

Creep Analysis of Lead-Free Solders Undergoing Thermal Loading

Summary

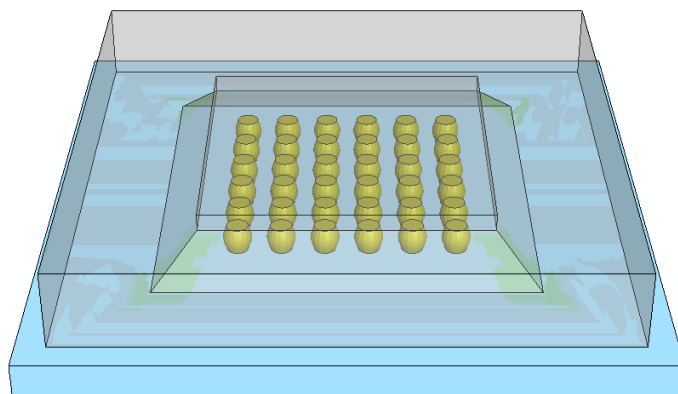
Lead and its compounds have been widely used for many years in the electronics industry. However, the global demand to reduce the use of hazardous materials has compelled electronics manufacturers to consider lead-free materials in future products. This transition has heightened the necessity for new finite element material models that can be used to evaluate the reliability of lead-free solders. Along with extensive nonlinear analysis capabilities, Abaqus/Standard includes a variety of creep models, including those applicable to lead-free solders. It is thus an ideal design tool for the electronics industry.

Background

Lead solders, such as the popular tin-lead variety, have been used in the electronics industry for the past 50 years. Subsequently, their long-term reliability is well understood. However, lead and its compounds are highly toxic and the entry of these materials into the environment has become an issue of great importance. In conjunction with legislation requiring the eventual use of lead-free materials, the electronics industry is working towards reducing the amount of lead in end-user equipment. This transition requires the development of new analytical capabilities for estimating the reliability of components that use lead-free solder.

During their working lives, electronic components are subject to a large number of thermal cycles. Mismatch between the thermal expansion behaviors of the various materials may induce severe stresses that are high enough to cause plasticity and creep. In particular, solder balls are at risk because they are stressed at temperatures above half of the solder's melting point. At such temperatures, the solder creeps; after a number of thermal cycles, the accumulation of large inelastic strains may lead to failure of the solder joints. Therefore, the creep analysis of solder balls under cyclic thermal loading becomes an important part of the design phase.

Beginning with Release 6.6, Abaqus offers several creep models that are widely used in the electronics industry for lead-free solders. The hyperbolic-sine model is available as a regular feature, and the modified Anand [1] and double-power [2] models are freely available as user subroutines. These models, together with its nonlinear solution techniques and thermal-mechanical coupling capability, make Abaqus/Standard an ideal tool for analyzing the reliability of electronics components.



Key Abaqus Features and Benefits

- Extensive material library that includes commonly used creep models for lead-free solders
- Sequentially or fully coupled thermal-mechanical analysis capability
- Direct cyclic capability as an efficient alternative to the classical transient approach for creep analyses
- Geometrically nonlinear analysis capability
- Scripting interface to allow customization of Abaqus/CAE

Analysis Approach

Building a BGA model using Abaqus/CAE

The scripting and GUI toolkit interfaces of Abaqus allow the capabilities of Abaqus/CAE to be customized for special applications. With this functionality, many of the specific tasks associated with the development of certain classes of models can be automated. Additionally, a customized application allows non-expert users to run pre-packaged analyses easily.

The Ball-Grid-Array (BGA) model used in this technology brief was built using an Abaqus/CAE custom application developed at Worley Parsons PTE Limited, Singapore. The user interface is shown in Figure 1.

The process of building a BGA model is captured in several icons, e.g., the Model icon, the Material icon, the Load icon, etc. For example, only the dimensions for a BGA model need to be specified in the Model dialog box, and the model is built and meshed automatically.

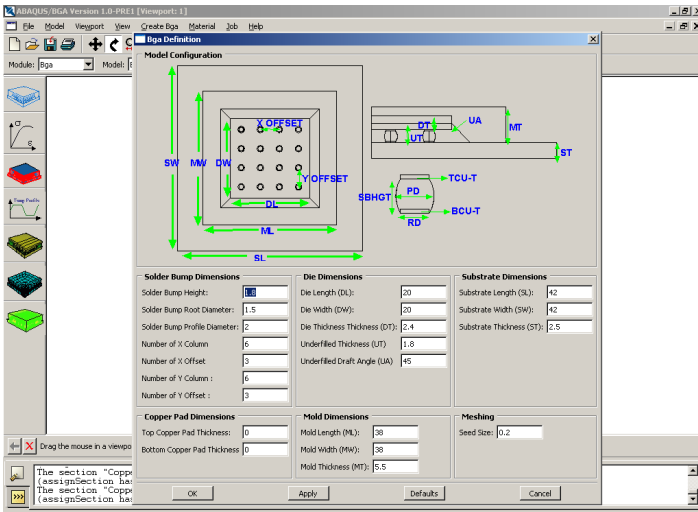


Figure 1: Abaqus/CAE BGA custom application

Model description

Figure 2 shows a section of the BGA model used in the present calculations. Thirty-six solder balls connect the silicon die and the substrate, with underfill material used in the space surrounding the solder balls. All components except the substrate are encapsulated in the mold.

The mechanical behavior of the solder is captured using temperature-dependent elasticity and the lead-free solder creep models available in Abaqus Answer 3049. The material data for creep behavior are those pertinent to Sn3.5Ag lead-free material [1]. All other parts are modeled with temperature-dependent linear elasticity only.

The materials have different thermal expansion coefficients, causing stresses to develop when the model is subject to thermal loading. For simplicity, it is assumed that the entire model is subject to uniform thermal cycling, with the temperature amplitude curve shown in Figure 3. In a more detailed analysis, the temperature field could be obtained from a previous heat-transfer analysis, or the entire simulation could be carried out as a fully-coupled temperature-displacement analysis. The bottom of the substrate is fixed and no other direct mechanical loading is applied.

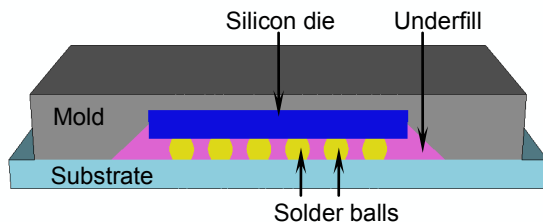


Figure 2: Schematic section view of the BGA model

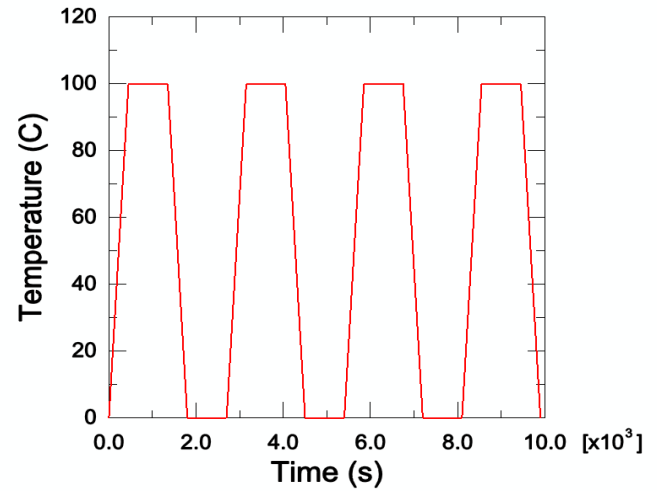


Figure 3: Temperature time history used to apply thermal load

Results and Discussion

In Figure 4, the distribution of equivalent creep strain (CEEQ) at the end of the analysis ($t=9900$ s) is shown for the array of solder balls. The top surfaces of the solders interface with the silicon die; thermal expansion mismatch between the solder and the surrounding materials results in high creep strain near the top and bottom surfaces of the solders. In addition, the creep strain in solders at the perimeter of the array is higher than that near the center. The solders with the highest creep strains are those at the four corners, suggesting that these are the critical joints for the simulated device.

The time histories of the Mises stress and the equivalent creep strain at locations A and B (see Figure 4) are shown in Figure 5. Note that the modified Anand [1] creep model was used to generate these results. In general, the Mises stress in the corner solder (location A) is slightly higher than that in the solders near the center of the device, especially during the time interval in which the temperature is held constant at 100 °C. The slightly high-

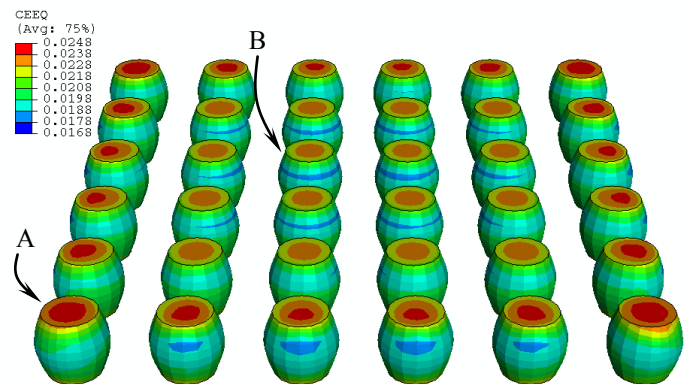


Figure 4: Equivalent creep strain at end of loading history

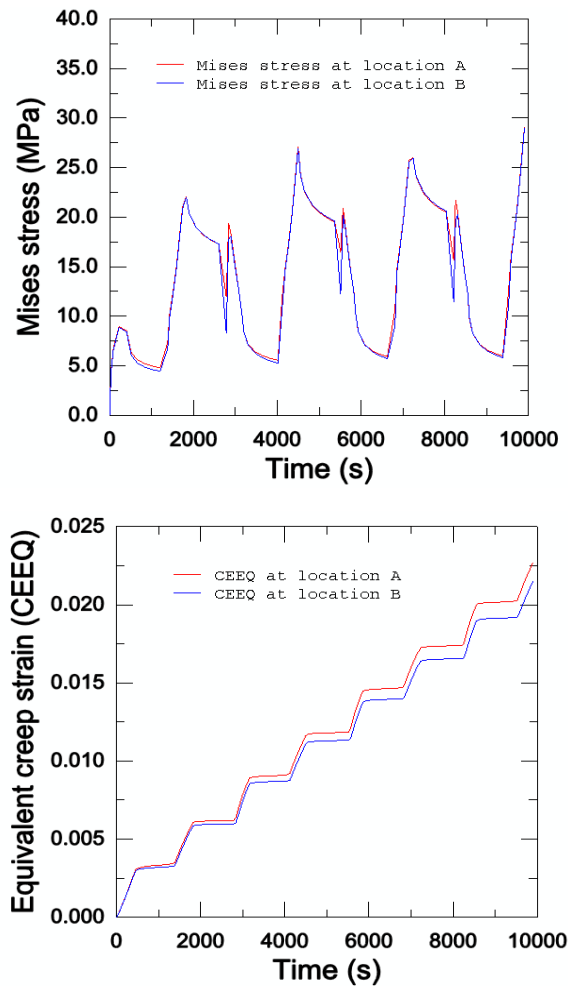


Figure 5: Stress and strain histories at points A and B (Fig 4)

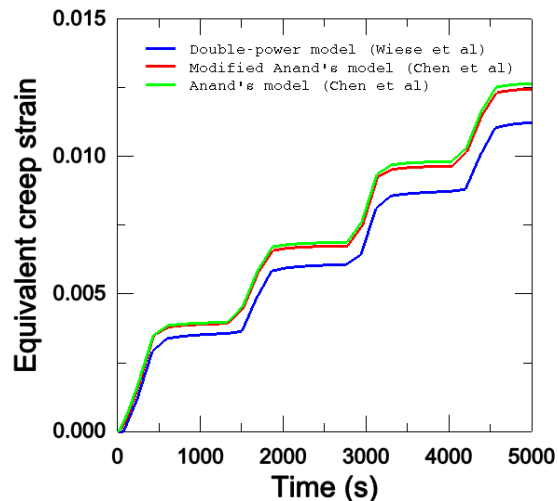


Figure 6: Creep strains obtained using three different creep models

er stress develops larger creep strains in the corner solders, and the difference in the creep strains steadily increases as the number of thermal cycles increases. Once the creep strain increment per cycle at the critical point of a solder reaches a constant, this value can be used in a fatigue law, such as the Coffin-Manson equation, to estimate the fatigue life of the solder ball.

As an additional comparison, Figure 6 shows the creep strains at location A (see Figure 4) obtained from analyses using three creep laws that are often cited in the electronics industry.

These results were obtained with a classical transient analysis approach that imposes the complete time history of the loading. If the long-term behavior of the system is needed, an alternative procedure for directly computing the stabilized response is available. The Abaqus 'direct cyclic' capability avoids the expense of repeatedly applying a large number of individual load cycles in order to determine the stable cyclic response of the structure.

The repetitive nature of creep analyses makes them perfect candidates for the direct cyclic method and this approach can lead to a large reduction in computational effort. The method uses a combination of Fourier series and time integration of the nonlinear material behavior to iteratively determine the stabilized cyclic response of the structure. This is a fundamentally different approach than a regular transient analysis.

For the BGA model, the direct cyclic method predicts that the structure reaches a stabilized state after 11 solver iterations; more specifically, 11 passes through the equation solver. Contrast this with a single application of an individual thermal cycle (length 2700s, Fig 3) in a transient analysis, which requires 132 passes through the equation solver. For the general case, this individual transient cycle would necessarily be applied many times to arrive at a stabilized state.

At the same time, the direct cyclic method produces accurate results. In Figure 7, the Mises stress at location A during the last cycle is compared to that from a transient analysis in which 11 thermal cycles are applied. Figure 8 shows the hysteresis loop at location A traced by the stress-creep strain curve in the solder axial direction. The peak and mean values of the stress and strain are again very similar between the two approaches, as well as the amount of energy dissipation (the area enclosed by the loop).

Conclusions

The fast-growing application of lead-free materials in the electronics industry has brought new challenges with regards to the simulation of creep behavior. The advanced features of Abaqus/Standard, including a large material library, extensive nonlinear analysis capability, thermal-mechanical coupling, and the efficient direct cyclic method, have made it a powerful design tool for the electronics industry in the lead-free era.

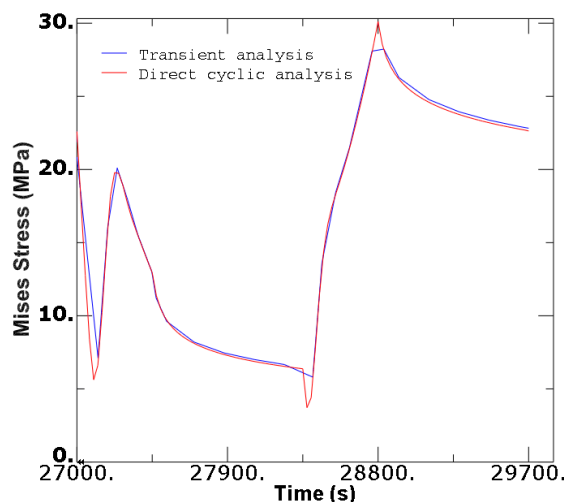


Figure 7: Comparison of Mises stress

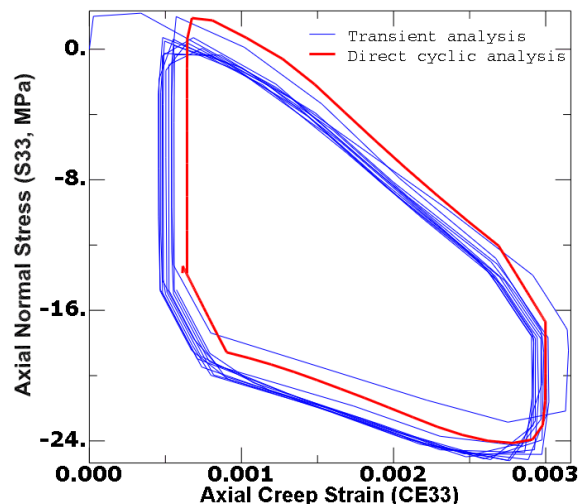


Figure 8: Evolution of the axial normal stress as a function of the axial creep strain

References

1. X. Chen, G. Chen, and M. Sakane, "Prediction of Stress-Strain Relationship with an Improved Anand Constitutive Model for Lead-Free Solder Sn3.5Ag," *IEEE Transactions on Components and Packaging Technologies*, Vol. 28, pp. 111-116, 2005.
2. S. Wiese, E. Meusel, K. J. Wolter, "Microstructural Dependence of Constitutive Properties of Eutectic SnAg and SnAgCu Solders," *Proceedings of the 53rd ECTC Conference*, pp. 197-206, 2003.
3. H.S. Ng, T.Y. Tee, S. Pan, et al, "Development and Application of Lead-free Solder Joint Fatigue Model for CSP," *Proceedings of the 6th International Conference on Electronics Materials and Packaging*, 2004.
4. Z. Du, J. Wang, and X. Fan, "Direct Cyclic Method For Solder Joint Reliability Analysis," *Proceedings of ASME International Mechanical Engineering Congress and Exposition*, 2006

Abaqus References

For additional information on the Abaqus capabilities referred to in this brief please see the following Abaqus 6.13 documentation references:

- Analysis User's Guide
 - "Rate-dependent plasticity: creep and swelling," Section 23.2.4
 - "Direct cyclic analysis," Section 6.2.6
- User Subroutines Reference Guide
 - "CREEP," Section 1.1.1
- DS Knowledge base Article QA00000008827 , "Creep models for lead-free solder"
- DS Knowledge base Article QA00000009149, "Modeling the creep of solder"

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