Creep Characterization Of Ceramic BGA

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Abstract

Long term creep of a ceramic ball grid array (CBGA) solder ball under compressive loading was investigated. An experiment was conducted with two levels of loading and four of temperature. Analysis of the data assumed the composite ball structure could be simulated by an interconnection having the same shape, but of a single equivalent material. Curve fitting determined the stress exponent and activation energy of the equivalent material in the Norton creep model; the values were consistent with the range of values of the individual components available in the literature. Nonlinearity of the change in ball height with time was hypothesized to be due to geometric stiffening, a hypothesis which was confirmed by a simplified model. The model may be used to estimate creep behavior of other ball geometries having the same material set. The final result of this work - a closed form equation describing height decrease as a function of compressive force, temperature and time - can be used to simplify complex modeling of an entire package, and as an aid in designing accelerated thermal cycles which appropriately synchronize solder creep and fatigue.

Key Words

BGA, Compressive Load, Creep, Deformation, Modeling

Introduction

High power microprocessor chips on PBGA (Plastic Ball Grid Array) or CBGA (Ceramic Ball Grid Array) chip carriers are increasingly being cooled by direct attachment of the heat sink to the back of the die. To protect and maintain the thermal interface the board is customarily bolted to the underside of the heat sink by (typically four) posts. The force of the bolts tends to bend the board slightly toward the heat sink which imposes a compression field on to the BGA array. Compressive force on an individual I/O can reach into the hundreds of grams. Creep of the solder balls is a significant concern: squashing deteriorates fatigue reliability; in extreme cases adjacent balls can be shorted.

It is of great importance to be able to characterize BGA creep under a uniform compressive force. Finite Element Modeling of an I/O when the total compressive strain exceeds 10% of the original height can be extremely time consuming and CPU-intensive. Moreover such modeling relies on data based on wire or bulk testing, which may not be appropriate for BGA structures for the following reason:

(1) the grain size relative to specimen size may be very different;
(2) intermetallics may dilute and affect the composition of the I/O;
(3) significant I/O creep distortion could change the grain shape and size which may alter the basic creep mechanism during lifetime;
(4) CBGA has two materials (10/90 Sn/Pb ball with 63/37 attachment fillets) which partially intermix.

A second, equally important reason to quantitatively understand creep is for accurate acceleration factors (AF) in accelerated module testing. In the accelerated cycling of BGA's, solder fatigue lifetime is generally the primary objective, and numerous methodologies are available to compute appropriate AF's. If concurrent creep deformation is significant, it

will play an important role in determining reliability, so it is equally important to understand creep acceleration factors (CAF). Ideally creep and fatigue acceleration can be synchronized by proper design of the accelerated cycle.

In this study an experiment was conducted to quantify the creep characteristics of an individual CBGA ball, the instantaneous creep rate being expressed in a Norton equation involving a power law stress dependency and a single activation energy. This relation does not specifically describe the individual alloys in the dual melt structure, but rather a single material which captures the composite behavior of the ball.

The experimental data showed significant flattening of the height change vs. time curve. A simplified model confirmed that this was due to the increase in cross-sectional ball area as creep progressed, and the ensuing decrease in stress and creep rate.

Experiment

16 test parts were fabricated with 32.5 mm x 32.5 mm x 1.5 mm alumina ceramic substrates, each joined to a matching 1.6 mm thick FR4 card with dual melt BGA balls only at the corners. The BGA ball solder was 10/90 Sn/Pb by weight, attached on either side with fillets made of 63/37 Sn/Pb by weight. Refer to Figure 1. Each ball was 890 micrometers in diameter. The fillets were made from (a) 500 micrometer diameter balls on the ceramic side, and (b) solder paste on the organic side. It is to be noted that during the fabrication of the solder joint, the 63/37 Sn/Pb alloys melts completely, whereas the 10/90 Sn/Pb ball does not melt at all.

During the creep testing, each assembled unit was carefully weighted with either a 1 or 2 kg weight, taking care to ensure that the weight was placed centrally on the unit, so that the weight was distributed as symmetrically as possible, across all four load-bearing points. The assemblies were then placed in an oven at either 75^0C, 100^0C, 125^0C or 150^0C.

Before placement in the ovens, individual ball heights were measured via the vertical distance from the top of each substrate to the point on the card directly beneath using a Unitron microscope. This measurement was repeated periodically through the lifetime of the test. Refer to Figure 2.

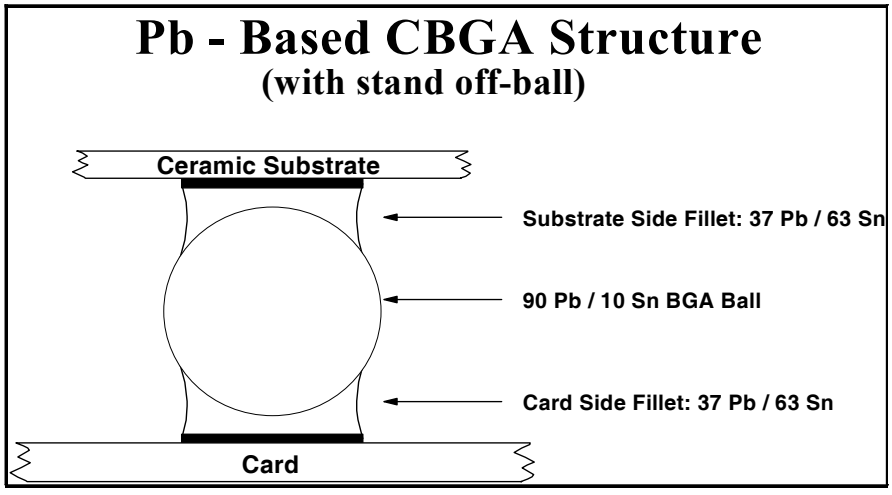


Figure 1: BGA Structure with central high Pb non-melting ball, and eutectic Sn/Pb fillets on either side [1].

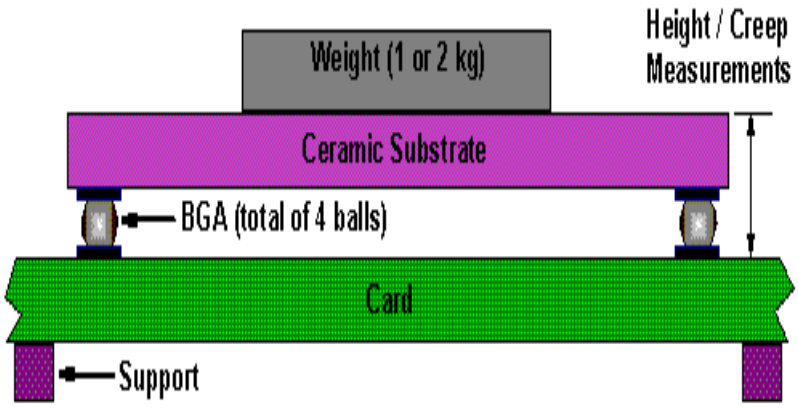


Figure 2: Schematic of Experimental Design

Test Matrix

Weight	75^{0}C	100^{0}C	125^{0}C	150^{0}C
1 kg	2	2	2	2
2 kg	2	2	2	2

Because of occasional non-uniform loading, changes in height were not always equal at all the four corners. Thus the average change from time zero readings was used for each test part.

It was observed that once the creep deformation had reached approximately .025" (0.63 mm) one or more substrate corners was making contact with a solder pad on an unused site. Data from these readings were excluded and testing on the effected part was terminated. Modules with the higher load and at the two highest temperatures were observed to have reached that condition even at the first readout - therefore there was no acceptable data for these cells.

Data Analysis

The Norton[1] creep model has the creep rate exponentially related to stress, the exponent staying constant as long as the basic creep mechanism is unchanged. Strain rate is related to temperature by a simple Arrhenius relationship with a constant activation energy. The generic equation is thus:

$$e' = C\, r^n\, e^{-Q/T} \qquad (1)$$

Where e' is the strain rate, r the stress and T the absolute temperature in ^{o}K. The purpose of the experiment is thus to find values of n and Q which best fits all the data.

The significant ball squashing observed in the experiment led to the compressive stress decreasing with time. Accordingly a factor was added to Eq. (1) to reflect shape stiffening. It was assumed that geometric stiffening is related only to the instantaneous ball height, h, and not to the prior creep history. For analysis of the experimental data, therefore, Eq. (1) was modified to

$$h' = C'\, f(h)\, F^n\, e^{-Q/T} \qquad (2)$$

where h' = dh/dt, and f(h) describes geometric stiffening. C and C' are empirically determined constants, and F is the compressive force.

An important ramification of geometric stiffening is that h(t) is highly nonlinear. It was thus necessary to evaluate n and Q by comparing the time to reach a particular height in different cells (f(h) thereby canceling out) rather than by considering the height history of a particular cell.

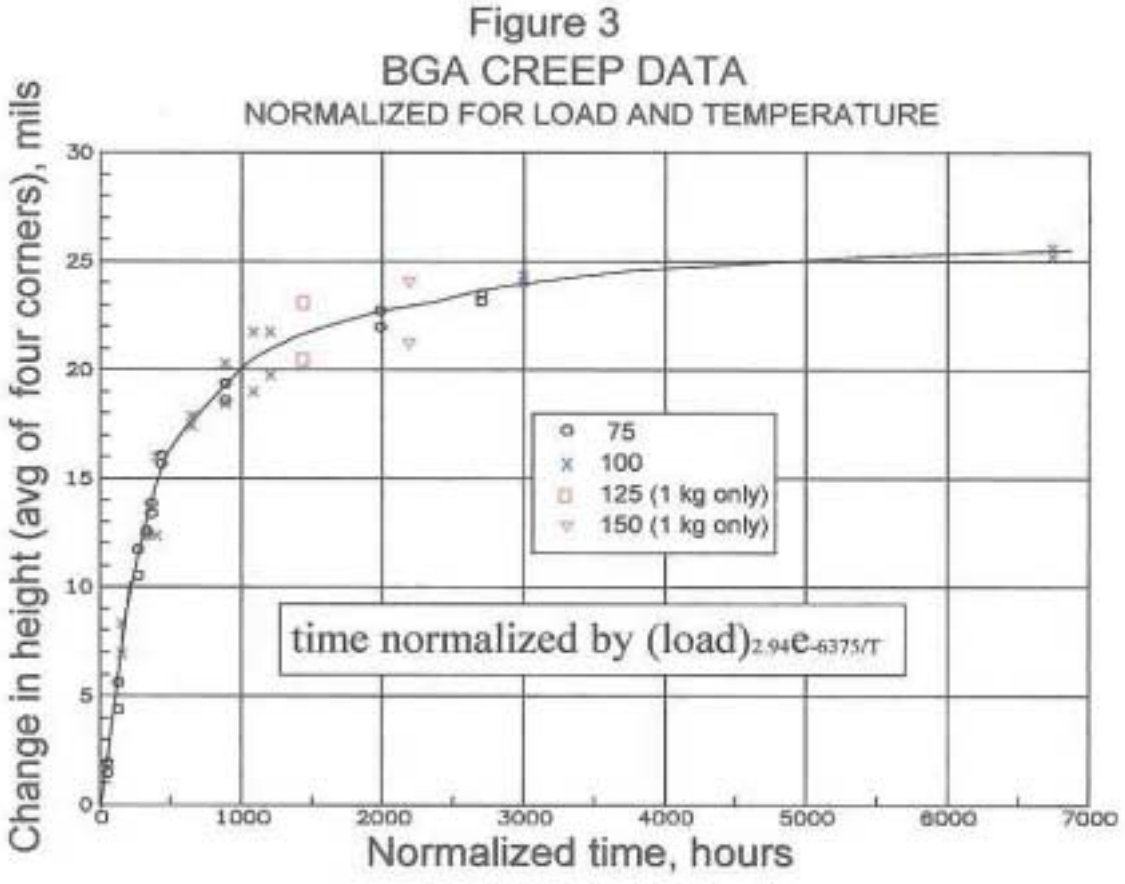
[1]The Garofalo equation, which replaces r^n with $(\sinh[a_r])^n$ may be shown to be equivalent to Eq. (1) for the low stresses with which we are dealing ($r/E \sim 10^{-4}$), where $(\sinh[a_r]) \sim a_r$.

Specifically, n was estimated by comparing the two load levels at the same temperature, 75C or 100C. The best fit exponent 2.94 was essentially the same for both temperatures. Likewise, Q was estimated by comparing the four temperature levels with the 1 kg load, and the two temperature levels (the 125 and 150C data having been lost) with 2 kg. The value Q = 6375 $^{o}K^{-1}$ provided the best fit.

Figure 3 shows height change as a function of normalized test time, with all data combined. The time is normalized by the above equation to the 75C, 1 kg (250 g per ball) cell. Each point represents the average of the four corners of a single test part.

Literature on creep of solder interconnections is voluminous for eutectic or near eutectic lead tin [2-9] and sparse for high lead alloys [10,11], and is divided between small tensile specimens and shear of actual interconnections. In the temperature and stress ranges of this study, which primarily drives dislocation climb and/or glide creep, most of the published n and Q values for both solders agree quite well with our values.

Figure 3



Simplified Model

To confirm that that the nonlinear shape of Fig. 3 was indeed a function of geometric stiffening rather than a change of creep mechanism. a simplified model was developed to simulate creep. An additional benefit of such a model is the ability to predict height change of dual melt structures of different geometries. For this model the ball was idealized as a stack of disks having the same profile as the actual I/O, but of a single homogeneous material. A similar procedure has been used to simulate the axial plastic deformation of a flip chip solder ball under ramp loading [12] and found to agree well with experiment.

In this case each disk was assumed to be uniformly compressed, the stress computed

simply as the applied force divided by the instantaneous area. In each time step, creep was calculated for each disk from Eq. (1) and an arbitrary value of C. The accompanying area increase was then calculated assuming constant volume, and this increased area used for the next time step. By trial and error the number of disks was increased and the length of each time step decreased until a convergent solution was reached. The entire calculation was programmed in APL. A value of C was chosen by trial and error to best match the experimental data: 0.00095 hr^{-1} when r is expressed in psi.

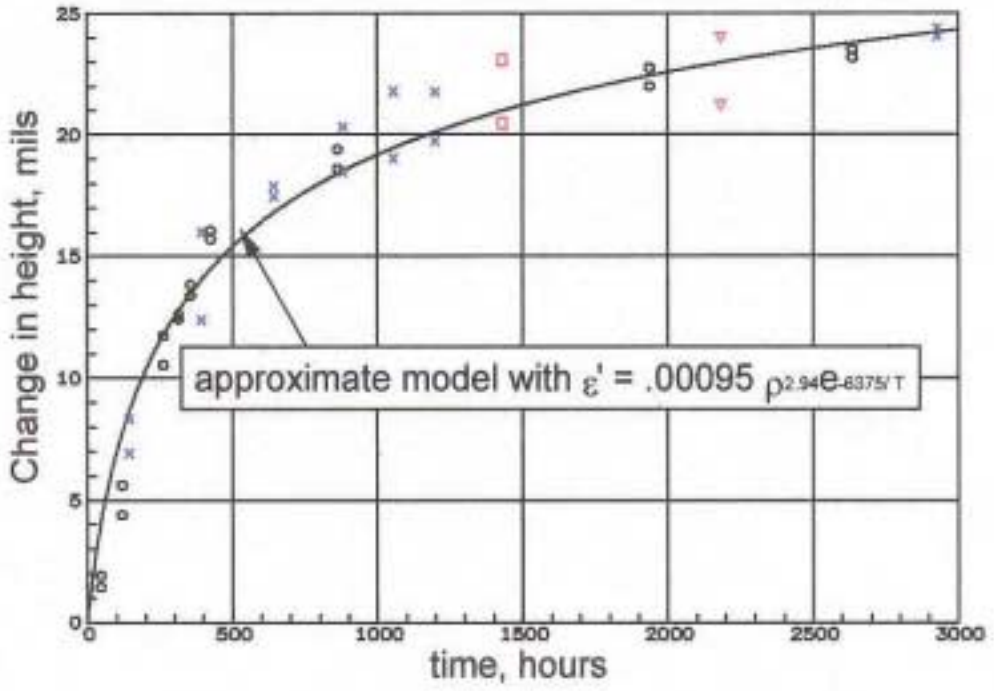
Fig. 4 shows the comparison between the experimental curve and the simplified model. The outer points on Fig. 3 have been excluded as they are presumed to have bottomed on unused pads as previously discussed.

The close agreement supports the hypothesis that nonlinearity of the creep curve is attributable essentially entirely to increased stiffness of the compressed ball, and that Equation (1) with the constants C = .00095 hr^{-1}, n = 2.94 and Q = 6375 well characterizes the response of the composite material throughout the temperature and load parameters of the matrix. For squashing up to about 60% of the initial height, a very good approximation for f(h) in Eq. (2) is

$$f(h) = (1 - e^{-bh/hi})/(1 - e^{-b}) \qquad (3)$$

where hi is the initial height, h the reduced height, and b is a dimensionless constant which for our geometry is equal to 5.25.

Figure 4
COMPARISON OF DATA WITH APPROXIMATE MODEL
EXPERIMENTAL DATA NORMALIZED TO 75C AND 250g/BALL



Conclusion

A methodology and approximate model have been presented to characterize creep behavior of BGA solder balls, with emphasis on a dual melt CBGA. Being able to characterize creep of a single I/O in a simple expression or algorithm greatly simplifies modeling of a full array under complex structural loading. By tailoring the profile of an accelerated thermal cycle, both fatigue and creep acceleration can be synchronized to provide a more realistic picture of field performance. Typically, adjusting the high temperature dwell is the most practical method to obtain synchronization. Finally, the approximate model can be used to project creep behavior for different size I/O's of the same material set and having a similar structure.

Acknowledgement

We would like to thank William Sablinski who prepared the test samples and made the height measurements.

References

1. M. Farooq, S. Ray, A. Sarkhel and C.Goldsmith, "Evaluation of Lead-free CBGA: Wettability, Microstructure and Reliability", Proceedings of the 51st Electronic Components and Technology Conference, IEEE, May 2001.

2. R. Darveaux and K. Banerji, "Constitutive Relations for Tin-Based Solder Joints", IEEE Trans. CHMT, Vol. 15, No. 6, Dec. 1992, pp. 1013-1023. Data presented in this paper for 97/3 Sn/Pb shows n = 7, which is considerably higher than the high lead data cited in Refs. 9 and 10.

3. S. Wiese, F. Feustel, S. Rzepka and E. Meusel, "Experimental Characterization of Material Properties of 63Sn37Pb Flip Chip Solder Joints", Mat. Res. Soc. Proc. Vol. 515, 1998, pp. 233-238.

4. H. Ishikawa, K. Sasaki and K. Ohguchi, "Prediction of Fatigue Failure of 60Sn-40Pb Solder Using Constitutive Model for Cyclic Plasticity", ASME Journal of Electronic Packaging, Vol. 118, Sept. 1996, pp. 164-169.

5. Z. Guo and H. Conrad, "Computer Modeling of Isothermal Low-Cycle Fatigue of Pb-Sn Solder Joints", Proc. 43rd ECTC, pp. 831-838.

6. X.Q. Shi, Z.P Wang, W. Zhou, H.L.J. Pang and Q.J. Yang, "A New Creep Constitutive Model for Eutectic Solder Alloy", ASME Journal of Electronic Packaging, Vol. 124, June 2002, pp. 85-90.

7. Z. Qian and S. Liu, "A Unified Viscoplastic Constitutive Model for Lead-Tin Solder Joints", *Advances in Electronic Packaging*, ASME Publication EEP-Vol. 192, pp. 1599-1604.

8. J. Lau, S.-W. Ricky Lee, and C. Chang, "Solder Joint Reliability of Wafer Level Chip Scale Packages: A Time-Temperature Dependent Creep Analysis", ASME Journal of Electronic Packaging, Vol. 122, Dec. 2000, pp. 311-316.

9. B. Wong, D.E. Helling and R.W. Clark, "A Creep Model for Two-Phase Eutectic Solders", IEEE CHMT, Vol. 11, No. 3, Sept. 1988, pp. 284-290

10. H.J. Frost, R.T. Howard, P.R. Lavery and S.D. Lutender, "Creep and Tensile Behavior of Lead-Rich Lead-Tin Solders", Proc. 38th ECTC, 1988, pp. 13-22.

11. Y. Tsukada, H. Nishimura, M. Sakane and M. Ohnami, "Fatigue Life of Solder Joints in Flip Chip Bonding", ASME Journal of Electronic Packaging, Vol. 122, Sept. 2000, pp. 217-213.

12. L.S. Goldmann, "A Model for Deformation of Solder Bumps From Ramp Loading", ASME Journal of Electronic Packaging, Vol. 118, March 1996, pp. 37-40.