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Fatigue life prediction of adhesive joint in heat sink using Monte Carlo method

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ABSTRACT

A finite element model of the heat sink along with a fatigue life prediction model can be used to investigate the thermal stress cyclic effect on thermo-mechanical reliability performance. However, the variability of the governing parameters makes the life prediction probabilistic. The Monte Carlo simulation is used to study the effect of random variation associated with the governing parameters on the predicted fatigue life of the heat sink. It has been found that the variability affects the predicted life significantly as almost half of the considered sample points have predicted life that differs from deterministic predicted values by some order of magnitudes.

1. Introduction

Heat sinks are used in modern electronic packaging system to enhance and sustain system thermal performance by dissipating heat away from IC components. Pin fins are commonly used in heat sink applications. The performance of a fin is well described by its efficiency which is defined as:

$$\eta = \frac{Q}{Q_{max}} \tag{1}$$

where Q is the actual heat loss by the fin and Q_{max} is the maximum possible heat loss through the fin (i.e. a fin without internal temperature gradient or infinite thermal conductivity so that the entire fin has the same temperature as prime surface).

High efficiency fins are desirable for effective heat dissipation. The rate of heat loss can be increased by using force convection e. g. by using a fan. However, for a given fin material and geometry, the maximum value of convective heat transfer coefficient is governed by a dimensionless parameter called Biot number. For a circular cross-section pin fin it is given by:

$$Bi = \frac{hr}{k} \tag{2}$$

where h is the convective heat transfer coefficient, k is the thermal conductivity and r is the fin radius. For metallic fin material, a fin has high efficiency ($>90\%$) values only in very low Biot number range $Bi \ll 1$. For a given fin material, this condition implies that low h values must be used to have high efficiency slender pin fins. This issue can be addressed by using a fin material with orthotropic thermal conductivity; i.e. a pin fin with different thermal conductivities k_r and k_z in radial and axial directions. The thermal conductivity of the polymer composite materials is significantly higher in fiber axis direction whereas the thermal conductivity in the orthogonal direction can be significantly lower. The thermal conductivities of some polymer composite are reported in Table 1.

The effect of orthotropic thermal conductivity on fin performance is presented in Fig. 1. The orthotropic property is defined by the thermal conductivity ratio $k^* = k_r/k_z$, and it is obvious that orthotropic fins have high efficiency in the range $0.5 < Bi < 1$ whereas an isotropic fin would be practically not useful in that range.

The difference in orthotropic thermal conductivity values must be taken into account while designing a complete heat sink system. It is obvious from Fig. 1 that the fiber alignment in the heat sink base must be such that it increases the thermal conductivity in the direction parallel to pin-fin axis. This aspect is important if the heat sink assembly is fabricated by separately manufactured base plate and pin fins. Alternatively, a metallic base plate can also be used with the orthotropic pin fins. Thus depending on the fin and base-plate materials and the manufacturing process; the fins may be manufactured as the integral part of the base-plate or they may be attached through some joining methods. Thermal conductive epoxy is commonly used in heat sink applications [3]. Thus, epoxy is a good choice to join the polymer composite pin fins with the aluminum base plate.

During the operation of an electronic device the heat sink element would undergo thermal cycling due to power on and power off conditions. Cyclic thermal stresses will be important at the pin-fin and base-plate interface due to coefficient of thermal

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Table 1
Polymer composite thermal conductivities [1].

Filler	*Matrix*	Parallel to fiber (W/m-K)	*Normal to fiber* (W/m-K)
Continuous Carbon fiber	Polymer	330	3–10
Discontinuous Carbon fiber	Polymer	10–100	3–10
Graphite	Epoxy	370	6.5

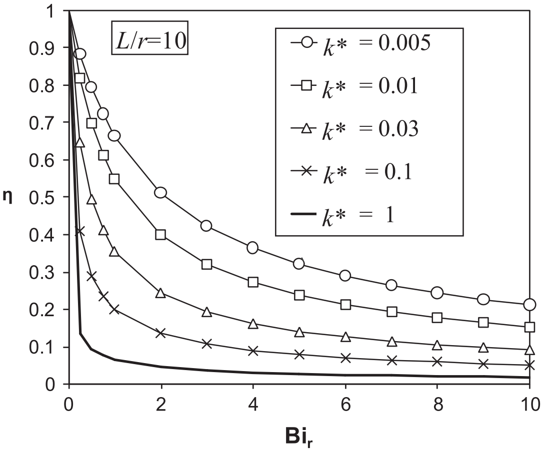

Fig. 1. Orthotropic pin fin efficiency as a function of radial Biot number Bi_r and thermal conductivity ratio for fin aspect (length to radius) ratio =10 [2].

expansion mismatch (CTE) of the mating materials. The cyclic nature of stresses can lead to fatigue failure that will affect the reliability of the heat sink and electronic packaging. Therefore, epoxies can have thermo-mechanical failures as the low-cycle fatigue is statistically prominent failure mode for epoxy [4]. The objective of the following section is to review available approaches for fatigue life estimation of an adhesive joint.

1.1. *Fatigue of adhesive joints*

The failure of an adhesive in a joint can be classified as adhesive failure and cohesive failure. The first mode is the debonding at the adhesive-joining surface interface, whereas the second one is a failure within adhesive thickness. The two types of failures are depicted in Fig. 2.

Under cyclic loading condition, a crack would initiate after a certain number of load cycles, and depending upon the specific application requirements, crack initiation can be considered as the fatigue life. Otherwise, the crack propagation up to a certain size or to complete failure can also be termed as the fatigue life. The fatigue life of an adhesively bonded joint can therefore be divided into two phases, the fatigue crack initiation (FCI) life and fatigue crack propagation (FCP) life. For non-cracked bonded joints, the FCI life covers the major part of the total life [5].

The approaches to estimate fatigue failure for metals is well developed and methods for the estimation of fatigue life prediction are available in the literature. The fatigue life methods attempt to predict the fatigue life as the number of load cycles before failure occurs under a specific level of loading. The life prediction methods are classified as stress-life method, strain-life method and linear-elastic fracture mechanics method [6]. The adhesive joints are very commonly used in composite structures therefore, the fatigue life approaches for adhesive joints in composite structures are categorized as stress-life method, fatigue crack propagation approach and the fatigue approach using finite element calculation method [7]. The first method can provide both FCI and FCP whereas the later two approaches are used for FCP life. This is due to the fact that the fatigue crack propagation approaches considers propagation of existing crack based on the strain energy released rate *G*. The finite element method has been used to study the fatigue crack growth in the adhesive joints due to its advantage that it can address the complexities due to joint configuration as well as material and geometric non-linearity, which cannot be easily handled through analytical approaches. For our case we will be interested in FCI life prediction, therefore only stress-life method will be considered for our study.

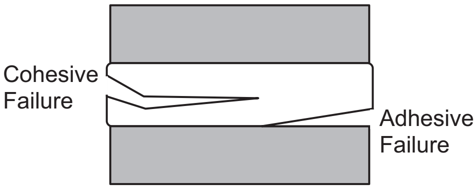

Fig. 2. Schematic of Adhesive and Cohesive fatigue fracture modes in an adhesive joint.

The stress-life method is the method of reporting experimental results fatigue life as number of cycles against different load levels relative to their quasi-static failure load. It is very common to conduct experiments for fatigue life estimation of a particular adhesive bond joint. The most common joint configurations are lap joints (single, double, overlap, stepped and scarf) and butt joints [7]. Based on the test result, an empirical correlation can be developed between number of cycles to failure for the considered joint geometry, type of applied cyclic load (mechanical, or thermal), and adhesive material. The basic question that arises is that whether or not a correlation obtained through a specific set of geometric, loading and material combinations can be used as a general life prediction model. For example, Gladkov et al. [4] developed some correlations for two packaging epoxy adhesives based on experiments with single lap joint specimen. The correlation is useful to predict the number of cycles to failure by knowing cyclic frequency, peak cyclic shear stress and adhesion strength at a specific temperature for a given specimen configuration. Therefore it can be applied to the specimens that conform to the specimen configuration (including materials and geometry) and loading conditions. The correlations are obtained for experiments with mechanical loading however their application for temperature cycling loading condition has been made by Tian et al. [8] for temperature cycling loading condition. Nevertheless, the application has been made after assessing the fact that the shear stress variation along the bond length for the temperature cycling is the same as it was for the mechanical loading condition. Therefore, the applicability of this approach is limited by the particular geometry of the tested joint.

The experimentally obtained fatigue life under temperature and power cycles have found to have different order of magnitudes. For example; Bjorneklett et al. [9] experimentally studied the reliability of three die bonding adhesives under thermal cycles which were analogous to power cycling described in Section 2.1 below. Extreme cycle temperatures of 10 and 150 °C, 10 min cycle time and a ramp of 2 min. The test specimen consisted of silicon chip attached to metallic substrates through a 30 μm thick adhesive layer. The measured parameter was the thermal resistance of the adhesive as a function of thermal cycles. The increase in thermal resistance implied to failure of the adhesive layer. Both adhesive and cohesive failures were observed in microscopic examination of post experiment specimen. Depending upon the substrate and adhesive materials the maximum number of cycles was in the range 800 to 2200 cycles. However, no discussion is made on how the accelerated test results can be used to predict the fatigue life under actual working conditions. Regarding