Drop test analysis of ball grid array package using finite element method

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Abstract. Proper design of semiconductors is the most essential step in ensuring electronic product reliability during manufacturing. The adoption of design optimization approach enhances the performance and reliability of the semiconductor package, hence, minimizes product failure. Semiconductor reliability especially in the application to automobiles is very crucial. High product failure tolerance in semiconductors in automobiles is required due to problems such as defects and malfunctions that are directly linked to casualty accidents. Such high tolerance requires keen quality control up to the semiconductor solder component level. This study aims to do a sensitivity analysis of the solder balls’ material properties and its effect on the stresses experienced by the semiconductor component with respect to its reliability using drop test. A drop test analysis was simulated wherein a shorter distance of 5 mm between the package and platform was implemented to make the simulation time faster. The density and modulus of elasticity of the solder ball material were identified as the independent factors while the stresses experienced by the BGA package during the drop test is the dependent variable. The results have shown that the maximum stress for all runs was found in the same area in the package. Changing the modulus of elasticity showed greater effect on the impact stress compared to the alteration of material density.

1. Introduction
Failure test analysis is a crucial step in the manufacturing of semiconductor packages to test its reliability. Crack propagation analysis, warpage analysis, and drop test are some of the examples of quality control measures to ensure product quality. This test analysis normally requires actual products from the manufacturing department that will be subjected to experimental analysis. Hence, it is expected to consume resources and time that can affect the manufacturing of products. Simulations of failure tests analysis can be introduced to the system to significantly reduce the enormous amount of physical testing while offering time efficiency to the manufacturing sector [1].

Semiconductor design is one of the considered critical measures for ensuring the reliability and lifespan of semiconductor packages [2]. Common cause of failure is generated by shared causes according to Sakurahara et al [3]. These causes had been quantified and modeled based on the study of Mi et al [2]. In association with the different system analysis for reliability, importance of component analysis is beneficial for system design, system control, and improvement of reliability [4]. This
highlights the importance of design optimization on the research and development portion of the product reliability test. According to Dunn et al. [5], the design optimization will aid the analysis by the identification of a system design that will produce a result for which the error is minimized when measuring a set of samples. This typically looks for objective functions that have the partial derivatives desired to be zero at value.

Semiconductors are considered to be one of the key components of an automobile. It plays an important role in modern automotive specifically on its electronic control units [6]. These controls provide stability of operations to the consumer, and fuel efficiency. These control units are typically used in automobile and space equipment applications [7]. These controls may be subject to free fall due to automobiles moving when in operation. In such cases, the mechanical and electrical functionality of these controls can be unreliable. Drop test analysis is a test that identifies the mechanical reliability of electronic components in drop. Using finite element analysis on simulation models will significantly reduce the control unit’s reliability risk in the design optimization stage. Automotive semiconductors often require higher levels of requirements on humidity, temperature, and most importantly, in tolerance rate when it comes to tolerance failure compared to general semiconductors [8]. The high tolerance is required due to problems such as defects and malfunctions that are directly linked to casualty accidents. Safety and reliability are essential requirements on the specification of automotive semiconductors. According to Chae and Kim [6], reliability refers to the magnitude where the product operates with no failure accounted for at a specific period while safety is the degree of minimizing the effect of product failures to consumers. Such high tolerance requires keen quality control up to the semiconductor solder component level. Ball Grid Array (BGA) is a popular technology used on semiconductor applications due to its dense interconnectivity and high lead count [9]. Its’ characteristic of self-centering has given its advantage on semiconductor applications. These are easy to install because it has no leads, but it still suffices the high thermoelectrical requirements of a semiconductor. BGA packages have high transistor counts but it has small footprint however, the technology is known to manifest cracking of solder joints between interconnections due to hard drops [10].

There are studies available on the drop test method to analyze the impacted state and expected vibration in automobiles. This particular test was run by Shirangi et al. [11] on Electronic Control Units (ECU) or known as the computer boxes of the automobiles. The experimentation set up and procedure can accommodate varying weight of the semiconductors while monitoring the speed of the test subject with the use of an on-board sensor. The actual results were the basis of the simulation model using ANSYS for validation.

A study made by Balakrishnan et al. [7] comparing the effectiveness of finite element analysis from drop test. The study had concluded the finite element analysis is suitable for capturing the dynamic behavior of the drop test analysis. Material properties of solder balls are to be varied due to the limited number of material compatible for semiconductor solders. To date, there are no direct relevant studies for the stress analysis with respect to drop tests.

In line with this, the study aims to perform a sensitivity analysis of the solder balls’ material properties and its effect on the stresses experienced by the semiconductor package with respect to its reliability on drop test.

2. Materials and Methods
A BGA assembly was employed for this analysis, the specifications are derived from the Intel databook on BGA packaging [12]. The BGA assembly consists of several components such as the die chip that is the heart of the semiconductor device, molding compound that protects the package, substrate, solder balls, and PCB that provides connectivity. An illustration of a BGA package together with its major components can be seen in Figure 1.
The symmetric nature of the BGA allowed further simplifications to the model such as incorporating a quarter model for the simulation in order to reduce the total number of nodes and elements needed in the analysis [13][14]. The model utilizes a die thickness of 0.27 mm and 1.16-mm-thick EMC. The ball grid array package that is used for solder ball attachment has the dimension of 40 x 40 x 1.7 mm. A symmetrical boundary constraint was applied in the model. It is noteworthy that the expanded center of the geometry model was fixed with dz = 0 to hinder the rigid body motion while the boundary of dx = dy = 0 was set due to the symmetry planes.

In this study, the following material properties of the BGA package derived from various literature [9][10] were applied and is summarized in Table 1.

| Component     | Modulus of Elasticity, $E$ (MPa) | Poisson’s ratio, $\nu$ | Density, $\rho$ (kg·m$^{-3}$) |
|---------------|----------------------------------|------------------------|--------------------------------|
| EMC           | 17000                            | 0.25                   | 1900                           |
| Die Chip      | 170000                           | 0.28                   | 2300                           |
| Substrate     | 11600                            | 0.42                   | 3950                           |
| PCB           | 17200                            | 0.42                   | 1850                           |
| Structural Steel | 200000                        | 0.30                   | 7850                           |

2.1. Meshing
The general meshing applied to the model focused on the application of second order hexahedral elements to yield as few elements as possible [14][15]. Refined meshing was applied towards the solder balls to ensure the accuracy of stress calculations around the area of concern. A total of 65000 nodes and 226000 elements were produced in the mesh generation. Through a mesh independence test, these numbers of nodes and elements were identified. The selected elements of these mesh settings were found to be excellent in both the orthogonal quality and skewness criteria for the finite element analysis [9].

2.2. Drop test analysis
For the analysis setup, the BGA assembly is to be dropped from a height of 1 m towards a structural steel platform. However, to speed up the analysis, the semiconductor package is moved to about 0.5 mm from the structural steel platform. Standard earth gravity load was applied towards the BGA
assembly while the bottom surface of the platform was fixed. By reducing the distance between the BGA and the platform, the time frame involved in the analysis is also reduced; hence, the simulation time is shorter.

![Drop test simulation setup](image)

**Figure 2.** Drop test simulation setup

Initial conditions were also applied in the model such as the instantaneous velocity the package experiences at about 50 mm from the platform. This can be computed using free fall equations and would yield to a velocity of 4.428 m/s. Consequently, for this analysis the end time was calculated to be 0.00015 s. Under these loads and constraints, the package is simulated to be free falling from a height of 1 m with an initial velocity of zero.

2.3. Design of experiment

The reliability of a BGA package is highly dependent on the state of the solder balls, as such, this study explores the variations in the material properties of the solder balls to be used in the BGA assembly and evaluates it in terms of a standard drop test. The density and modulus of elasticity of the solder is identified as the independent variables while the von-Mises stress during impact is recorded as the dependent variable. In order to determine the effects of these material properties on the stress experienced by the package, particularly in the solder balls, a two-factor factorial design is implemented where the extreme “-” and “+” conditions from the nominal value are subject to the design. A -10% of the nominal value was set for the “-” condition while a +10% of the nominal value was set for the “+” condition. Table 2 summarizes the simulation runs for this study.

This design ensured an adequate spread of data points, while gaining an accurate correlation between the targeted material properties versus the resulting impact stress. This allowed the researchers to utilize a lower density of data points.

3. Results and discussion

The maximum impact stress has been consistently located in the solder balls for all runs. Figure 3 illustrates the impact stress experienced by the BGA package in the various runs.
Figure 3. Stress profile showing the resulting equivalent stress on the solder ball area for a) Run 1 (-,-), b) Run 2 (-,+), c) Run 3 (+,-), and d) Run 4 (+,+). All values in MPa.

The tabulated results can be seen in the last column of Table 2.

| Run   | \( \rho \) (kg·m\(^{-3}\)) | \( E \) (MPa) | Impact Stress (MPa) |
|-------|-------------------|-------------|---------------------|
| 1 (-,-) | 6624              | 31896       | 137.83              |
| 2 (-,+)| 6624              | 38984       | 141.24              |
| 3 (+,-)| 8096              | 31896       | 139.82              |
| 4 (+,+)| 8096              | 38984       | 151.51              |

The results were further subjected to statistical tests to determine the significance and influence of the identified variables towards the stress experienced in the solder balls. A multivariate regression analysis was applied and it was determined that the overall p-value of the fit model based on the gathered simulation data is 0.39 which is greater than 0.05. This implies that there is not enough statistical evidence to support the claim that varying the density or modulus of elasticity can significantly affect the stress experience in the ball solder area of a BGA package when subjected to a drop test. Upon further inspection, the parameter estimate of density is 0.38 which is slightly higher than the modulus of elasticity which has a p-value of 0.32. This suggests that based on the available simulation data on this scenario, the modulus of elasticity has a slightly higher influence over the impact stress in the package than the density parameter.
4. Summary and Conclusion
For a BGA package, one of its major design points to be considered is its solder balls. Majority of its functionality is highly dependent on the connectivity and state of the solder balls attached to it. As such, it is important that these components survive the operating conditions where the package will be subjected to. In this paper, the idea of conducting a sensitivity analysis on the material properties of the solder ball is done to determine its influence over the stresses that the package experiences. A drop test analysis was simulated wherein a shorter distance of 5mm between the package and platform was implemented to make the simulation time faster. The density and modulus of elasticity of the solder ball material was identified as the independent factors while the stresses experienced by the BGA package during the drop test is the dependent variable. A sensitivity analysis was conducted where a two-factor design was developed to determine the significance of altering the identified parameters over the stress in the package. The maximum stress for all runs is found in the same area in the package. Moreover, the gathered simulation data suggests that there is no significant evidence to imply that varying the material properties of the solder ball would affect the stresses it experiences. However, it would be interesting to further evaluate the other components of the package and identify the significant factors that might contribute to reliability concerns from a drop test.

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