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Fuse Modeling for Reliability Study of Power Electronic Circuits

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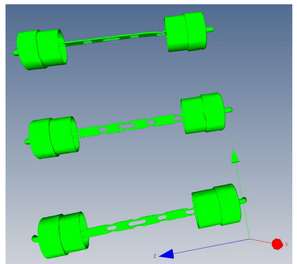
Abstract –This paper describes a comprehensive modeling approach on reliability of axial lead fuses used in power electronic circuits. When fuses are subjected to current pulses, cyclic temperature stress is introduced to the fuse element and will wear out the component. Furthermore, the fuse may be used in a large variation of ambient temperature, e.g. in deserts and the accumulated damage in the fuse elements is gradually increasing due to thermo-mechanical stress that results in resistance increase and further unexpected failures. Therefore, in such cases, a reliable protection required for the other circuit components will not be achieved. The thermo-mechanical models and fatigue analysis are presented by FEM simulations in order to identify the important factors affecting the performance of fuses at different ambient temperatures and cycling operation.

1. Motivation and Background

- Cyclic thermal stress influence the lifetime of fuses.
- Accumulated damage in the fuse elements is gradually increasing due to thermo-mechanical stress that results in resistance increase and further unexpected failures and the breakage in the neck of the first hole in the fuse silver element.
- This paper investigates the thermo-mechanical and thermo-electrical modeling of fuses by FEM simulations in order to identify the important factors affecting the performance of fuses at different ambient temperatures and cycling behavior.

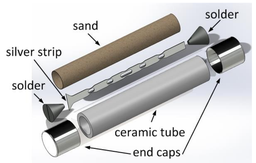
PCB holding different fuses being thermal cycled



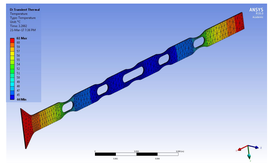
3D X-ray of a fuse, after 200 thermal cycles [-40 – 125°C]

2. Thermal Analysis

- ANSYS® is used to model the thermo-mechanical stress in the fuse.
- The heat is mostly transferred inwards through the caps because the ceramic tube has a much lower thermal conductivity compared to copper caps.
- The design goal is to have an expected life time of 10 years (360 days), thus a total of 3600 cycles. The design load case is referred to as the "*Desert Scenario*", where thermal loads are in the following distribution of temperature range cycles:
  - 1200 cycles of ΔT = 55°C - [25 – 80°C],
  - 1500 cycles of ΔT = 45°C - [25 – 70°C],
  - 900 cycles of ΔT = 35°C - [25 – 60°C].



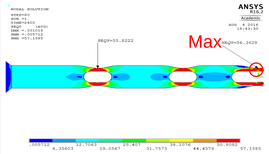
Schematic of opened fuse modeled in ANSYS



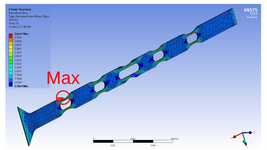
Temperature profile in the thermal cycling [25–70°C]

3. Thermo-Mechanical Analysis

- Preliminary simulations show a weakness at the center of the silver strip, which is in contrast with the experimental investigation.
- A hypothesis involving pre-tension at the manufacturing time due to soldering of the fuse element to the end caps has been formulated.
- In agreement with the formulated hypothesis, it has been inspected by the microscopic imaging that the holes closer to the end caps have thinner neck compared to the center hole.
- Considering the pre-tension, the Von-Mises stress distribution states the highest stress is in the neck of the first hole closer to the trapezoidal end.



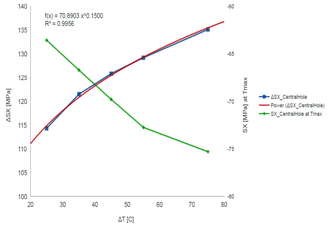
Von Mises stress without considering pre-tension



Von Mises stress considering pre-tension

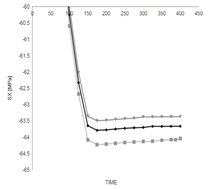
4. Thermo-Mechanical Sensitivity Analysis

- Sensitivity to temperature range
  - ΔT = 25°C, for range [50–25°C]
  - ΔT = 35°C, for range [60–25°C]
  - ΔT = 45°C, for range [70–25°C]
  - ΔT = 55°C, for range [80–25°C]
  - ΔT = 75°C, for range [90–15°C]

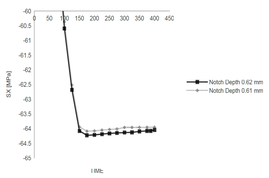


- Sensitivity to geometry

Effects of changing notch radii

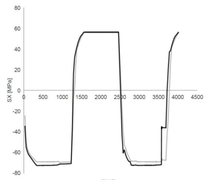


Effects of changing notch depth

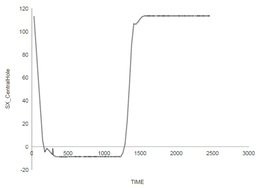


- Sensitivity to pre-tensioning

Without considering pre-tension

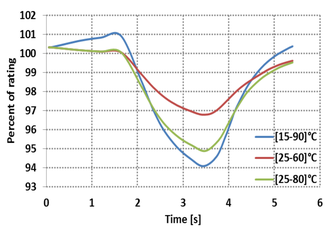


With considering pre-tension

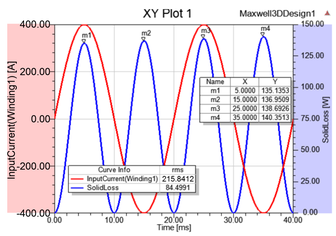


5. Thermo-Electricla Analysis

- The breaking capacity tests of fuses are typically carried out at 25°C.
- In higher thermal stress, the fuse rating is decreased significantly.
- Losses and i^2t are function of temperature due to the joule heating.



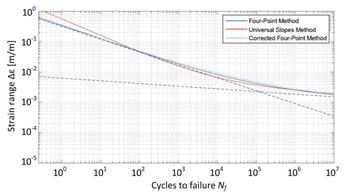
Temperature cycling effects on current carrying capacity of the fuse



Current and solid losses of the fuse considering the self-heating

6. Fatigue Analysis

- Any thermal/mechanical loads that vary with time can potentially cause fatigue. The significant factors are the amplitude and mean value of the stress/strain – time waveform and the total number of stress/strain cycles.
- For fatigue life assessment, it is preferred to use the (ε-N)-approach due to the local plasticity experienced in the notched regions and regions around the holes.



Estimate of (ε-N) - curves. Fully reversed loading.

- Palmgren-Miner linear damage rule:
  A damage D should be less than unity for no failure

$$D = \sum_{i=1}^{n} \frac{n_i}{N_{fi}} < 1$$

n_i: number of cycles experienced by the specimen for the i_{th} load
N_{fi}: number of cycles to failure if only the i_{th} load were acting

$N_1^{\Delta T55} = 1200$ $N_2^{\Delta T45} = 1500$ $N_3^{\Delta T35} = 900$	$N_{f1}^{\Delta T55} = 1300$ $N_{f2}^{\Delta T45} = 2900$ $N_{f3}^{\Delta T35} = 7900$	❖ Damage predicted with the *Desert Scenario* is 1.55 that predicts failure.

Conclusions

In this paper, a comprehensive study has been devoted to reliability analysis of cartridge fuses for the first time by variation of ambient temperatures to investigate the effect of thermal cycling on the behavior of fuses. The FEM structural analysis proves that the notches regions experience higher stress in a single thermal cycling. The proposed fuse models can be used in a mission-profile based approach that considers the reliability in the design and application of fuses. Moreover, the proposed models can be used to improve the thermal cycling capability of fuses and to increase the lifetime in real operating conditions.

GRUNDFOS

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