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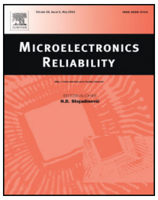

Review paper

Creep fatigue models of solder joints: A critical review

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ABSTRACT

The goal of creep fatigue modelling is the compounding of the damage caused by creep and fatigue mechanisms. The different approaches for compounding these damage mechanisms have led to several different creep fatigue models: (i) ignore fatigue damage — the creep ductility (energy density) exhaustion models; (ii) lumping plastic and creep strain (energy) into inelastic strain (energy) — the model of Dauvearx's crack initiation and propagation; (iii) linearly sum fatigue and creep damage — the model of linear damage summation; (iv) model creep and fatigue damage using a common parameter — the models of fracture mechanics; (v) partition damage into fatigue, cyclic creep, and cyclic creep-fatigue interaction — strain range/energy partitioning models; (vi) model creep and fatigue damage using a common parameter at rates that are dependent on the current state of damage — the model unified damage; (vii) model creep and fatigue damage using separate damage parameters — the mechanism based model; and (viii) integrate creep damage into the fatigue equation — creep modified strain-life equations. The rigour of the approaches increases from (i) to (vii). The creep modified strain-life equation requires no evaluation of creep strain and facilitates design analysis and evaluation of acceleration factors; however, its rigour depends on the choice of the creep functions. The unified equation is capable of covering the full spectrum of creep-fatigue from pure fatigue to pure creep rupture.

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1. Introduction

An electronic/microelectronic assembly is typically made of two outer members that are interconnected by a middle layer of solder joints. As the electronic/microelectronic assembly experiences temperature cycling, the mismatched thermal expansion between the outer members is accommodated by the interconnecting solder joints, putting them under alternating strains of large magnitude. At the same time, the elevated temperature induces creep strain in the solder joints. The mechanics of damages due to the combined effects of creep and fatigue are generally referred to as creep fatigue. Besides alternating mismatched thermal expansion, creep fatigue could also be induced by mechanical cycling at elevated temperatures under isothermal conditions as experienced by turbine blades in the power and the aviation industries.

Our understanding of metal fatigue in general is attributable to the fifteen decades of investigative efforts of researchers in the power and transportation industries [48]. More recently, since 1950, the rapid development in power generation has fuelled investigative efforts in the creep fatigue of metals, notably those in the aviation, power, and nuclear power communities [43]. On the other hand, investigations into the creep-fatigue of solder joints by the electronic/microelectronic communities gain momentum only in the 1980s. The electronic/microelectronic communities have benefited from the experiences of the power and aviation communities. At the same time, creep fatigue modelling in the electronic/microelectronic communities has evolved into different practices from those of the power and the aviation communities. We shall investigate the rationales for the different practices. More importantly, we shall examine the robustness of the creep-fatigue models. The authors recognize the inevitable evolution of microstructures (and even metallurgy) with creep-fatigue, especially in solder joints, leading to the evolution of constitutive property and creep-fatigue resistance. However, review of metallurgy, microstructures and constitutive models are beyond the scope of this article. The evoluting creep-fatigue resistance is indirectly captured in creep-fatigue models as material constants. Explicit and detailed modelling of evoluting metallurgy/microstructures is not practised in the creep-fatigue modelling of engineering alloys and its review is beyond the scope of this article.

The fundamental theories of fatigue and creep are introduced in Section 2, serving as the foundations for the materials that follow. Section 3 is dedicated to reviewing the creep fatigue models that have, at different levels, prevailed in the power and aviation communities. In Section 4, the unique features in the creep fatigue of solder joints that have led to the unique practices in the electronic/microelectronic communities are discussed. The creep fatigue models for solder joints are critically reviewed and, whenever appropriate, parallels are drawn with those in other communities. Section 5 is dedicated to the review of the creep-modified fatigue equation, which is particularly attractive in that it does not require the direct evaluation of creep strain/energy.

2. The fundamental theories of fatigue and creep

2.1. The fundamental equations of pure fatigue

The fatigue life of a material experiencing pure fatigue may be expressed either in the form of stress-life ([8,62],

$$\sigma_{ref} = C_\sigma N^{-\beta_\sigma}, \tag{1}$$

or strain-life [11,33],

$$\varepsilon_{p,ref} = C_o N^{-\beta_o}, \tag{2}$$

or energy-life [37],

$$w_{p,ref} = C_w N^{-\beta_w}, \tag{3}$$

where $\sigma_{ref}(N)$ and $\varepsilon_{p,ref}(N)$ are the amplitudes of the von Mises' stress cycle and the work-conjugate equivalent plastic strain cycle, respectively; $w_{p,ref}(N)$ is the hysteretic plastic work density enclosed by the cyclic stress–strain locus; $\sigma_{ref}(N)$, $\varepsilon_{p,ref}(N)$, and $w_{p,ref}(N)$ are effectively fatigue capacities expressed as a function of fatigue life; C_σ, C_o, and C_w are the fatigue capacities for one cycle of fatigue life; and β_σ, β_o, and β_w reflect the rate of reduction of the fatigue capacity with increasing fatigue life. The subscript "*ref*" emphasises the condition of pure fatigue — in the absence of environmentally aggressive mechanisms [23,15] or elevated strain rate [63]. Dividing both sides of Eq. (1) by elastic modulus, *E*, and adding to Eq. (2) leads to the total strain-life fatigue equation [37].

Through expressing the cyclic stress–strain relation using the Ramberg–Osgood relationship [46]

$$\begin{aligned} \varepsilon_{ref} &= \varepsilon_{e,ref} + \varepsilon_{p,ref} \\ \varepsilon_{e,ref} &= \frac{\sigma_{ref}}{E} \\ \varepsilon_{p,ref} &= \left(\frac{\sigma_{ref}}{K'}\right)^{1/n'}, \end{aligned} \tag{4}$$

where n' is the cyclic strain hardening index and K' a fitting constant, and substituting Eq. (1) into the last equation of (4), the coefficients for strain-life and stress-life may be interrelated mathematically as [37,15]:

$$\begin{aligned} C_o &= \left(\frac{C_\sigma}{K'}\right)^{1/n'} \\ \beta_o &= \beta_\sigma / n'. \end{aligned} \tag{5}$$

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