### Sensitivity Evaluation on Sphere Attachment Shear Strength

T. E. Wong\* and H. K. Jew\*\*

Hughes Aircraft Company Sensors and Communications Systems 2000 E. Imperial Highway El Segundo, California

### ABSTRACT

A submodeling technique using MSC/PATRAN program and ABAQUS nonlinear finite element code, combined with a Taguchi design-of-experiments approach, was used to optimize the shear strength of spherical ball attachment on an aluminum nitride substrate. In the current design, the sphere is brazed onto a gold solder pad on the backside of the substrate using a gold-tin solder.

In the present study, the finite element model was first calibrated by test. Three design parameters were then chosen to evaluate the impact of variation of these parameters on the attachment shear strength. Analysis results indicate that the solder pad size is the most critical parameter affecting this shear strength, and the misalignment between the sphere and the solder pad is the next most critical. Therefore, to effectively improve the attachment shear strength, it is recommended to: (1) Use a larger solder pad; and (2) Minimize the misalignment between the sphere and the mounting solder pad. By implementing only the first recommendation into the current design, i.e., increasing the pad diameter from 0.02 in. to 0.03 in., the attachment shear strength could be improved by 160%.

<sup>\*</sup> Senior Scientist

<sup>\*\*</sup> Staff Engineer

## INTRODUCTION

The DoD has emphasized the application of Total Quality Management (TQM) to military programs to acquire quality hardware and systems that are reliable and cost-effective. The Taguchi design-of-experiment (DOE) approach (called the Taguchi method), which is an integral part of TQM, can be used to identify key parameters that affect system performance. Since application of the Taguchi method in other industries has resulted in improved product quality, the aerospace industry has recently given the method considerable attention. Examples of applying this method for the component designs in electronic package can be found in References 1 and 2.

In the present work, a nonlinear finite element analysis (FEA) was used to determine the shear strength of a spherical ball attachment assembly (Figure 1), which is used as a vertical I/O to conduct an electrical signal. The sphere (25 mils OD) is brazed onto a gold solder pad (0.15 mils thickness) on the backside of the substrate using a 78% Au/22% Sn solder. The minimum solder thickness between the sphere and the solder pad was estimated as 0.5 mils based on micro-section results (Reference 3).

The analysis approach combinedsubmodeling technique, using MSC/PATRAN program and ABAQUS code, with the Taguchi method. The Taguchi method was used to evaluate the impact of sphere attachment design parameters on the shear strength of the attachment using a minimum number of FEA runs. The detailed analysis procedures and the theoretical background of the Taguchi method will not be addressed in this paper, however, this information can be found in References 4 and 5.

Note that a submodeling (Reference 6) is the technique of studying a local part of a model with a refined mesh. This is based on interpolation of the solution from an initial, relatively coarse, global model on to the nodes (called "driven nodes") on the appropriate parts of the boundary of the submodel. The technique is most useful when it is necessary to obtain an accurate, detailed solution in the local region, and the detailed modeling of that local region has negligible effect on the overall solution. The response at the boundary of the local region is defined by the solution for the global model and it, together with any loads applied to the local region, determines the solution in the submodel.

# ANALYSIS

To estimate the shear strength of the sphere attachment assembly, a nonlinear FEA with the submodeling technique was used to estimate the stresses and strains in the assembly when subjected to a shear loading. The analysis results were then compared with test data to calibrate FEM and determine the shear strength or the maximum allowable shear load of the assembly. The nonlinear deformation analysis was performed with the ABAQUS finite element code on a SUN Ultra workstation. The ABAQUS code is a general purpose FEA program with special emphasis on advanced nonlinear structural engineering applications.

A 3-D global FEM (Figure 2) with a coarse mesh was constructed by using the MSC/PATRAN program to determine the deformation of the assembly when subjected to a shear load. This model consisted of 3820 solid elements and 4538 nodes. Due to the symmetric condition in the assembly, only one half of the assembly was modeled. The symmetric plan is at z=0. For the boundary conditions, the bottom surface of the substrate was constrained in the y-direction. Next, all lateral sides of the substrate (except the symmetric plane) were assumed to remain as flat planes during the deformation. Finally, the center node at the bottom surface of the substrate was constrained in all directions. For the loading condition, a concentrated load shown in Figure 1 was applied at the center of the sphere and parallel to the surface of the substrate. A 3-D finite element submodel (Figure 3) with a refined mesh was also constructed by using MSC/PATRAN program to determine the stresses and the strains in the assembly. This submodel is located at the interface between the sphere, the

solder and the substrate (shown in Figure 3). This submodel consisted of 5478 solid elements and 6576 nodes.

The material properties of brass, aluminum nitride (AIN), and gold (References 7 and 8) are listed in Table 1. Due to a lack of information in the 78% Au/22% Sn solder, the material properties of 80% Au/20% Sn solder (Reference 8) were used in the present study. The global/submodel analysis procedures described as follow was then used to determine the shear strength of the assembly. The procedures are: (1) Running a global analysis and saving the results in the vicinity of the submodel boundary; (2) Defining the total set of driven nodes in the submodel; (3) Defining the time variation of the driven variables in the submodel analysis by listing the actual nodes and degrees of freedom to be driven in each step; and (4) Running submodel analysis using the "driven variables" to drive the solution. Note that those degrees of freedom at nodes on the submodel boundary whose values are defined by interpolating the solution from the global are called "driven variables".

There is a concern when conducting a shear test or predicting the shear strength of the attachment assembly, it is essential that peak stresses or/and strains of the assembly be calculated accurately. However, the peak stresses and strains are known to be heavily dependent on finite element mesh size. The smaller the element size, the higher the resulting peak stresses and strains. This finite element mesh size dependency is primarily due to the stress singularity (References 9 through 12) at the edge of a bi-material. To make a meaningful shear strength prediction, the same finite element sizes must be used during the analysis. The selection of the element sizes, depended on and calibrated by a sphere shear test result, is described as follow.

A shear test was conducted and the sphere was sheared off the substrate when the shear load reached 1.79 lbs (Reference 3). The breakage was at the substrate, in which a crater was formed. Since the substrate of AIN is brittle, the breakage would occur as long as a crack is initiated in the substrate. Therefore, a peak principal stress was used to compare with the allowable strength of AIN in order to determine the shear load of the sphere attachment assembly. In the FEA, a convergence study was conducted by refining the element sizes in the submodel. The peak principal stress of the substrate in the submodel (Figure 3) was calculated as 38.3 ksi when a 1.79 lbs shear load was applied in the center of the sphere. This stress is about a 10% difference from the AIN flexure strength of 43 ksi obtained from an in-house test (Reference 13). Although the peak principal stress of the substrate obtained from the FEA can approach the AIN flexure strength by using smaller element sizes in the submodel, no further reduction in the element sizes was performed due to budget and time constrains. Therefore, the element mesh sizes in the submodel (Figure 3), which is approximately 0.0001 in., was selected for the stress prediction.

### PARAMETRIC STUDY

The Taguchi method (References 4 and 5) was adopted for establishing the analysis matrix. This method was also used to analyze the finite element calculation results to identify critical sphere attachment design parameters affecting the shear strength of the attachment. The principal goal of this effort was to maximize the attachment shear strength to sustain a larger loading from handling, and/or vibration and thermal environments.

In the parametric study, the sensitivity of the sphere attachment shear strength to variations of three design parameters was evaluated. Table 2 summarizes the three selected parameters and their variation levels. In general, the larger allowable variation for each parameter corresponds to higher product yields and/or cost savings. For parameters B and C, the variations could occur during manufacturing processes. The offset between the sphere and the solder pad (parameter C) was chosen as 0.0025 in.

A Taguchi analysis matrix with four study cases (a L<sub>4</sub> orthogonal array), shown in Table 3, was established to study the criticality of these three parameters. Note that the possible combinations of

these three parameters with two levels of variation are  $2^3$  or 8. However, with the assumption of noninteraction effects between these parameters, only four models are required. With this approach, the number of required FEA runs were reduced by about 50% as compared to the full factorial DOE approach. Based on the analysis matrix shown in Table 3 and the chosen parameters listed in Table 2, four different FEMs were constructed. In the case of Run 4 in Table 3, for example, the model includes 0.03-inch solder pad (A<sub>2</sub>), 67.5-degree solder wetting height (B<sub>2</sub>), and no offset between the sphere and the solder pad (C<sub>1</sub>). Note that the subscript of each parameter represents the variation level of the parameter. During the construction of these four models, all other parameter values of the sphere attachment assembly, except the three selected parameters in Table 2, remained constant.

The results of the analyses for the sphere attachment shear strength for the four study cases are listed in Table 3. Since the primary goal in the current study is to maximize the attachment shear strength, a signal-to-noise ratio ( $\eta$ ) for the larger-the-better problem (References 4 and 5) is defined as:

$$\eta = -10\log_{10}\left[\frac{1}{y^2}\right],$$
(1)

where y is the sphere attachment shear strength/load in lbs. To determine which parameters have the most effect on the attachment shear strength, attachment shear strength averages are computed by averaging the two analysis results of a parameter at a particular level. For example, when the effect of parameter C is to be estimated, the data corresponding to level 1 in column C is compared to that of level 2 in column C. In column C of Table 3, the average of the data for level 1 is  $(\eta_1 + \eta_4)/2$  and

level 2 is  $(\eta_2 + \eta_3)/2$ . The averages for other parameters were calculated in a similar manner and

are shown in Figure 4. Critical parameters can thus be identified by simply comparing the differences among two levels for each parameter. The larger the difference, the more critical that parameter. Consequently, it can be concluded that the solder pad size is the most critical parameter affecting the attachment shear strength, and the misalignment between the sphere and the solder pad is the next most critical.

Based on the approach described in Reference 4, the predicted attachment shear strength is calculated by an additive model, which is

$$\eta_{pre} = m + (m_{Ai} - m) + (m_{Bi} - m) + (m_{Ci} - m),$$
<sup>(2)</sup>

where m is the overall mean value and  $m_{Xi}$  is the mean value for parameter X at level i, X = A, B, and C.

The current design of the sphere attachment assembly is similar to the case of  $A_1B_1C_1$  in Table 3. A modified sphere attachment design of the parameter setting of  $A_2B_1C_1$ , which is the increase of the solder pad diameter from 0.02 in. to 0.03 in., is proposed. By using Eq. (2), the predicted attachment shear strength/load of this setting is estimated to be 5.09 lbs. This prediction is consistent with the FEA result of 4.7 lbs. Thus, the additive model of Eq. (2) can be used to predict the attachment shear strength for other parameter settings from the combinations of the three parameters in Table 2. In addition, the proposed design modification could improve the attachment shear strength by 160%.

### SUMMARY AND RECOMMENDATIONS

A submodeling technique using MSC/PATRAN program and ABAQUS FEA code, combined with the Taguchi method, was used to optimize the shear strength of the sphere attachment on the substrate. The element mesh sizes were first selected according to the sphere shear test result. The parametric study by the Taguchi method was then performed to identify critical sphere attachment design parameters affecting the shear strength of the attachment. Analysis results indicate that the solder pad size is the most critical one and followed by the parameter, which is the misalignment between the sphere and the solder pad. Therefore, to effectively improve the attachment shear strength, it is recommended to: (1) Use a larger solder pad; and (2) Minimize the misalignment between the sphere and the mounting solder pad. By implementing only the first recommendation into the current design, i.e., increasing the pad diameter from 0.02 in. to 0.03 in., the attachment shear strength could be improved by 160%.

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Table 1. Material Properties

Material	Elastic Modulus, 10 <sup>6</sup> psi	Yield Strength, ksi	Ultimate Strength, ksi	Elonga- tion, %	Poisson's Ratio	Ref.
Brass	16.0	_	-	_	0.3	7
AIN	50.0	_	—	-	0.3	8
Gold	11.5	1.53	18.38	33	0.42	8
Solder ^	8.6	39.5	40.5	2 *	0.42 *	8

^ 80% Au/20% Sn

\* Assumed values

Table 2. Input Parameters and Their Variation Levels in Sphere Attachment Shear Strength/Load Parametric Study

Parameter	Description		
		1	2
A	Solder Pad Diameter, mil	20	30
В	Solder Wetting Height or Sphere/Solder Interface Angle, degree	52.5	67.5
С	Sphere/Solder Pad Offset	No	Yes

Table 3. Parametric Study Matrix/Response (L4 Array) in Sphere Attachment

Analysis	Parameter		er	Sphere Attachment Strength		
Run	Α	В	С	Shear Load, lbs	Signal-to-Noise Ratio, dB	
1	1	1	1	1.79	5.06	
2	1	2	2	1.50	3.52	
3	2	1	2	3.82	11.64	
4	2	2	1	5.67	15.07	



Figure 1. A Cross-Section of Spherical Ball Attachment



Figure 2. A 3-D Global Finite Element Model







Figure 4. Parameter Effects in Sphere Attachment Shear Strength/Load