Pad Cratering Based Failure Criterion for the Life Prediction of Board Level Cyclic Bending Test

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***Abstract*-The root causes of pad cratering may be divided into two categories, namely, overloading induced pad cratering and fatigue induced pad cratering. The former occurs when the interfacial stresses between the epoxy resin and the pad exceed the failure criterion based on the monotonic loading test. The latter happens under cyclic loading conditions, typically with interfacial stresses much lower than the former. Therefore, it is desirable to define an effective failure criterion for the life assessment of pad cratering based on fatigue induced pad cratering. In this research, a fatigue failure criterion for pad cratering is proposed with a correlation between the board level cyclic bending test and repetitive drop test. Time scaling is applied to bridge the cyclic bending test and repetitive drop test, and finite element analysis (FEA) is conducted for pad cratering loading matching to seek the equivalent bending strain of various G-level drop impacts. With the experimental study of cyclic bending tests and pad cratering failure detection, the strain-number of cycle (S-N) curve is able to be defined. This S-N curve can also be verified by repetitive board level drop tests, and it means this curve is able to be defined as a common failure criterion for fatigue induced pad cratering. Thus, a universal life prediction method for fatigue induced pad cratering is built. This method can be applied in the design for reliability (DfR). In addition, the repetitive drop test can be replaced by the cyclic bending test under the equivalent loading condition for pad cratering evaluation. It not only provides the faster and simpler characterization of pad cratering fatigue behavior, but also makes the failure able to be real-time monitored.**

Keywords-pad cratering; fatigue; failure criterion; time scaling; S-N curve; cyclic bending test; repetitive drop test

I. Introduction

The definition of pad cratering is the fracture phenomenon in which a contact pad on a PCB is torn out, leaving a ‘crater’ in the underlying epoxy resin [1]. In a printed circuit board (PCB) with a non-solder mask defined (NSMD) pad opening configuration assembled with a ball grid array (BGA) device, pad cratering is a predominantly observed failure mode with relatively high loading rate [2]-[6]. Figure 1 shows the initiation and propagation of pad cratering on the edge solder joint of a BGA-PCB assembly and a scanning electron microscope (SEM) cross-section view of pad cratering. Due to the internal or external bending moment (caused by bending, drop, or thermal shock) on the PCB, the crack is initiated at the edge between the copper pad and underlying epoxy resin part of the PCB and propagates across the whole area of the solder joint [3], [7].

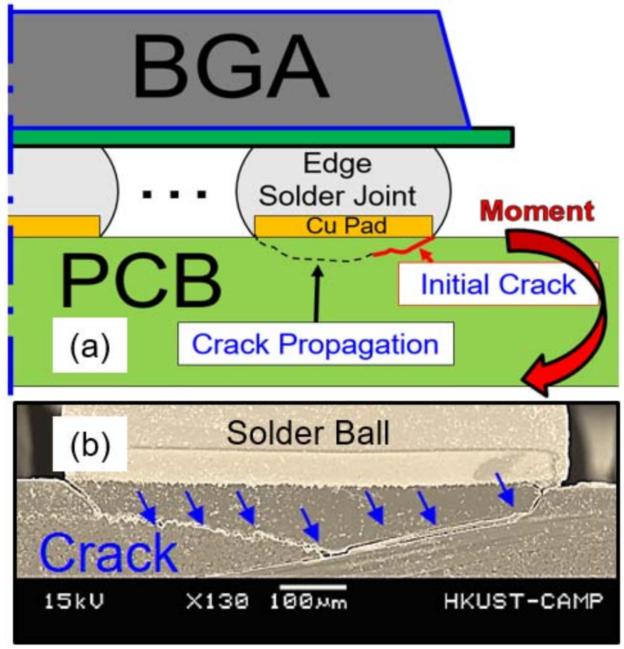

Figure 1. Pad cratering on a BGA-PCB assembly: (a) schematic demonstration; (b) SEM cross-section view.

Pad crater is a typical brittle failure mode, which means the pad is pulled off without any sign of distress, and it cannot be repaired by a conventional rework operation [8]. In consequence, this failure becomes highly pernicious, and it is always desirable to estimate the pad cratering failure in the design phase of product.

Pad cratering also follows the fracture properties of epoxy resin. It is well known that epoxy based polymer material can be subject to fractures other than those caused when the loading exceeds the strength [9]. The fatigue is also another more important consideration of pad cratering failure [10]-[12]. This research proposes a fatigue failure criterion for pad cratering which is suitable for conventional board level loading conditions, including cyclic bending and repetitive drop tests. With a correlation between the board level cyclic bending test and repetitive drop test, a time scaling scheme is defined to convert the equivalent pad cratering loading of a drop test to a bending test. Based on the experimental study and FEA of a cyclic bending test, the S-N curve of fatigue induced pad cratering is defined. The corresponding repetitive drop test is also conducted to verify the validity of this S-N

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curve. Then, this S-N curve is able to be used for life prediction of fatigue induced pad cratering. Additionally, due to both the cyclic bending test and repetitive drop test sharing the same failure criteria for pad cratering, it is possible to use the cyclic bending test to predict the life of a repetitive drop test, which makes the testing simpler and less time consuming.

II. The Time Scaling Scheme for Bridging Repetitive Drop Test and Cyclic Bending Tests

A. Time Scaling Principle for PCB Fatigue Behavior

To define common fatigue failure criteria of pad cratering in both repetitive drop and cyclic bending tests, the most challenging issue is to evaluate the fatigue behavior difference of epoxy resin under different loading rates. In a repetitive drop test, the during time of the drop pulse is in the millisecond level. Compared with the cyclic bending test (1Hz frequency), the loading frequency rises about 1000 times. For most non-crystal polymer material, the simplified derivation of Willams-Landel-Ferry (WLF) equation describes that the fatigue behavior at different loading frequency is equivalent to the fatigue behavior at the same loading frequency with different temperature [13], [14]:

$$ln\frac{\omega'}{\omega} = B'(T' - T) \quad (1)$$

where B' is the kinetics properties shifting factor (material constant), ω' and ω are the equivalent loading frequency at temperature T' and T. For the typical epoxy resin based PCB, the value of B' is 0.46/℃ (from the Perkin Elmer material database). When ω'/ω is $1\text{Hz}/1000\text{Hz}$ (1000 times loading frequency difference approximation between the repetitive drop and cyclic bending test), the $T' - T$ is -20℃. This value indicates that the fatigue behavior with 1000 Hz frequency is equal to the fatigue behavior with 1Hz frequency at -20℃ relative temperature difference.

Figure 2 shows the dynamic mechanical analyzer (DMA) result of the PCB material. This graph reveals the dynamic mechanical spectra (including fatigue behavior) of this PCB remains steady below glass-transition temperature (~170℃) [15]. It means that the influence from 20℃ temperature difference is insignificant for the fatigue properties of PCBs. In consequence, the hypothesis, which can be obtained, is that the 1000 times loading frequency difference is negligible for the fatigue test of PCBs in the temperature range below the glass-transition temperature.

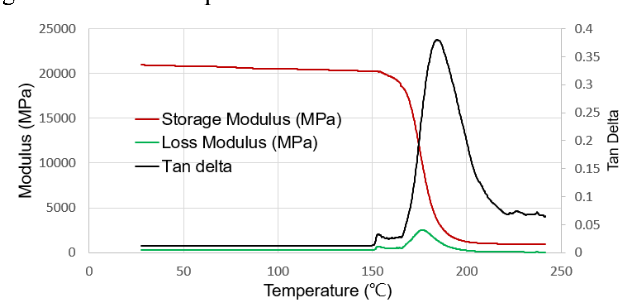

Figure 2. DMA graph for PCB

B. Building of the FEA model

The ultimate purpose for this research is to define a universal fatigue failure criterion of pad cratering for various board level loading conditions. The preceding research indicates that the dominant loading mode of common board level tests is the bending moment [16]. Then the loading rate becomes the major difference in the various board level tests. To define a common failure criterion for fatigue induced pad cratering at different loading rates, it is necessary to analyze the loading rate related properties of the solder joint. Figure 3 shows the conventional simplified 1-D expression of one solder joint series stiffness system. The external loading in the driving block can be expressed in force (Γ_{DB}) or in displacement (u_{DB}) with a loading rate $\dot{u}_{DB}$. Due to the strain rate insensitivity of epoxy resin, the pad cratering elastic modulus can be defined as a loading rate independent parameter E_{PC} [17]. In the Sn-Cu alloy part of solder joint, the visco-plasticity behavior can be expressed by the simplified dash pot (ν) and plastic-frictional resistance (σ_y) model. From this 1D simplified expression, the loading rate effect comes from the solder alloy. Due to the visco-plasticity of solder, the higher loading rate transfers more loading on the underlying epoxy. This phenomenon is the so called 'strain rate effect' for pad cratering. For accurate description of the 'strain rate effect', both the Anand model and Johnson-Cook model are used to simulate the visco-plastic behavior of SAC 305 solder in the bending model and the drop model respectively.

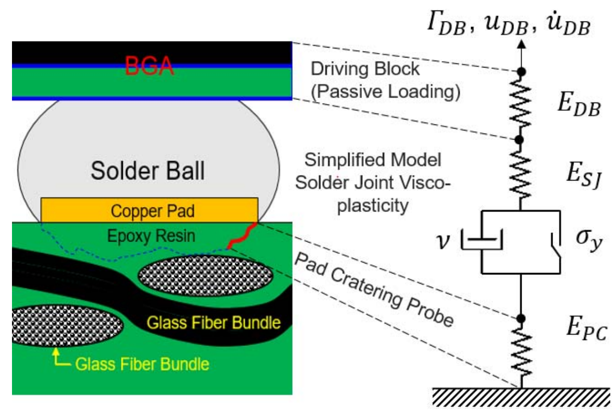

Figure 3. Simplified 1-D expression of solder joint series stiffness system

TABLE I. THE MATERIAL PROPERTIES OF FEA MODELS

<table>
<tr><th>Material</th><th colspan="3">Young's Modulus (GPa)</th><th colspan="3">Poisson's Ratio</th></tr>
<tr><td>EMC</td><td colspan="3">22</td><td colspan="3">0.3</td></tr>
<tr><td rowspan="2">BT Substrate</td><td colspan="3" rowspan="2">23</td><td>y-z</td><td>x-z</td><td>x-y</td></tr>
<tr><td>0.39</td><td>0.11</td><td>0.39</td></tr>
<tr><td>Ceramic</td><td colspan="3">370</td><td colspan="3">0.22</td></tr>
<tr><td>Copper Pad</td><td colspan="3">127 + bi-linear plasticity</td><td colspan="3">0.33</td></tr>
<tr><td>SAC 305 Solder</td><td colspan="3">30 + Anand (bending) or Johnson-Cook (drop) Plasticity Model</td><td colspan="3">0.33</td></tr>
<tr><td rowspan="2">PCB (Epoxy Resin + Glass Fiber Bundle)</td><td>x</td><td>y</td><td>z</td><td>y-z</td><td>x-z</td><td>x-y</td></tr>
<tr><td>22</td><td>8.8</td><td>22</td><td>0.38</td><td>0.38</td><td>0.38</td></tr>
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