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Ball-grid-array solder joint model for assembly-level impact reliability prediction

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ABSTRACT

It has been well established that lead-free solder underperforms conventional leaded solder in reliability under dynamic impact. Common failures observed on ball-grid-array (BGA) solder balls on chip under board level impact include bulk solder ductile failure, intermetallic (IMC) layer crack and pad-lift. In this work, a finite element modeling approach was proposed to model bulk solder ductile failure and intermetallic layer crack. The use of beam elements and connector elements to represent the bulk solders and board/component side intermetallic layers, respectively, offers the advantage of simplicity over the use of continuum elements and cohesive elements for solder joints. This approach enables the modeling of assembly level impact with significantly less computational resources. The model was verified by comparing its prediction of BGA solder reliability against actual test results in a dynamic four-point bend test. The physical tests consist of ball impact at varying heights on a board with a mounted chip, and the subsequent analysis of the failure modes of the BGA solder joints. Simulation results were in good agreement with test results. The study shows that it is feasible to model BGA solder joint ductile failure and intermetallic layer crack under impact with simple elements with reasonable accuracy.

1. Introduction

Portable device miniaturization and green-product requirement have led to the use of lead-free ball-grid-array (BGA) to connect chip package and printed circuit board (PCB). However, lead-free BGA is susceptible to drop impact failures [1]. Conventional solder bump shear and pull tests, usually performed at high ($>300\ s^{-1}$) or low speed levels ($<0.1\ s^{-1}$), fail to replicate BGA brittle interface failures at medium strain rate during dynamic impact [2]. In addition, it was found that BGA joint reliability correlated well with the percentage occurrence of interface bond failures and not solder interface fracture strength [3].

To characterize the BGA impact reliability, a number of experimental approaches had been proposed. Among them are JEDEC shock tower test [4], dynamic four-point bend test [5], dynamic spherical bend test [6], steel-rod-drop impact test [7], and Miniature Charpy Test [8]. These tests and other high-speed ball pull/shear tests are effective in unearthing common failures observed on ball-grid-array (BGA) solder balls under chip, including bulk solder ductile failure, intermetallic (IMC) layer crack and pad-lifts [9]. However, the availability of a model to reliably and accurately predict such failures will greatly save cost and time.

There have been some successes in modeling BGA failures using the finite element method. Caroll et al. [10] proposed the use of connector elements to model individual solder joints in a BGA, and correlated their model with experimental findings. Their model, however, did not distinguish bulk solder failure and IMC layer crack. Lall et al. [11] proposed the use of smeared property to model the solder interface, and compared it against another model using Timoshenko beam for individual solder. Their focus was to verify the use of sub-modeling approach for assembly level impact. Progressive damage of the joints was not modeled, which could limit the model prediction related to the solder joint progressive failures. In another effort, the use of cohesive elements for the solder interface was proposed [12], coupled with the sub-modeling approach [13]. However, it was not clear how the effect of sub-model changes, such as solder joint progressive failures, on the global model was accounted. Yeh and Lai [14], and Kim et al. [15] modeled one individual solder ball with many continuum elements, whose approach require significantly more computational resources than practically available for assembly level modeling.

The primary challenge in finite element modeling of BGA failures for assembly level impact lies in the selection of elements for their available failure models and practicality, namely the accuracy and ease of modeling with reasonable amount of resources. The selection of failure models, in turn, depends on the availability of test data. While bulk solder material property can be obtained with standard and non-standard test methods, the efforts to quantify the tensile and shear strengths of IMC are relatively more involved. Past researchers had derived IMC failure data from characterization tests such as solder ball high-speed shear [15,16] and pull test [3,9,16], and compression test with micro-force tester [17] to isolate tensile and shear contribution to individual solder

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intermetallic bond failures. As a result of past efforts, there is now evidence that with increased strain rate, the failure mode of lead-free BGA shifts from ductile bulk failure and to brittle IMC interface failure [3,8,16]. In addition, the tensile/shear stress and strain at IMC interface failure is dependent on the strain rate, solder alloy, solder geometry, mask design, pad finishes and thermal history [18–20].

In this work, a dynamic four point-bend-test was conducted on a BGA package mounted on a test board. The dynamic four point-bend-test was chosen primarily due to its simplicity and cost effectiveness [21], and had been used by other researchers in similar efforts [6]. BGA failures were then analyzed and categorized into bulk solder failure, IMC failures and pad lift at board side and component side, respectively. A numerical model for use in assembly level was proposed to simulate BGA bulk solder and IMC failures to predict the BGA mechanical reliability under dynamic impact. The prediction agrees quite well with the experimental findings.

2. Experiment

Fig. 1 illustrates the four-point dynamic impact test setup of the experiment. A steel ball of 136 g is dropped from varying heights as listed in Table 1. Each drop height was tested five times, each time on a fresh board with mounted chip. The corresponding initial velocity can be determined using the principle of conservation of energy. The ball impact upon the relatively stiff top span of 90 g (weight inclusive of bumper and rollers) then translates to deflection of the test board. The printed circuit board (PCB) dimensions are 75.0 × 40.0 × 1.08 mm. The BGA package is mounted at the bottom of the board, with its diagonals aligned with the sides of the board, such as shown in Fig. 2. A quarter of the PCB, such as shown in the dashed box, is use for modeling purposes.

Table 2 gives important BGA solder ball properties, while Fig. 3 is a schematic of a solder ball and its surrounding geometry. Upon completion of the impact test, BGA failures were then analyzed using the red dye test [22,23] with the following procedure. Flux from the board and package was first removed by soaking the board with BGA package in flux removal solvent such as Ensolve for at least 1 h, with the help of ultrasonic agitation. After cleaning, the board was rinsed in water to remove the residual cleaner, and the board dried using compressed air. Red dye (i.e. Dykem Red Layout Fluid) was applied sufficiently underneath the package using a pipette, upon which the board was placed under vacuum (~25 in. of Hg) for about 30 s to facilitate dye flow through solder joints. The board was then left in an oven at 100 °C for at least 30 min to dry the dye. Package was then removed by prying, and the dye-penetrated sites were failure sites ready for visual inspection using a stereo microscope. A joint with >80% of dye penetration was considered to have failed. Observed failures were then categorized into bulk solder failure, IMC failures and pad lift at board side and component side, respectively, such as illustrated in Fig. 4.

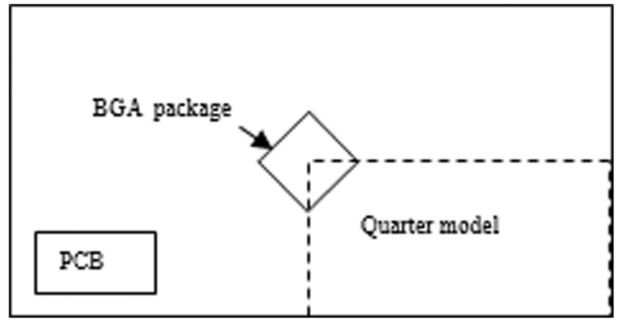

Fig. 2. Bottom view showing the placement of the BGA package on PCB.

Table 2
Solder ball properties.

Solder composition	95.5Sn/3.8Ag/0.7Cu (SAC387)
Solder ball diameter	Nominal 0.40 mm
Pad type	Solder Mask Defined (SMD)
Pad pitch	0.65 mm
Pad finish	OSP
Pad diameter	0.381 mm
Pad thickness	0.135 mm

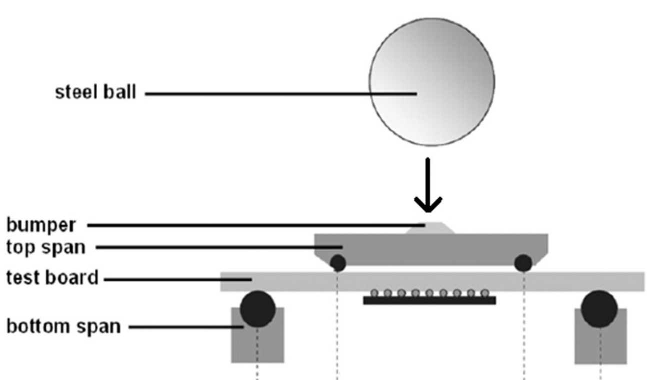

Fig. 1. Four-point dynamic impact test setup.

Table 1
Ball drop height and initial velocity.

Ball drop height (mm)	Velocity before impact (mm/ms)
166	1.805
254	2.232
361	2.661
488	3.094
636	3.532

3. Simulation

ABAQUS commercial finite element software was used to model the four-point dynamic impact test to simulate bulk solder ductile failure and IMC layer crack failure. Due to the symmetry of the board, the

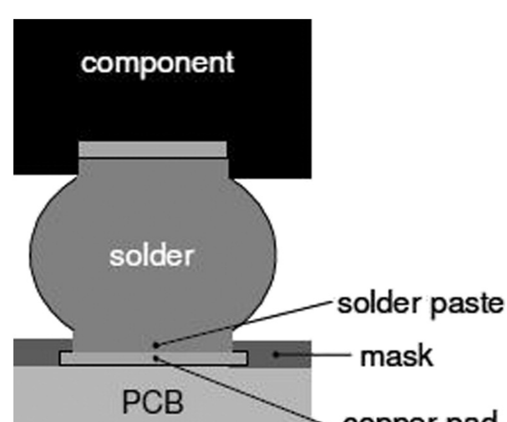

Fig. 3. Solder ball and its surrounding geometry.

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