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Failure mechanism analysis of fuses subjected to manufacturing and operational thermal stresses

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ABSTRACT

This paper identifies failure mechanisms of axial lead fuses subjected to real field ambient thermal profiles by finite element simulations and experimental testing. Experimental observation of failed fuses attributes fatigue failure of fuses to breakage of the fuse element. The fuse elements consistently fail at the notches adjacent to the end caps accompanied by a localized out-of-plane bend. Identification of the failure mechanism motivates a comprehensive thermo-mechanical study of the fuse deformation response prior to failure, which is rather involved due to the complex interactions of the fuse components, and residual effects of manufacturing processes. An investigation on the pre-operational state of fuses evaluates damage introduced during manufacturing of the fuse. In specific, the work simulates soldering induced residual stresses and addresses their impact on the fatigue damage and lifetime of the fuse. In the paper a lifetime model of the fuse is proposed and tested.

1. Introduction

Fuses are safety devices used to protect electrical circuits from excess currents and short-circuit events, and are compulsory components in modern power designs. The fuse includes a highly conductive perforated strip, known as the fuse element, which blow-up in case of short circuit events. The fuse element is enclosed by a protective tubular ceramic case, which is filled with sand to extinguish efficiently the arc that forms during intervention. End caps in each end of the tube and provide electrical contact with the fuse element through a soldered joint.

Conventional approaches to assess fuse reliability against variations of ambient temperature, subject the fuse to five thermal cycles [1] and assume an infinite lifetime with respect to cyclic ambient temperature if the fuse endure these cycles. However, fatigue failure of axial lead fuses has been observed experimentally after just 100–200 thermal cycles due to variations of ambient temperature within the fuse-rated min/max-operating thermal range [2]. During operation of the fuse, it will experience thermal loading from a variety of sources e.g. environmental thermal loading and self-heating due to current flow. Cyclic loading causes successive expansion and contraction of the fuse components, which result in thermal stresses and accumulation of damage. The thermal stresses wear out the fuse over time and become an important reliability concern.

Thermal fatigue and premature fuse element breakage is one aspect of ambient temperature effects on the lifetime of fuses. Another aspect is the influence of ambient temperature variations on fuse characteristics. Ambient temperature variation cause plastic deformation of the fuse element, which gradually accumulates damage and affects electrical resistance of the fuse element. This is an example of fuse ageing, which affects fuse performance, e.g. i^2t characteristics.

Various attempts have been done to uncover the problem of ageing and lifetime prediction of fuses due to Joule-heating by either continuous currents or pulse currents [3–8]. Despite a similar thermo-mechanical response and impact on fuse reliability, little work has been done on fatigue failure and fuse ageing caused by variations in ambient temperature. Such investigations have recently been initiated in [2] through a multi-physics finite element analysis (FEA), and a framework of a methodology has been proposed for lifetime prediction of fuses subjected to real thermal profiles of ambient temperature. However, the root cause of fuse element failure according to previous FE simulations and lifetime models is not consistent with experimental observations regarding fuse element deformation and breakage location.

This paper addresses the uncertainties related to failure mechanisms of fuses by thorough thermo-mechanical FEA of deformation mechanisms of the fuse element, interactions of fuse components, residual effects of fuse manufacturing, and monitoring of cyclic stress- and strain responses. Assessment of fatigue failure is based on Manson-Coffin lifetime modelling and Smit-Watson-Topper (SWT) damage parameters [9]. Fatigue properties of the fuse element are measured experimentally

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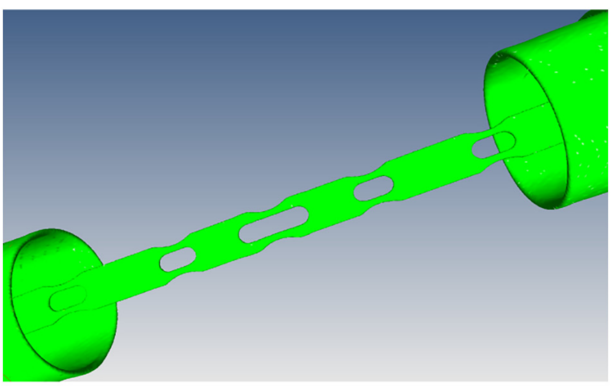
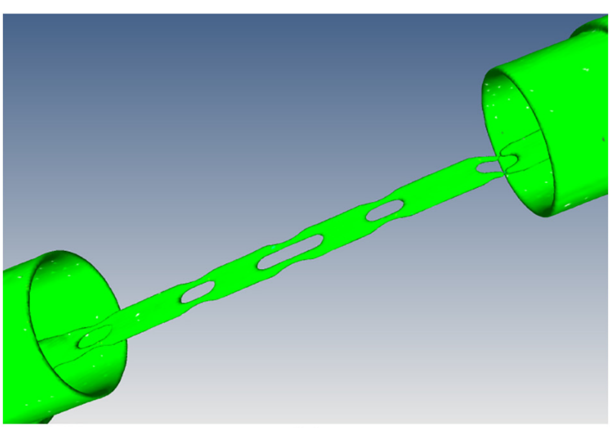
Fig. 1. Tested axial lead fuses.



(a)



(b)

Fig. 2. X-ray scan of fresh fuse (a), and failed fuse (b), tested at cyclic ambient temperature.

using strain-controlled dynamic mechanical analysis (DMA). The lifetime model is compared to actual test of fuses subjected to cyclic ambient temperatures in a heat chamber.

2. Thermal loading and deformation of fuses

The fuse under study is a commonly-used fast-acting axial lead fuse [1], as shown in Fig. 1. X-ray studies of failed fuses that has been tested at cyclic ambient temperature, attribute fatigue failure of fuses to breakage of the fuse element. All the tested fuse elements consistently fail at the notches adjacent to the end caps accompanied by a localized out-of-plane bend, as shown in Fig. 2. Identification of the failure mechanism motivates a comprehensive thermo-mechanical study of the fuse deformation response, which is rather involved due to complex interactions of the fuse components, and residual effects of manufacturing processes.

Upon increasing the ambient temperature, the rigidity and relatively low coefficient of thermal expansion (CTE) of the ceramic tube cause compressive thermal strains to develop in the fuse element. The slenderness of the notched fuse element, in combination with a state of compressive membrane strain energy, makes it susceptible to thermal buckling. The surrounding sand impose restrictions on the free deformation of the fuse element and might prevent it from deflecting out-of-plane, depending on the stiffness of the surrounding sand. A FE model of the full fuse structure is built, as shown in a Cartesian coordinate system in Fig. 3; inclusion of all fuse components allows for assessment of their interaction.

The element type and discretization differs between the fuse components, depending on requirements of convergence, simulation accuracy, and computational efficiency. Thermal and structural symmetry is applied at the plane y = 0 to gain computational efficiency.

The fuse is modelled using solid quadratic elements with reduced integration order and a pure displacement formulation. The notched regions of the fuse element necessitate a fine mesh due to significant stress gradients, plasticity, and simulation accuracy. Given the ductility and low yield strength of the fuse element, nonlinear plastic behavior needs inclusion in the constitutive formulation.

The plastic material behavior of the fuse element is assumed rate-independent, and uses a Von Mises yield criterion, an associated flow rule, and a multilinear kinematic hardening law for inclusion of Bauschinger effects in case of cyclic plasticity. The material responses of the remaining fuse components are limited to the elastic regime. The solder is a lead-free binary alloy of composition Sn97Cu3. In spite of its low yield strength, solder-plasticity is neglected in the finite element simulation. The effect of solder plasticity proves to have a significant influence at the interconnection of the solder and fuse element, however, the influence drops rapidly as one moves away from the interconnection, and becomes negligible in the regions of interest i.e. the fuse element notches. Effectively, the simplification becomes a reasonable approximation with notable computational benefits. Material properties of the fuse element are available in [10].

Apart from the filler sand, the fuse components are represented as three-dimensional continuums. The intent of modelling the filler sand is to represent the effect of the medium on the fuse element, not to analyze the medium itself. A Winkler foundation [11] represents the mechanical effect of the filler sand on the fuse element. The foundation applies a resisting pressure to the surface of the fuse element, which depends on the foundation modulus and the magnitude of the lateral deflection at the foundation surface.

Apart from material nonlinearity, geometrical nonlinearity is also included in the finite element model. The simulations are solved using a full Newton-Raphson procedure, and automatic time stepping- and line search algorithms [12].

The thermal loading of the fuse is introduced by assigning a spatially uniform temperature distribution, which varies with time in accordance with ambient temperatures in real operating conditions. The load introduction invokes an assumption of zero thermal gradients across the fuse components. The assumption is reasonable for low heating- and cooling rates up to approximately 10 °C/min. The thermal loading cause deformations and stresses in the fuse components due to