 4 72 22 66 30
Fax : 33 (0) 4 72 22 66 14
jean.louis.gelet@fr.ferrazshawmut.com

Abstract: *In ultra-fast fuses, current-density can reach values as high as several hundred of A/mm². This induces an important heating and consequently stresses in the more fragile area of the conducting element, i.e. the notches. As the fuse is often submitted to cyclic loads, ageing of the notches occurs and then the fuse opens. FERRAZ-SHAWMUT is for a long time aware of this phenomenon and since years has carried out many tests on his fuses. Rules does exist in order to choose the right fuse for a given application [1]. But, keeping in mind the permanent will of better service to his customers, FERRAZ-SHAWMUT is now working for improving the calculation of the life-time of the fuses in case of long durations (typically ten to thirty years).*
As it is not possible to wait for years, an accelerated tests-method has been settled in additional with pure mechanical tests, allowing to reach millions of cycles. Analysis of the tests-results shows that ageing of fuses is a combination of both fatigue and creep. Furthermore, validation of the accelerated tests is assured by SEM-observations.

Keywords: electric fuse, cyclic load, fatigue, creep

1. Definition of the problem

For the protection of power-semi-conductors, specific ranges of fuses are designed, following IEC standard 269-4. The fundamental specificity of these fuses is to be able to operate very rapidly in case of short-circuits in the field. That means that for a given rated-current, these fuses are required to have a minimal conducting area; or, on another hand, for a given I^2t, to carry a maximal current.

But carrying a maximal current doesn't go without any risks. The biggest of them is the occurrence of some metallurgical fatigue phenomenon. Indeed, by Joule-effect, the current-conduction induces a heating of the conductors, specially at the notches of fuse-elements. Then, the temperature would cause some dilatation of the metal. But, as this dilatation is interfered with sand around the notches, stresses are developed. Note that stresses are generated all along the element, but they are amplified on the restrictions of the necks.

When fuses are used in a cyclic way, the alternation of stressed and relaxed states leads to ageing by fatigue phenomenon.

The problem with power-semi-conductor-fuses is to find the better compromise between I^2t and ageing. For a long time, FERRAZ-SHAWMUT is aware of this phenomenon and thanks to many tests, could develop the method allowing to correctly choose a fuse.

Nowadays requirements from customers concern figures for very long life-durations, up to thirty years, and statistical considerations giving evaluation of tolerances around mean values.

This requires new tests-programs. It is very understandable that testing fuses for excessive long times is not possible and that accelerated tests are to be thought.

One idea is to heat only the notches, which are actually the only part of the fuses subject to ageing. Even though the nearest environment of the notches is kept as in fuses, it is possible to drastically reduce the thermal time-constant of the test-sample and then to reach high numbers of cycles, comparable with long life-durations.

2. Tests

2.1. Principle of the tests

A single fuse-element is supporting the current. This element is placed on an aluminium cooling-water-box. Electrical insulation between fuse-element and water-box is done by an insulating tape. In spite of this, there is a good thermal conductivity between the fuse-element and the cooling-box. Notches are surrounded by sand. The sand is held inside a fuse-ceramic-body.

In addition, the drop-voltage between each side of the raw of notches is permanently measured. It allows to get the mean temperature of the notches from the variation of resistivity of the fuse-element-metal versus temperature. See Fig.1.

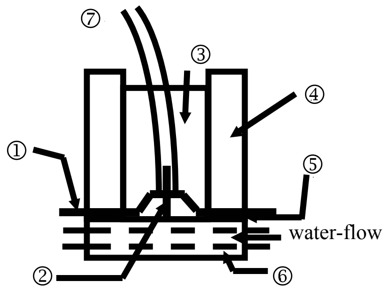

Fig.1 : Principle of the tests :①fuse-element; ②notches; ③sand; ④ceramic body; ⑤ insulating tape; ⑥water-box for cooling; ⑦drop-voltage measurement.

It has been checked that ON/OFF cycles such short as 10 sec/10 sec will allow to get significant temperature-rise during the ON-phase and a cooling to sufficiently low temperature during OFF-phase. For example and depending on the current, the mean temperature of the notches can reach 200÷300°C during ON-phase and decreases to 25÷40°C during OFF-phase.

Large interest of this accelerated test is demonstrated if we take care that same temperature-rises as for 1 hour ON/1 hour OFF-cycles is got within 10 + 10 seconds. In other words, number of cycles is multiplied by 360 within the same time. Thirty years will be reduced to 1 month.

2.2. Tests-results

These accelerated tests bring several levels of results.

2.2.1. Increase of temperature at the end of fuse-life :

Thanks to the temperature-measurements, it appears that the fatigue phenomenon doesn't occur suddenly. The increase of the resistance begins to be significant when a half to a third of the life-duration is still remaining.

When tests are carried out on complete semi-conductor-fuses, with many rows in series and in parallel, the death of the fuses is very sudden, as only a few percents of the life-duration is still remaining.

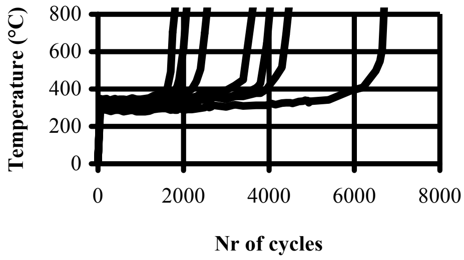

Fig.2 : Measurement of temperature through the drop voltage allows to show that the damage increases first slowly and then is accelerated at the end of life-time.

2.2.2. Numbers of cycles versus current

Numbers of cycles have been plotted versus test-current. Afterwards, statistical treatment of the results gives the mean value

$$\log(N) = -23.\log(I) + cste \qquad (1)$$

and the tolerance for the life-duration.

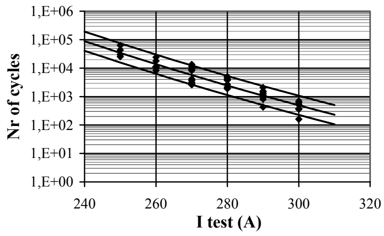

Fig.3 : Numbers of cycles are plotted versus the test-current, here with log-lin scale. Mean curve and 90%-tolerance-curves are also plotted.

2.2.3. Numbers of cycles versus temperature

Numbers of cycles have been plotted versus maximal temperature at the end of 10s/10 sec. cycle. Afterwards, statistical treatment of the results gives the mean value :

$$\log(N) = -8.\log(\theta maxi) + cste \qquad (2)$$

and the tolerance (for instance at 90%) for the life-duration.

In addition with thermal models giving the temperature of the notches during cyclic use, they will allow to determine the numbers of cycles a fuse will withstand in the field.

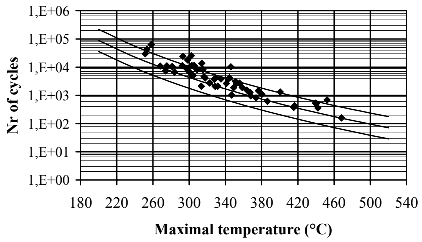

Fig.4 : Numbers of cycles are plotted versus the maximal recorded temperature, here with log-lin scale. Mean curve and 90%-tolerance-curves are also plotted.

2.2.4. Numbers of cycles versus temperature-increase

Statistical treatment of the results gives the mean value

$$\log(N) = -5.5.\log(\Delta\theta) + \text{cste} \qquad (3)$$

and the tolerance (for instance at 90%) for the life-duration.

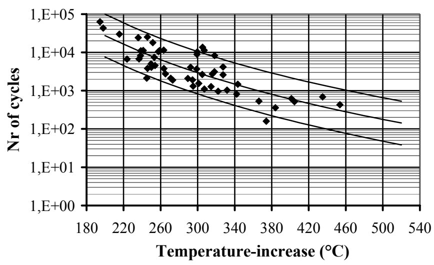

Fig.5 : Numbers of cycles are plotted versus the recorded temperature-increase, here with log-lin scale. Mean curve and 90%-tolerance-curves are also plotted.

3. Validation

3.1. From theory of fatigue

In the 60's, COFFIN [2-3] and MANSON [4] carried many works on fatigue-phenomenon. One of their more interesting results is that the life-duration of the materials depends on the level ε of the strains according to the expression :

$$\log(N) = a.\log(\varepsilon) + \text{cste} \qquad (4)$$

According as strains are plastic or elastic, these authors announced following values for coefficient a:

for plastic strains, a varies from –1.4 to –2,
for elastic strains, a varies from -6 to –10.

These results came mainly from tests carried out on steels and stainless steels. FERRAZ-SHAWMUT did tests on pure silver, as used for manufacturing fuse-elements.

Mechanical bending tests have been carried out on a rotating machine. They led to the following values for the coefficient a :

for plastic strains, a varies from –2.5 to –3,
for elastic strains, a varies from -6 to –8.

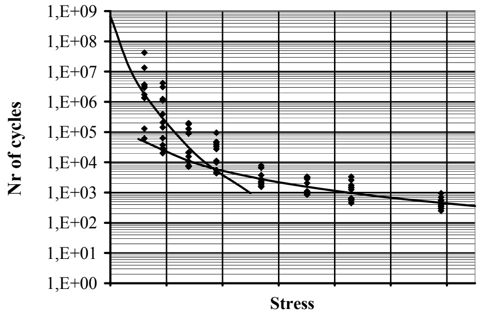

Fig.6 : Numbers of mechanical cycles are plotted versus the stress, here with log-lin scale. Two kinds of behaviour are observed according to the level of stresses.

3.1.2. Extension of the model to thermal fatigue

LEMAITRE and CHABOCHE [5] have first introduced the idea that thermal fatigue was a combination of mechanical fatigue and creep. After them, MANSON [6-7], HALFORD [7-8] and HIRSCHBERG [8] proposed four typical four typical cycles :

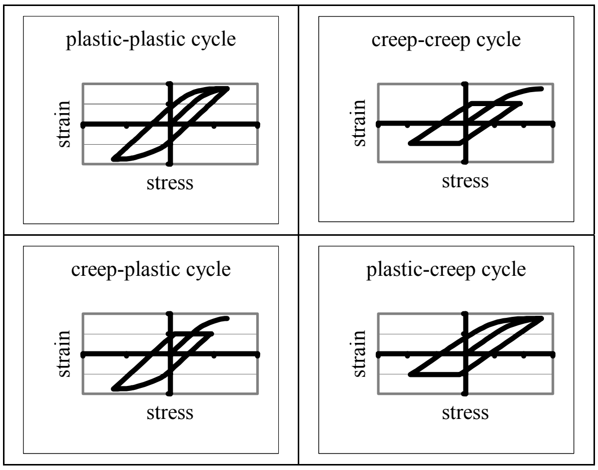

Fig. 7: Four typical cycles combining plastic strain and creep.

For each one of these typical cycle, a law gives the number of cycles versus the strain :

$$\log(N_{ij}) = -\gamma_{ij}.\log(\varepsilon_{ij}) + cste \qquad (5)$$

where the indexes i and j represent c or p, for plastic and creep,

εij is the part of the total strain corresponding to the typical cycle ij.

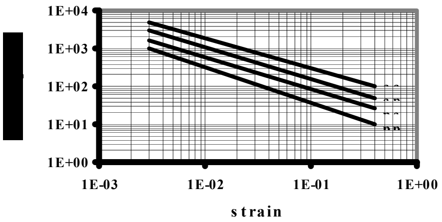

Fig. 8: For each one of the typical "plastic-creep" cycles, it is possible to estimate one ageing-law.

The total strain is the summation of the different strains of each typical cycle :

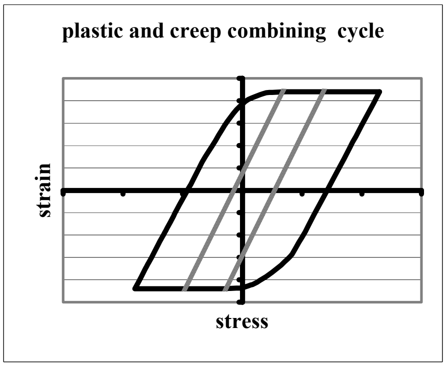

Fig. 9: Example of combination of 3 typical cycles.

The number of cycles for the total strain is assumed to follow a law as :

$$\frac{1}{N_{total}} = \sum \frac{\varepsilon_{ij}}{\varepsilon_{total}} x \frac{1}{N_{ij}} \qquad (6)$$

$$\varepsilon_{total} = \varepsilon_{pp} + \varepsilon_{pc} + \varepsilon_{cp} + \varepsilon_{cc} \qquad (7)$$

As presented previously, FERRAZ-SHAWMUT carried out accelerated tests. Different relationships have been found, according to what parameter was considered as stress :

$$\log(N) = -23.\log(I) + cste \qquad (1)$$

$$\log(N) = -8.\log(\theta maxi) + cste \qquad (2)$$

$$\log(N) = -5.5.\log(\Delta\theta) + cste \qquad (3)$$

Note that there is a good coherence between expressions including current and maximal temperature. Indeed, it is possible to approach that temperature is as the 3rd power of the current :

$$\theta = \theta_0 + (1+\alpha.\theta)Ri^2 \approx Ri^3 \qquad (8)$$

Furthermore, we could make the assumption that stresses or strains are directly proportional to the temperature θ or to the temperature-increase Δθ. Indeed, as θ is due to the sand-interfered thermal expansion, we could write :

$$\varepsilon = \frac{\Delta l}{l} = \frac{1}{l}.\lambda.\Delta\theta \qquad (9)$$

were :

l is the concerned length of material,

Δl is the linear expansion of the material due to temperature,

λ is linear-expansion-coefficient of the material,

Δθ is the temperature-increase.

If this assumption was true, we would have to find out the same coefficients a as for mechanical-tests on pure silver. As we don't, that means that actual strain might be a combination of both fatigue and creep phenomena.

3.3.2. From SEM-observations

We did SEM observations on fuse-elements after ageing by different ways (usual electrical cycle, accelerated tests, mechanical tests). The main pieces of information concern:

<u>Slip-bands :</u> traces observed on the surface of the samples. They correspond to a displacements at crystallographic plans inside the metal-grain. Slip-bands may be at the origin of a crack.

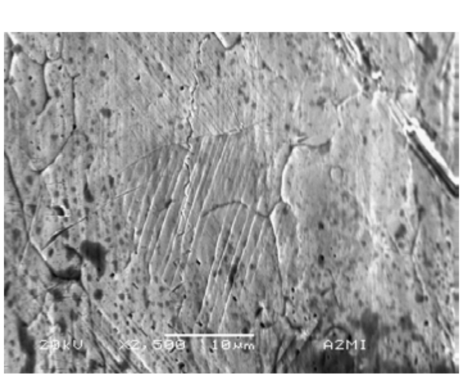

Fig. 10 : Slip-bands on a fuse-element after rupture. 450 electric cycles 1h ON/1 h OFF.

Fatigue lines : traces observed on the crack-area. They correspond to the incremental successive steps of the propagation of the cracks.

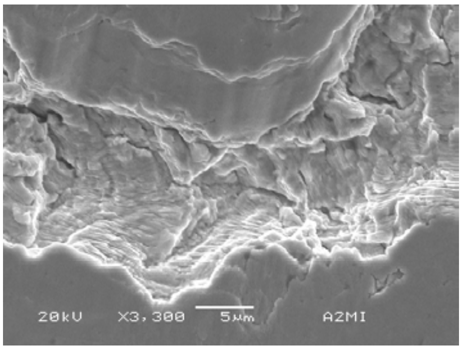

Fig. 11: Fatigue-lines on a sample after rupture. 39000 mechanical bending-tests cycles.

Grain-decohesion : observed at both surface and crack-area. They correspond to the opening of cracks between metal-grain (intergranular cracking).

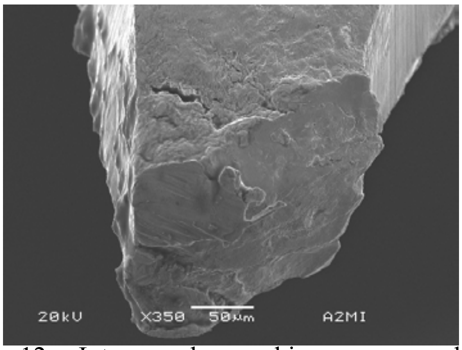

Fig. 12 : Intergranular cracking on a sample after rupture. 1200 mechanical bending-tests cycles.

Transgranular cracking : observed at both surface and crack-area. They correspond to the opening of cracks through one metal-grain.

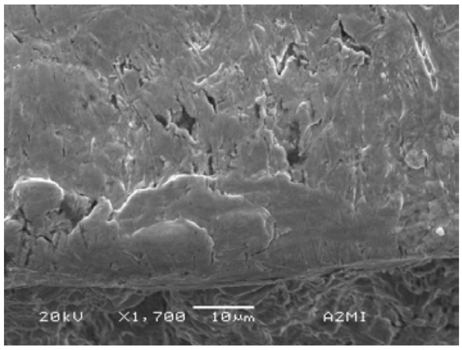

Fig. 13 : Transgranular cracking on a sample after rupture. 39000 mechanical bending-tests cycles.

3.2.2. Comparison of the observations:

The following table 1 summarizes what kind of indications have been got, depending on the kind of the test and the level of solicitation. In addition to this chart, some comments may be done :

- fatigue lines always occur,
- slip-bands have been clearly observed in case of plastic strains. Some indications have been observed in case of elastic strains, but for the time being, it has been difficult to settle if there were actually slip-bands,
- in case of plastic strain, cracks are transgranular and intergranular ; in case of elastic strains, only transgranular cracks have been observed.

tests	Nr of cycles	slip-bands	fatigue-lines	grain-crack	strain
mechanical	$2.2.10^6$	no		transgranular	elastic
mechanical	180.10^3	no	yes	transgranular	elastic
mechanical	39.10^3	yes	yes	trans & inter	transition e/p
mechanical	$1.2.10^3$	yes far from crack	yes	trans & inter	plastic
accelerated	$>25.10^3$		yes	trans & inter	transition e/p
accelerated	$>1.2.10^3$		yes	trans & inter	plastic
electric 1hON/1hOFF	540	yes far from crack	yes	trans & inter	plastic

Table 1 : Summary of the SEM-observations.

4. Conclusions:

A set of conclusions have been drawn out of this study :

a) ageing of the necks of the fuse-element occur slowly, in contradiction with what is observed on complete fuses.
b) mechanical tests show that up to 10^4 cycles, strains on pure silver are plastic,
c) mechanical tests show that over 10^5 cycles, strains are elastic,
d) electrical tests (usual and accelerated) led to ageing by both plastic strain and creep.
e) the knowledge of the partition between plastic strains and creep will be necessary in order to reach a good ageing-model.

Nevertheless, it seems that these conclusions could be appreciated by additional tests :

- accelerated tests up to 500.10^3 to 10^6 cycles in order to clearly check the sharing between elastic and plastic behaviours,
- accelerated tests with different ON-times in order to underline the effect of creep,
- continuous-creep tests in order to know actual withstanding of pure silver versus this kind of solicitations and to compare the crack-aspect to the ones got under cyclic loads.

References

[1] FERRAZ-SHAWMUT– leaflet NT59.
[2] Coffin L.F. : “Internal stresses and fatigue in metals”. *Elsevier,* New-York 1959.
[3] Coffin L.F. :“Fatigue” *Corporate Research and Development, GE Company, Schenectady,* New-York 1972
[4] Manson S.S. “Fatigue, a complex subject, some simple approximations”. *Experimental Mechanics* 1965.
[5] Lemaître J., Chaboche J.L. : “Method of metal characterization for creep and low cycle fatigue prediction in structures.” *1st symposium on Mechanical Behaviour of Metals,* Kyoto 1973.
[6] Manson S.S. “Thermal stress and low Cycle fatigue” *McGraw Hill* 1966.
[7] Manson S.S., Halford G. “*Int. Conf. Thermal and High Strain fatigue*” London 1967.
[8] Hirschberg M.H., Halford A.J. “Strain range partitioning. Atool for characterizing high temperature low cycle fatigue” *NASA* 1975