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# Behavior and failure of adhesive bonds in pin fin heat sinks using cohesive zone model

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ABSTRACT

Adhesive bonding is a versatile material joining method that tends to distribute the load over the bonded area and provide more flexibility in selecting the base material without worrying about the joining process and its effects. To improve the performance of heat sinks, polymer composite pin fin are used to improve the thermal conductivity. Adhesives are usually used in bonding composite fins to their metal base plate. In this work we provide a methodology for estimating the fatigue life of the adhesive joint. A thermo-mechanical cohesive zone model (CZM) is used at the interfaces to measure the softening of the bond under thermal cyclic loading which in turn decreases the critical stress for failure. A summary of the fatigue crack initiation (FCI) life prediction model is presented before a qualitative study is performed to estimate the effect of convection environment on the life and behavior of the adhesive bond.



## 1. Introduction

Adhesive bonding is a versatile method of assembling like or dissimilar materials. Whereas holes, rivets, clamps, and screws usually tend to cause stress concentration in some areas, adhesives tend to distribute the load over the entire bonded area in addition to their better fatigue properties. They also provide more flexibility in the selection of the base materials allowing for the selection of the best material for the application without having to worry about the joining process and its effect on the substrate properties. Plus reaming and drilling holes is often related to failure due to delamination. Certain criteria must be considered in the process of selection for a proper adhesive bond for a particular application. These criteria include, but not limited to, characteristics of the materials to be joined, surface preparation, type of adhesive and its handling and ultimate strength and environmental performance requirements of the adhesive bonded assembly. Adhesive bonded joints are becoming more popular and particularly more effective in assembling complex and large scale structures [1]. Their effectiveness is more noticeable in joining structures and composites from different materials as they offer an easy to use option in terms of applying them compared with other methods such as fasteners and bolts. When designed properly, adhesive joints are supposed to be the strong part of the structure and should not have any limitations from the components' life prospective. Adhesive bonds, like any other type of bonding, do face issues related to its failure which leads to the decohesion between the two substrates. The lack of complete understanding of the adhesive bond failure mechanisms has resulted in improper testing for the failure analysis as well as in the selection of the proper adhesive material depending on the substrates [2]. Fracture and delamination between two interfaces is crucial in limiting the toughness of the bond between two layers in a composite structure. One of the common techniques nowadays to model the softening and the fracture of adhesive bonded joints is the use of cohesive zone models (CZM). These models are capable of modeling the fracture using a traction–separation law that accounts for the softening of the adhesive bond between the two surfaces. These models can be applied using different traction–separation laws along with the finite element method (FEM) [3,4].

Heat sinks are used heavily in modern electronic packaging systems to sustain the thermal performance by dissipating the heat away from the component. Heat sinks, in which the material of the base and the fin are the same, do not require a joining process as they are usually manufactured as a whole. A lot of research has been done to improve the efficiency and thermal performance of heat sinks by improving the fin properties. One common way is the use of orthotropic pin fins instead of pure aluminum or copper. This tends to improve the heat transfer quality of the heat sinks but requires an adequate joining process between the orthotropic pin fin and the metal base plate.

### 1.1. Adhesive bonds and CZMs

Adhesive bonded joints are becoming used more widely than traditional methods like screws and fasteners. They are easy to use in addition to the fact they can be used with a wide variety of

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materials and to form composites. Due to their flexibility, different cohesive zone models (CZMs) were presented in the literature for different composites of materials. These CZMs are used to track the traction–separation behavior of the bonding between materials to measure the softening and failure of the bonds. Jiang et al. [5] studied the mechanical behavior of fiber-reinforced polymer decks to steel composite girder system used in bridge constructions. Li et al. [6] presented mixed-mode cohesive zone models to study the fracture of adhesively-bonded polymer–matrix composites. Other work presented in the literature also focused on the mode-mixity of CZMs. Continuum mixed-mode cohesive damage models were presented by De Moura et al. [7] for the simulation of the mechanical behavior of bonded joints. The cohesive zone properties were determined using the double cantilever beam and the end-notched flexure tests. A systematic procedure was developed by Lee et al. [8] to determine the cohesive parameters by introducing an optimization technique by defining the cohesive zone parameters as design variables that affects the response of a system. Chai [9] studied the Interfacial fracture of adhesive bonds undergoing large-scale yielding is studied using a combined experimental/finite-element approach. A wide range of bond thickness values was used in his study to cover the full range of in-plane mode-mixity. Choupani [10] also performed a broad range of experiments and analytical effort to improve the understanding of the mixed-mode cohesive fracture behavior of bonded joints. As a part of his experimental efforts, mixed-mode fracture tests were performed using modified Arcan specimens consisting of several combinations of adhesive, composite and metallic adherents with a special loading fixture, in which by varying the loading angle, from 0° to 90°, mode-I, mixed-mode and mode-II fracture data were obtained. Finite element analyses were also carried out on specimens with different adherents. The main objective of this study was to determine the fracture toughness in both modes for a range of substrates under mixed mode loading conditions.

A lot of effort have been done to obtain the cohesive zone parameters and to investigate their effect on the behavior of the bonded joint. Different aspects such as the critical fracture energies, adhesive thickness, thermal cycling, and the rest of the cohesive constitutive parameters were considered to study their effect on the strength of the adhesive bond between the two substrates [11–14]. The characterization of critical energy release rates of adhesive joints in laminated composite structures is an important issue when it comes to failure analyses. In that regard, Balzani et al. [15] determined a criterion which gives the critical energy release rate as a function of the mode mixing ratio. A multiscale cohesive approach that predicts the macroscopic properties of heterogeneous thin layers was presented by Matous [16]. The proposed multiscale model relies on the Hill's energy equivalence lemma, implemented in the computational homogenization scheme, to couple the micro- and macro scales and allows relating the homogenized cohesive law used to model the failure of the adhesive layer at the macro-scale to the complex damage evolution taking place at the micro-scale. Predicting the fatigue damage and fatigue life of adhesively bonded joints was also achieved by utilizing different cohesive zone models [17,18]. Xu and Wei [19] used the finite element method to systematically study the overall strength and interface failure mechanism of single lap joints, which are subjected to tensile loading, focusing on the effects of various system parameters including fracture energy of the adhesive layer, overlap length and adhesive layer thickness on the load-bearing capability of the joints.

### 1.2. Pin fin heat sinks

Heat sinks are needed when the heat transfer to the ambient air directly from the top of the package or via the system board is not sufficient to keep the semiconductor device within the allowable temperature range. The beauty of a heat sink is that, in most cases, it could be applied as an afterthought in cases where the chip temperature proved higher than expected. This led to the need for a great variety of form factors to allow the heat sinks to be put into spaces not originally designed to support them. The recent developments of electronics technology and demand for high performance components have prompted a significant interest in thermal management challenges. Various alternative thermal solutions are being considered such as advanced air-cooled heat sinks, high performance air movers, or liquid cooled heat exchangers. Extended surfaces or heat sinks are commonly used in both natural and forced convection electronics cooling applications. Dogruoz and Arik [20] indicated that new fabrication types, such as bonding, folding and swaging for the classical metal based materials, provided high aspect ratio heat sink manufacturing. A very interesting study was performed by Marotta et al. [21] on the development of a bonded fin graphite/epoxy heat sink for high performance computer servers. This study aimed at experimental measurements of the thermal conductivity of the graphite–epoxy composite as a function of temperature. The authors compared the performance of graphite composite heat sinks with aluminum and copper heat sinks for both direct impinging and cross flows. The graphite/epoxy and copper heat sinks demonstrated almost similar thermal performance with the former weighing only about 25% of the latter. In another study, Bhattacharya and Mahajan [22] presented the results of a study on the finned metal foam heat sinks in forced convection. Experiments were conducted on aluminum foams of 90% porosity and pore size corresponding to 5 and 20 pores per inch. For forced convection, the heat transfer was greatly enhanced at the expense of increased pressure drop. As much as six times the heat transfer rates obtained from a commercially available aluminum finned heat sink are achieved with the use of metal foams. However, the pressure drop being an important design parameter, therefore this enhancement is limited to a factor of 2 for all practical purpose.

### 1.3. Objective of the present work

This work is a continuation of the previous work [23] that covered the fatigue life of a heat sink composed of graphite/epoxy composite pin fins and aluminum base plate with an epoxy bonded joint at fin–base plate interface. The previous work studied the effect of variability of the main parameters on the fatigue life of the heat sink. In this work, we model the epoxy bonded joint interfaces using a CZM that can account for the softening of the bonding strength as well as add the effect of thermal cycling on the behavior of the heat sink which was neglected in the previous work.

## 2. Thermo-mechanical cohesive zone model

In this section we will develop the simulation capability to model the adhesive bonds using the cohesive zone model. In order to model the interface between any two adhesively bonded substrates, we consider the decohesion between the two surfaces as a gradual process in which degradation of the bond takes place across a cohesive zone, and is resisted by cohesive tractions. This approach in modeling fracture requires some constitutive parameters of the interface, such as the interface stiffness, peak cohesive tractions, and the fracture energy – as represented by the area under the cohesive traction–separation relation. Attractive features of this approach to model delamination fracture are that it is independent of: (a) the far-field geometry of the component containing the interface; (b) the specific constitutive response of