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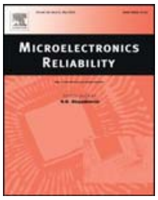

Solder joint fatigue life prediction using peridynamic approach

Forrest Baber, Ibrahim Guven *

Department of Mechanical and Nuclear Engineering, School of Engineering, Virginia Commonwealth University, 401 West Main Street, Richmond, VA 23284-3067, United States

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ABSTRACT

Solder joint fatigue life prediction using peridynamic approach is presented for the first time. The underlying premise is that material degradation through energy dissipative mechanisms play a central role in crack initiation and propagation, and that fatigue cracks follow paths similar to cracks form under quasi-static loading. The new method uses peridynamic approach in simulating crack initiation as well as propagation. Dissipated energy in the vicinity of newly generated fracture surfaces are calculated as the cracks propagate. Once failure starts taking place, load rebalance leads to further propagation. The method is first demonstrated using controlled experimental measurements of compact tension test specimens that were subjected to mechanical loading only. The fatigue life predicted by simulations of compact tension test specimens is within 12% of the measurements. The methodology is then applied to solder joint fatigue problems. The nonlinear thermo-mechanical problem is first solved by finite element analysis for four thermal cycles. The most severe deformation configuration during the fourth thermal cycle at the most critical solder joint is identified and applied as the static loading in the peridynamic simulation. Number of cycles to crack initiation and propagation on five distinct packages are predicted. The combined finite element and peridynamic approach yielded predictions within 25% of the experimentally measured fatigue life values for four packages. In the fifth package, a close match is not achieved. Overall, the results point to the conclusion that the peridynamic approach has great potential to accurately predict solder joint fatigue life.

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1. Introduction

Prediction of service life of electronic packages that fail due to solder joint fatigue fracture remains to be a daunting task. The problem involves combined thermal and mechanical loading on packages made up of multiple dissimilar materials, highly nonlinear solder material behavior in the form of creep and visco-plasticity, micro-structure evolution in solder material over the life of package. There are several different compositions used as soldering material, each with their own thermo-mechanical properties. Further, electronic packages and thus solder joints themselves come in different sizes and shapes, which in turn make great influence on the deformation field outcome. In an electronic package there may be tens or hundreds or in some cases more than a thousand solder joints; it takes a single solder joint failure to render the electronic package and subsequently the device useless. Therefore, value of accurate predictive computational methods that tangibly aid in search of better package designs cannot be overstated.

Solder joints serve as electrical connections between the package and the device's board (substrate and/or motherboard); these connections may carry input/output or power. Additional essential function of the solder joints is to provide mechanical support and connection mechanism between the package and the board. Very few, if any, solder joints are electrically “dummy,” serving mechanically only. Thus, interruption of connection between the package and the board through failure of a solder joint causes the device to not function properly, or stop functioning entirely. The solder joint failure involves one or more cracks near the package side or the board side of the joint to initiate and propagate. The driving mechanism for the failure is the thermo-mechanical deformation field. When an electronic package is in use, due to its electronic function, its temperature rises first at the chip (die). Heat transfer through conduction causes package's remaining constituent materials to experience elevated temperatures. A wide range of coefficient of thermal expansion (CTE) values exists for materials used in an electronic package. While exceptions may be present, typically the chip (e.g. Si) and ceramic constituent materials exhibit lower CTEs, the metal materials (e.g. Cu) have higher CTEs, and finally the polymeric materials possess the highest values. It is not uncommon to observe a range of CTEs varying from 2.6 ppm/°C to 40–60 ppm/°C in a package. These CTE mismatches lead to thermal stresses along material interfaces and cause the package to deform, which is transferred to the solder joints that connect the package to the board.

The thermo-mechanical deformation happens in a cyclic fashion; every time the package performs its intended function, the temperature rises, and when the performance subsides/ends the temperature drops. Repeated deformation leads to crack initiation at high stress regions

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* Corresponding author.
E-mail addresses: baberf@vcu.edu (F. Baber), iguven@vcu.edu (I. Guven).

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such as solder joint interfaces near the package or the board. Once a crack initiates, with every thermal cycle it is considered to be propagating. Introduction of a crack into the geometry changes the stress field with elevated stresses around the crack front, which is not necessarily a straight line. In fact, the crack faces are not necessarily flat surfaces. As the crack front advances with every cycle, the intact region becomes smaller, thus the overall stress level increases, which may then influence the next crack advance. It is also possible that the elevated overall stresses initiate a secondary crack across from the first (primary) crack. Once the intact area reaches a critically low value, the crack experiences fast growth (or coalescence with the secondary crack) leading to "catastrophic" failure. The crack growth rate is affected by the changing stress field and also evolving microstructure of the solder material due to the cyclic loading involving elevated temperatures. It should be pointed out that the solder materials used in electronic packages are eutectic and typically have melting temperatures ranging from 180 °C to 220 °C. During normal operation, temperature near solder joints may reach 80 °C to 100 °C, which represents a considerable fraction of the melting temperature, providing conditions suitable for rapid microstructure evolution.

As explained briefly in the above paragraphs, the underlying mechanisms of fatigue failure of solder joints are extremely complex. Reliably accurate solder joint life prediction methodology may serve as a powerful tool aiding the design process in the industry. Reference [1] provides a complete and thorough review of the existing methods for solder joint fatigue life prediction up to 2000. The methods discussed in [1] largely rely on empirical material parameters related to damage and fracture that are found through fitting against experimental measurements. Some of the sophisticated approaches utilize computational approaches, mostly finite element analysis (FEA). The aforementioned material parameters may be strain-based [2,3] or energy-based [4]. The methods that make use of FEA generally produce acceptable results for the prediction of cycles to crack initiation as the local geometry is not changing due to fracture. However, once a crack initiates, the stress field changes with evolving crack geometry and thus the validity of the model with no crack present in the geometry becomes questionable. The aforementioned methods do not take into account the possibility of two cracks concurrently propagating towards each other at variable propagation rates. However, it was clearly demonstrated in [5] that solder joint cracks propagate at a variable rate, and it is common to find two concurrent cracks in the solder joints propagating towards each other. Not accounting for the variability in crack propagation rate during its entire run may lead to inaccurate predictions of solder joint fatigue life.

More recent research has focused on modeling the microstructure of solder. In 2005 Abdul-Baqi et al. [6] simulated damage in a solder joint subjected to mechanical loading. A two-dimensional finite element model was created with idealized lead and tin phase regions. Cohesive elements were placed along the boundaries of these regions and a damage parameter was used to incorporate the degradation of material properties with increased number of cycles. The cohesive interfaces exhibited separation fairly uniformly over the two-dimensional mesh in contrast to the experimentally observed failure near one of the interfaces. Erinc et al. [7] also used a cohesive zone approach to investigate interfacial damage in lead-free packages undergoing mechanical loading in which a two-dimensional model with an effective damage parameter indicated crack propagation without explicitly capturing the propagating nature of fatigue cracks In 2006 Syed [8] studied the removal of modeling assumptions that are commonly used but no longer necessary due to increased computational power in recent years. Recently, Ladani et al. [9] used a submodeling approach to conduct a parametric study on the effect of void size, location, and quantity on the thermomechanical durability of a CTBGA132 assembly. Both Syed [8] and Ladani et al. [9] are similar to the conventional FEA prediction of solder joint fatigue life in which fatigue cracks are not explicitly represented.

Current study presents a new approach for fatigue life prediction that takes into account variable crack growth rate as well as possibility of non-planar crack faces. The premise of the approach rests on two assumptions:

1. Dissipated energy is directly related to the material degradation leading to crack initiation and propagation, and
2. Fatigue cracks propagate in quasi-static mode [10,11].

The new method uses peridynamic approach [12–14] in simulating crack initiation as well as propagation, which provides the means of keeping track of dissipated energy in the vicinity of newly generated fracture surfaces. Although peridynamics has been used for fatigue crack propagation modeling by Silling and Askari [15] and Oterkus et al. [16], neither study addressed fatigue life prediction in electronic packages due to thermal cycling. In the current work, relationships between the peridynamic calculated dissipated energy and experimentally measured crack propagation rates for each material are established. In order to represent the fatigue loading convenient for the peridynamic approach, the most severe deformation state during a loading cycle is identified and applied as the static loading to the peridynamic model. Assuming that fatigue cracks follow paths similar to cracks that form under quasi-static loading, critical stretch of the material under consideration is gradually reduced to allow for the most deformed regions to fail first. Gradual reduction of the critical stretch ensures that the fracture is not dynamic in nature.

The new method is first demonstrated by considering controlled experimental measurements of compact tension (CT) test specimens that were subjected to cyclic mechanical loading [17,18]. The previously mentioned relationship between the experimental measurements and the peridynamic calculated dissipated energy is constructed for one set of CT test and applied to the other test blindly. The fatigue life predicted by simulations of the blind test is within 12% of the experimental measurements. The new method is then applied for prediction of solder joint fatigue life in packages with leaded and lead-free solder joints. In all the electronic packaging problems considered, the nonlinear thermo-mechanical problem is first solved by finite element analysis for four thermal cycles. The most severe deformation configuration during the fourth thermal cycle at the most critical solder joint is identified; the deformation field at this configuration is subsequently applied as static loading in the peridynamic simulation. Similar to the CT cases, for each solder material type, one experiment is chosen to extract the empirical constants that are then used in the remaining simulations for life prediction. Number of cycles to crack initiation and propagation on five distinct packages are predicted. The combined finite element and peridynamic approach yielded predictions within 25% of the experimentally measured fatigue life values for four packages. In the fifth package, a close match is not achieved. Overall, the results point to the conclusion that the peridynamic approach has great potential to accurately predict solder joint fatigue life.

2. Problem description

The current methodology is first tested by simulating compact tension (CT) tests. The experiments involve only mechanical loading performed on simple geometry of the CT test, leading to a highly controlled environment that produces repeatable and largely 2D fracture behavior. Once demonstrated within this controlled environment the same methodology is applied to the highly nonlinear 3D electronic package problem under thermal cyclic loading conditions.

2.1. Compact tension test specimens

The CT test specimen dimensions are 40 mm × 40 mm × 8 mm as shown in Fig. 1. The specimen is of SAE 1020 steel with an elastic modulus of 205 GPa and a yield strength of 285 MPa. It is loaded at the pins

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