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Creep of Sn-(3.5-3.9)wt%Ag-(0.5-0.8)wt%Cu Lead-Free Solder Alloys and Their Solder Joint Reliability

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Abstract
A new set of constitutive equations for a class of lead-free solder alloys, Sn(3.5-3.9)wt%Ag(0.5-0.8)wt%Cu is proposed in this investigation. These equations are applied to a 256PBGA (plastic ball grid array) package assembly. The creep results in the PBGA solder joints are compared against those with other constitutive equations reported in the literature.

Introduction
Since February 13, 2003, lead-free has been law in the European Union (EU). Starting from the implementation date, July 1, 2006, all electronic products (except those with exemptions) cannot be made in or shipped to the EU if they have lead content. Presently, China is planning to publish her own lead-free law by the end of 2003.

High-density packages such as plastic ball grid array (PBGA), chip scale package (CSP), flip chip, and wafer level chip scale package (WLCSP) have been very popular for consumer, computer, and communication products. Most of these packages use solder as an interconnect material, thus they are affected by the lead-free regulations. As with any new technology, lead-free soldering is not without its problems. In the development of lead-free, the following issues must be noted and understood in order to avoid mistakes and obtain its full benefits:

- •Overall costs increase
- •Impact of PCB finishes
- •Impact of component finishes
- •Backward incompatibility
- •Forward incompatibility
- •Component reliability
- •PCB reliability
- •Impact of multiple heat cycles
- •Tin whisker (short) reliability risk
- •Solder joint reliability – thermal and mechanical
- •Solder joint reliability –shock & vibration
- •Solder joint reliability – electromigration
- •Reliability tests and acceleration factors
- •Electrochemical reliability
- •Infrastructure

In this study, the focus is on the lead-free thermal-mechanical solder-joint reliability of high-density packages. Emphasis is placed on proposing a set of constitutive equations for Sn3.5-3.9wt%Ag0.5-0.8wt%Cu solder alloys.

Useful constitutive equations of SnAgCu have been given in.[1-16] Schubert, et al., based on 108 data points from the literature and their own measurements, presented a new creep constitutive equation at the IEEE Electronic Components and Technology Conference.[7] At the same conference, Lau, et al., based on 32 data points measured by Sandia, presented another new creep constitutive equation.[1, 2] In this technical brief, a new set of creep constitutive equation is proposed which is based on the average values of.[1, 2, 7]

Constitutive Equations of SnAgCu Lead-Free Solders
Garofalo-Arrhenius steady-state creep constitutive equation expressed by:

$$\frac{d\gamma}{dt} = C\left(\frac{G}{\Theta}\right)\left[\sinh\left(\omega\frac{\tau}{G}\right)\right]^n \exp\left(-\frac{Q}{k\Theta}\right) \qquad (1)$$

where γ is the creep shear strain, $d\gamma/dt$ is the creep shear strain rate, t is the time, C is a material constant, G is the modulus, Θ is the absolute temperature (^{o}K), ω defines the stress level at which the power law stress dependence breaks down, τ is the

shear stress, n is the stress exponent, Q is the activation energy for a specific diffusion mechanism (for example, dislocation diffusion, solute diffusion, lattice self-diffusion, and grain boundary diffusion), and k is the Boltzmann's constant (8.617×10^{-5} eV/^{o}K). Eq. (1) can be rearranged by lumping certain coefficients and expressed as:

$$\frac{d\varepsilon}{dt} = C_1 \left[\sinh\left(C_2\sigma\right)\right]^{C_3} \exp\left(-\frac{C_4}{T}\right) \qquad (2)$$

where C_1, C_2, C_3, and C_4 are determined by creep tests (curves) at various sets of constant stress and temperature. It should be noted that the last equation is exactly the same as the input form of the implicit creep model (TBOPT = 8) in ANSYS. [17] In the above two equations, σ is the effective normal stress; τ is the shear stress; and $d\varepsilon/dt$ is the effective normal creep strain rate. The unit for both σ and τ is MPa.

Figures 1 and 2 show, respectively, the plots of the effective normal creep strain rate vs. the effective normal stress at 0^{o}C and 100^{o}C for the various creep constitutive equations of different SnAgCu solder alloys reported in the literature (Table 1). Significant differences exist in the predicted creep responses of the SnAgCu alloys. In this study, the focus will be on Alloy No. 1 and Alloy No. 2.

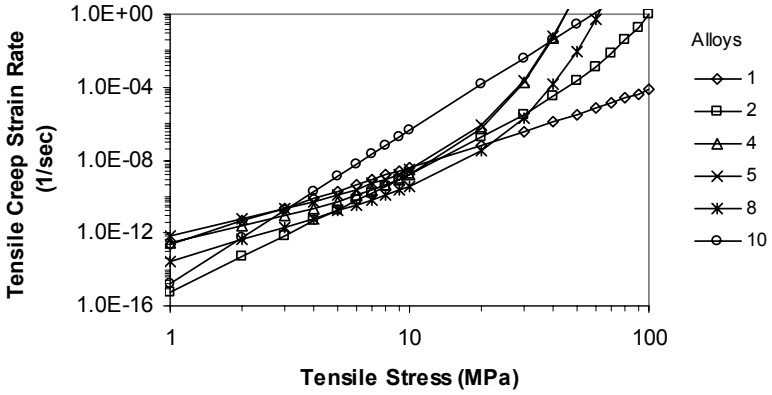

Figure 1 - Steady State Creep at 0^{o}C

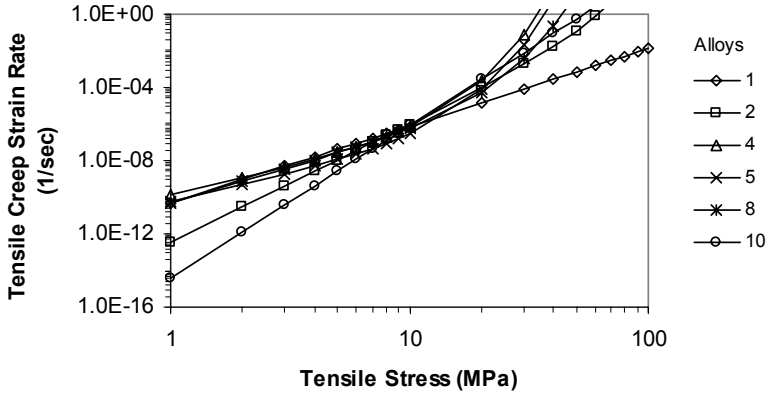

Figure 2 - Steady State Creep at 100^{o}C

Table 1 – Material Properties

Alloy No.	Alloy compositions	$E=E_0+E_1*T(C)$ (GPa)		$\alpha=\alpha_0+\alpha_1*T(C)$ (ppm/ºC)		ν	C_1 (sec^{-1}) or (sec^{-1} Mpa^{-C3})	C_2 (MPa^{-1})	C_3	C_4 (eV)	Lab	Comments
		E_0	E_1	α_0	α_1							
1	Sn-3.9Ag-0.6Cu	53	-0.08	21.301	0.017	0.34	441000	.005	4.2	0.466	Sandia	Refs 1, 2, bulk sample, compression, strain rate=$4.2x10^{-5}$, and TMA, -25ºC to 160ºC
2	Sn-3.8Ag-0.7Cu Sn-3.5Ag-0.75Cu Sn-3.5Ag-0.5Cu Castin™	45.056	-0.0574	20		0.36	277984	0.02447	6.41	0.56	Fraunhofer Institute & Dresden U. Tech.	Ref 7, various specimens types, fit to numerous researchers results, -55ºC to 150ºC
3	Sn-(3.5-3.9)Ag-(0.5-0.8)Cu	49	-0.07	21.301	0.017	0.35	500000	0.01	5	0.5	Agilent Recommended	Average of values for solder alloys in 1 and 2
4	Sn-3.8Ag-0.7Cu						~0.5	0.1878	3.07	0.545	Fraunhofer Institute & Dresden U. Tech.	Ref 6, bulk, tension, C_1 obtained by inspection, 23ºC to 150ºC
5	Sn-3.8Ag-1Cu						0.0026	0.185	3	0.401	Fraunhofer Institute & Dresden U. Tech.	Ref 8, bulk, tension, 20ºC to 180ºC
6	Sn-3.8Ag-0.7Cu			14.9	0.018						Fraunhofer Institute & Dresden U. Tech.	Ref 8, bulk, TMA, 20ºC to 150ºC, calculated at 100ºC and 150ºC
7	Sn-4Ag-0.5Cu	41.75	-0.075				$2 x10^{-21}$	1	18	0.861	Fraunhofer Institute & Dresden U. Tech.	Ref 9, flip chip bumps, shear, 5ºC and 50ºC
8	Sn-3.9Ag-0.6Cu	18.596	-0.0206				143.41	0.10854	3.7884	0.652	CALCE	Ref 3, thin disk, shear, 25ºC, 75ºC, 125ºC
9	Sn-3.8Ag-0.7Cu	56.571	-0.25								Nanyang Tech. U.	Ref 4, bulk-dog bone, tension, bulk, 25ºC, 75ºC, 125ºC, strain rate=$5.6x10^{-3}$ /sec
10	Sn-4Ag-0.5Cu						$2.474 x10^{-14}$	-	8.36	0.062	Ford	Ref 5, shear, 40ºC to 140ºC
11	Sn-3Ag-0.5Cu							6.6 to 10.7		0.776 to 0.983	U.C. Berkley/Intel	Refs 10, 11, BGA-like, 60ºC to 130ºC, anomalous creep behavior
12	Sn-3Ag-0.5Cu	54									Nagaoka U.	Ref 12, bulk–ASTM E606, tension, strain rate=$4x10^{-2}$ /sec, 20ºC
13	Sn-3.9Ag-0.6Cu					0.34					NIST/Sandia	Ref 13
14	Sn-Pb	34.4	-0.152	24.5			926(508-T(K))/T(K)	1/(37.8-.07*T(K)	3.3	0.548		Ref 14
15	Sn	44.3		21.743	0.0139	0.33					Textbook Sn	Refs 15, 16

Based on 32 samples, Vianco, et al.,[1, 2] obtained the creep constitutive equation for the Sn3.9Ag0.6%Cu solder alloy (Alloy No. 1 in Table 1). In,[7] Schubert and his colleagues, based on 108 measurement data, obtained a new creep constitutive equation for the Sn3.8Ag0.7Cu, Sn-3.5Ag0.75Cu, Sn-3.5Ag0.75Cu and Castin™ alloys. These two equations are plotted in Figure 3. It can be seen that for the temperatures (-25ºC, 50ºC, and 125ºC), Sandia's data tend to predict faster creep rates at lower stresses and slower creep rates at higher stresses. Averaging the values of these two sets of data at different temperatures leads to a new creep constitutive equation, called Alloy No. 3, as shown in Figure 3 and described in Table 1.

Figure 4 details the normal creep rates for Alloy No. 3 and SnPb solder at -25ºC, 50ºC, and 125ºC. It can be seen that the creep strain rate difference between the lead-free solder and the SnPb solder is temperature dependent, and that the higher the temperatures are associated with faster creep strain rates. For a given stress level, the creep strain rates of the lead-free solders are lower than that of the SnPb for most all the temperatures. For example, at temperatures greater than or equal to 50°C, the lead-free solders have a creep rate that is one-half to two orders of magnitude lower than that of the SnPb solder at the given stress level. Hence, significantly lower creep strains are expected with the SnAgCu solders in comparison with the SnPb solder.

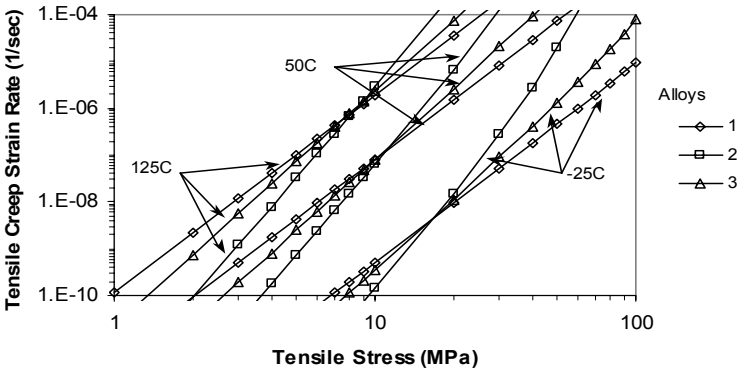

Figure 3 – Selected Creep Responses (Alloys 1, 2 and 3)

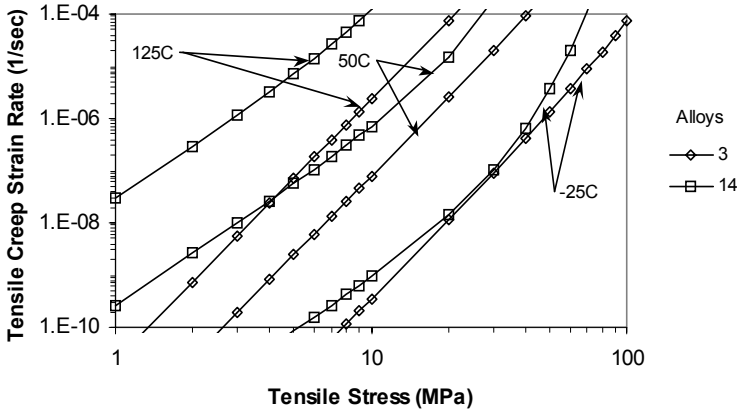

Figure 4 – Selected Creep Responses (alloy 3 vs Sn-Pb)

The Sn-4Ag-0.5Cu (Alloy No. 10) is modeled with the Norton equation (power law) by Pao, et.al.,[15, 16] as follow:

$$\frac{\partial \varepsilon}{\partial t} = C_1 \sigma^{C_3} \exp\left(\frac{-C_4}{T}\right)$$

where the values of C_1, C_3, C_4 are presented in Table 2[5, 16] and they are the inputs for ANSYS.[15] The unit for σ is MPa, C_1 is $sec^{-1}MPa^{-C3}$, and C_4 is eV.

Table 2 - Properties of the 256 PBGA Assembly

Component	E (GPa)	α (ppm/°C)	ν	C_1 (sec^{-1})	C_2 (MPa^{-1})	C_3	C_4 (eV)
PC board	27	18	0.39	-	-	-	-
Copper pads	76	17	0.35	-	-	-	-
Laminate substrate	27	18	0.39	-	-	-	-
Die	167	2.54	0.28	-	-	-	-
Overmold	13	15	0.3	-	-	-	-
Alloy 1	49-0.07T	21.301+0.017T	0.35	441000	.005	4.2	0.466
Alloy 2	49-0.07T	21.301+0.017T	0.35	277984	0.02447	6.41	0.56
Alloy 3	49-0.07T	21.301+0.017T	0.35	500000	0.01	5	0.5

Note: All temperatures are in °C

Figure 5 shows the Young's modulus vs. temperature plots of the lead-free solders reported in the literature. Again, it can be seen that data are quite varied. The closest data are Alloy No. 1 and Alloy No. 2. By taking the average of these two sets of data, the modulus of the proposed Alloy No. 3 is obtained.

The Young's modulus of SnPb solder is also plotted in Figure 5. It can be seen that the Young's modulus of the lead-free solders is larger than that of the SnPb solder. Thus, when like PC board-components assemblies are subjected to thermal cycling loadings, the stresses in the lead-free solder joints are expected to be higher than those in the SnPb solder joints.

The coefficients of thermal expansion (CTE) of various lead-free solders reported in literature are shown in Figure 6. Since most of the data agree with Sandia's data, this value chosen for Alloy No. 3.

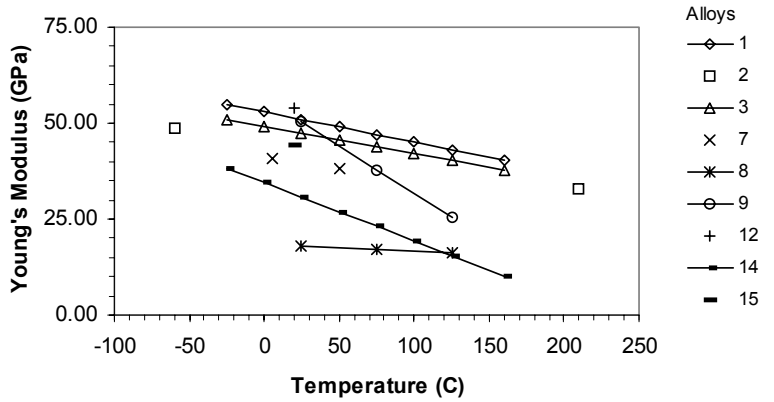

Figure 5 - Young's Modulus

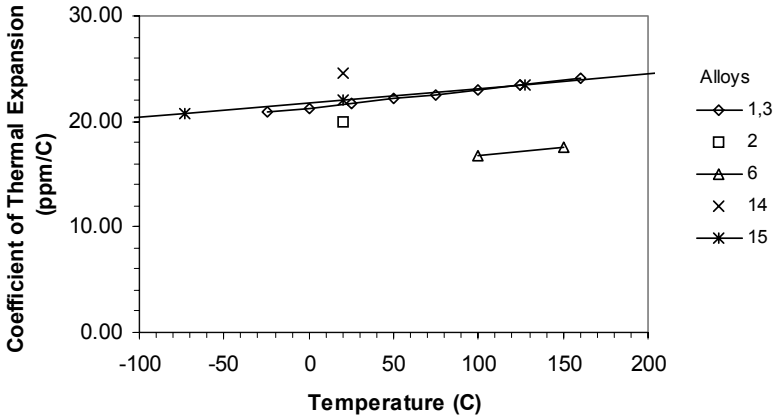

Figure 6 – The Coefficient of Thermal Expansion

Creep Analyses and Results of an 256PBGA Assembly

Figure 7 shows the x-ray image of a 256-pin PBGA package on PCB with lead-free solder balls and paste assembly. The BT (bismaleimide triazene) substrate is 0.36mm thick with a 12.5x12.5x 0.3mm silicon IC chip and a 1.17mm thick overmold. The package has 0.635mm diameter pads (with a pitch of 1.27mm) on the substrate and the assembled lead-free (95.5wt%Sn-3.9wt percent Ag-0.6wt percent Cu) solder joints are assumed to have a height of 0.5mm and a maximum diameter of 0.9mm. The PCB thickness is 1.6mm and the pad diameter is 0.635mm.

Figures 8 and 9 show the 3-D finite element model that captures the construction along a diagonal strip from the 256-pin PBGA lead-free assembly's geometric center to a corner. Because of the mid-plane symmetry, the mesh actually models a one-half strip (with one-half of a solder joint) using the appropriate in-plane constraints placed on one symmetry plane. Coupled in-plane translations are applied to the other symmetry plane to produce a state of generalized plane strain. Using exclusively hexahedral solid elements, the model can capture the precise shape of the packages' solder joints and potential DNP (distance to neutral point) effects while retaining significant computational efficiency over full octant models. ANSYS is the code selected for the modeling and analyses.

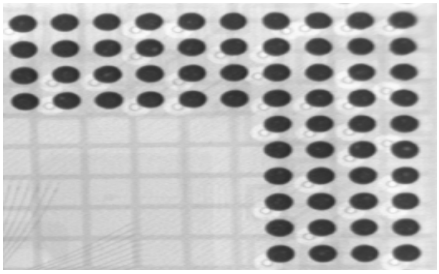

Figure 7 – X-ray Image of One Quarter of a 256-pin PBGA PCB Assembly

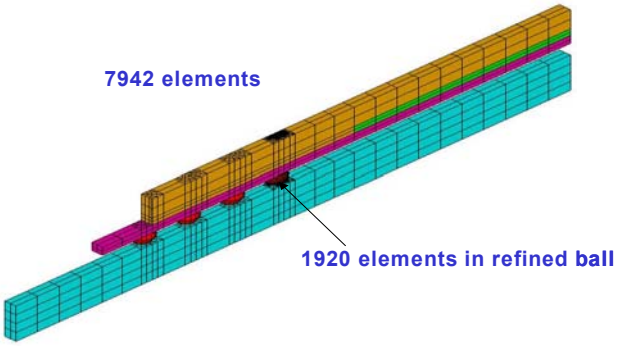

Figure 8 – Finite Element Model of the 256 PBGA

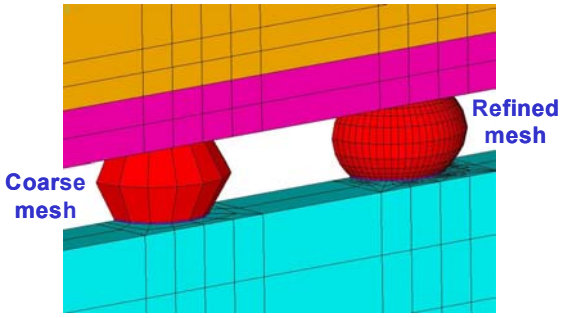

Figure 9 – Details of the Refined and Coarse Ball Meshes in the PBGA Package

Figure 10 shows the temperature profile to be imposed on the PBGA assembly. It can be seen that the loading condition is: 0 ↔ 100°C. The cycle time is 40 minutes and the ramp-up, ramp-down, dwell-at-hot, and dwell-at-cold are each 10 minutes. Five thermal cycles are executed. The analysis is performed with the appropriate constitutive relations for each of the solder alloys 1 – 3. Material properties are presented in Table 2.

The maximum creep shear strain and shear stress time histories in the 256PBGA solder joint with these material models are shown in Figures 11 and 12, respectively. It can be seen that: (1) the creep shear strain range predicted by Schubert, et.al.,[7] is larger than that by Vianco, et.al.,[1, 2] (2) however, the shear stress range predicted by Schubert et.al.,[7] is smaller than that by Vianco, et.al.,[1, 2] and (3) as expected, the values of creep strain and stress predicted by the present material model are near the mid-values of Schubert's and Vianco's.

It is important to study the creep responses for multiple cycles by observing when the hysteresis loops become stabilized. Figure 13 show the shear stress and shear creep strain hysteresis loops for multiple cycles at the critical solder joint with the Alloy No. 3 material model. It can be seen that the creep shear strain vs. shear stress loop is quite stabilized after the fourth temperature cycle. The response shown in Figure 13 is typical of Alloys 1 and 2 also. Figure 14 shows the hysteresis loops at the critical solder joint for the 5th thermal cycles and Alloys 1 – 3. From the Figure: (1) the area within the loop (strain energy density per cycle) predicted by Schubert, et.al.,[7] is larger than that by Vianco, et.al.,[1, 2] and (2) the area predicted by the present material model is between those by Schubert and Vianco. Figure 15 shows the creep strain energy density time history with these three different material models.

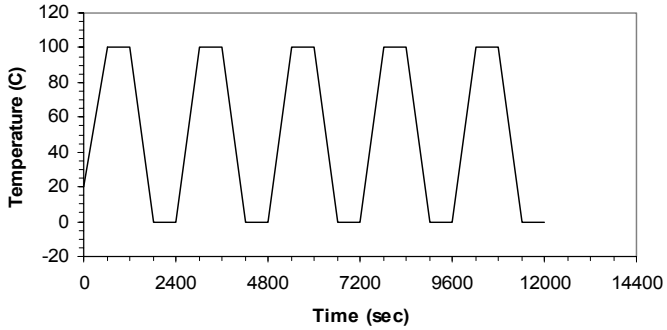

Figure 10 – The Time Temperature Profile

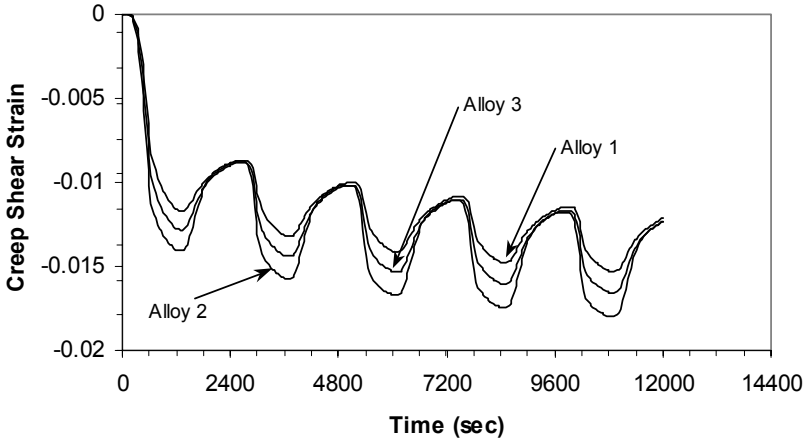

Figure 11 – The Maximum Creep Shear Strain in the 256 PBGA with Select Creep Constitutive Models

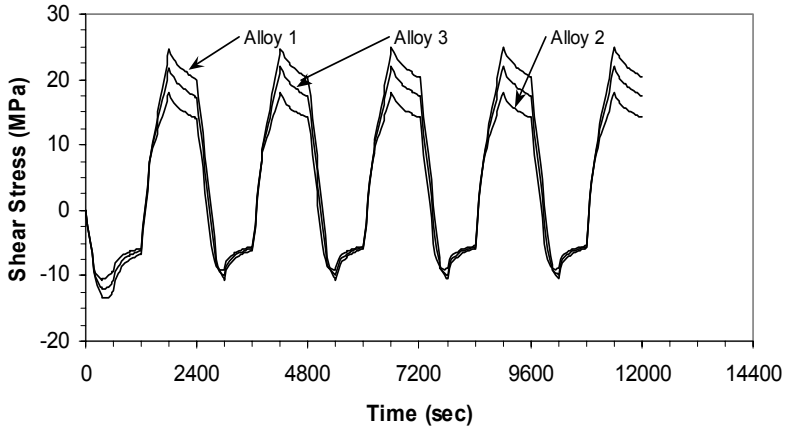

Figure 12 – The Maximum Shear Stress in the 256 PBGA with Select Creep Constitutive Models

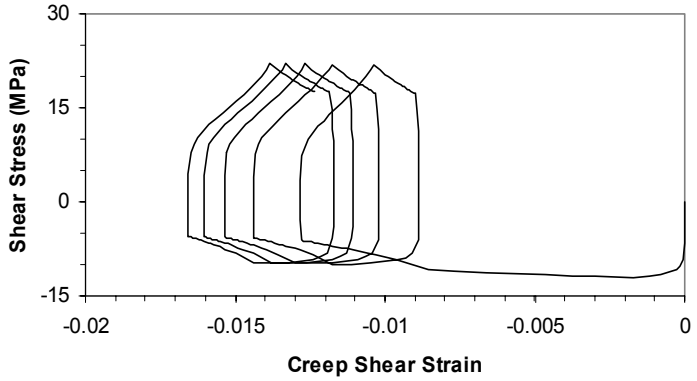

Figure 13 – Typical Hysteresis Response with the Agilent Recommended Properties

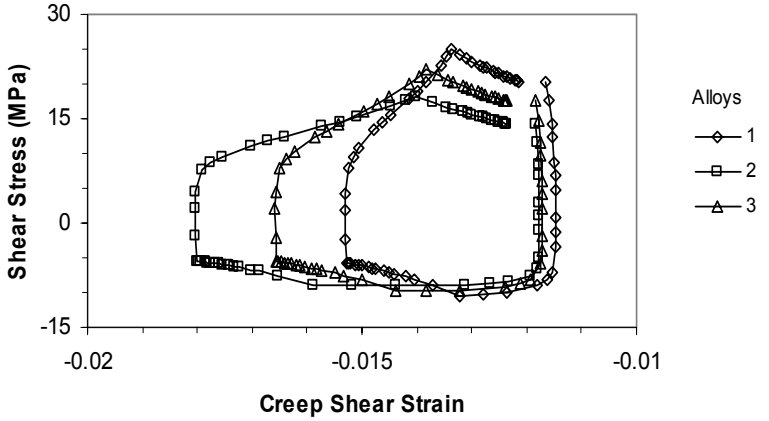

Figure 14 – The Hysteresis Loops for the 256 PBGA with Select Constitutive Models During the 5th Thermal Cycle

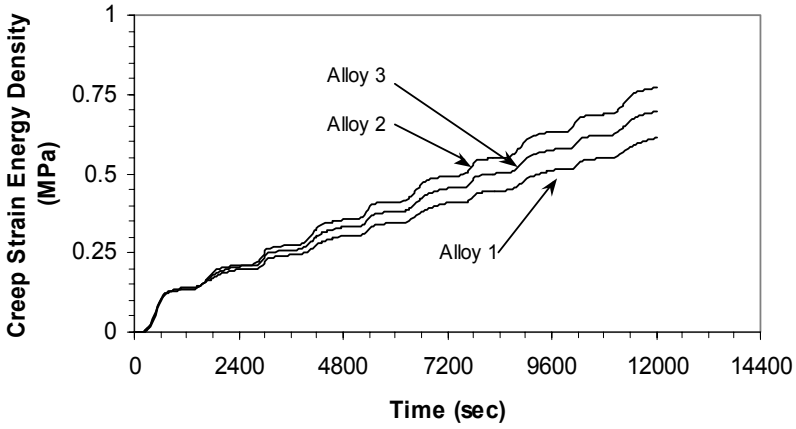

Figure 15 – The Creep Stain Energy Density for Select Constitutive Models and the 256 PBGA

Thermal-Fatigue Life Prediction of Lead-Free Solder Joints

Based on a material constitutive model, the creep strain energy density per cycle (ΔW) can be determined by the area within one of the hysteresis loops (after the fourth temperature cycle). Thermal fatigue life of solder joints (dominated by creep responses) may be predicted by the following equation.

$$N_f = \psi(\Delta W)^{\varphi}$$

where N_f is the number of cycle to failure, ΔW is the creep strain energy density per cycle, and ψ (always positive) and φ (always negative) are constants for the solder joints. In this equation, ΔW can be determined by creep analysis of the structure (IC package, solder joints, and PCB) subjected to the specified loading conditions. The preceeding finite element analysis captures ΔW. However, ψ and φ are usually determined by isothermal fatigue tests of the real solder-joint. Since the constants for the lead-free PBGA solder joints are not available at this moment, thermal fatigue life prediction of the 256-pin PBGA lead-free solder joints is impossible. Thus fatigue crack-growth constants (which can be determined by isothermal fatigue tests) for the lead-free PBGA solder joints are desperately needed in order to make quantitative solder-joint thermal-fatigue life predictions of PBGA package family for any loading conditions. These will be presented at the IEEE ECTC.[18]

Summary and Recommendations

Based on the data by Schubert, et al.,[7] and Vianco, et al.,[1, 2] a new set of constitutive equations has been proposed for Sn(3.5-3.9)wt%Ag(0.5-0.8)wt%Cu lead-free solder alloys. The creep responses of 256PBGA solder joints have been obtained with the proposed equations and compared with those from[7] and.[1, 2] Some important results are summarized in the following:

- For all the temperatures, comparing with Schubert's data, Vianco's data tend to predict faster creep rates at lower stresses and slower creep rates at higher stresses.
- Comparing with Schubert's data, Vianco's data predicts a larger Young's modulus.
- The creep shear strain range in the critical solder joint of the 256PBGA assembly predicted by Schubert's material model is larger than that by Vianco's.
- The shear stress range in the critical solder joint of the 256PBGA assembly predicted by Schubert's material model is smaller than that using Vianco's model.
- As expected, the responses predicted by the present material model, Alloy No. 3, are between those using the Vianco and Schubert models, since Alloy No. 3 is obtained by averaging theirs.
- The isothermal fatigue test data of real solder joints are desperately needed in order to make quantitative solder-joint thermal-fatigue life prediction.

Acknowledgements

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18. Lau, J. H., R. Lee, D. Shangguan, "Isothermal Fatigue Test of wafer-Level Chip Scale Package (WLCSP) and Plastic Ball Grid Array (PBGA) Lead-Free Solder Joints on Printed Circuit Board (PCB) with Immersion Silver (ImAg) Surface Finish", to be published in the *IEEE Electronic Components and Technology Conference Proceedings*, Las Vegas, June 2004.

Creep of Sn(3.5-3.9)wt%Ag(0.5-0.8)wt%Cu Lead-Free Solder Alloys and Their Solder Joint Reliability

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IPC APEX, Anaheim, CA, February 24-26, 2004

PURPOSE

To propose a new set of constitutive equations for the leading lead-free solder alloys,

Sn(3.5-3.9)wt%Ag(0.5-.8)wt%Cu

CONTENTS

Lead-Free's Most Technical Concern

Currently,
SnPb solders [MP (melting Point) ~ 183°C)

For the leading lead-free soldering,
SnAgCu solders (MP ~ 217°C)

Thus, the components and PCB will be subjected to higher temperatures during leadfree soldering and their reliability is of great concern! Also, leadfree solder joint reliability data are lacking.

Lead-Free Critical Issues

- Overall costs increase
- Impact of PCB finishes
- Impact of component finishes
- Forward in-compatibility
- Backward in-compatibility
- Component reliability
- PCB reliability
- Impact of multiple heat cycles
- Tin whisker (short) reliability risk
- **Solder joint reliability – thermal & mechanical**
- Solder joint reliability – Shock & Vibration
- Solder joint reliability – electromigration
- Reliability tests and acceleration factors
- Electrochemical reliability
- Infrastructure

Garofalo-Arrhenius Creep Constitutive Equations:

$$\frac{dg}{dt} = C\left(\frac{G}{\Theta}\right)\left[\sinh\left(w\frac{t}{G}\right)\right]^n \exp\left(-\frac{Q}{k\Theta}\right) \quad \text{or} \quad \frac{\partial e}{\partial t} = C_1\left[\sinh\left(C_2 s\right)\right]^{C_3} \exp\left(\frac{-C_4}{T}\right)$$

g is the creep shear strain,
dg/dt is the creep shear strain rate,
t is the time,
C is a material constant,
G is the temperature-dependent shear modulus,
Q is the absolute temperature (^{o}K),
w defines the stress level at which the power law stress dependence breaks down,
t is the shear stress,
n is the stress exponent,
Q is the activation energy for a specific diffusion mechanism,
k is the Boltzmann's constant (8.617×10^{-5} eV/^{o}K).
s and e are the uniaxial stress and strain
C_1, C_2, C_3, and C_4 are the input constants for ANSYS

Constitutive Equations of SnAgCu Lead-Free Solder Family

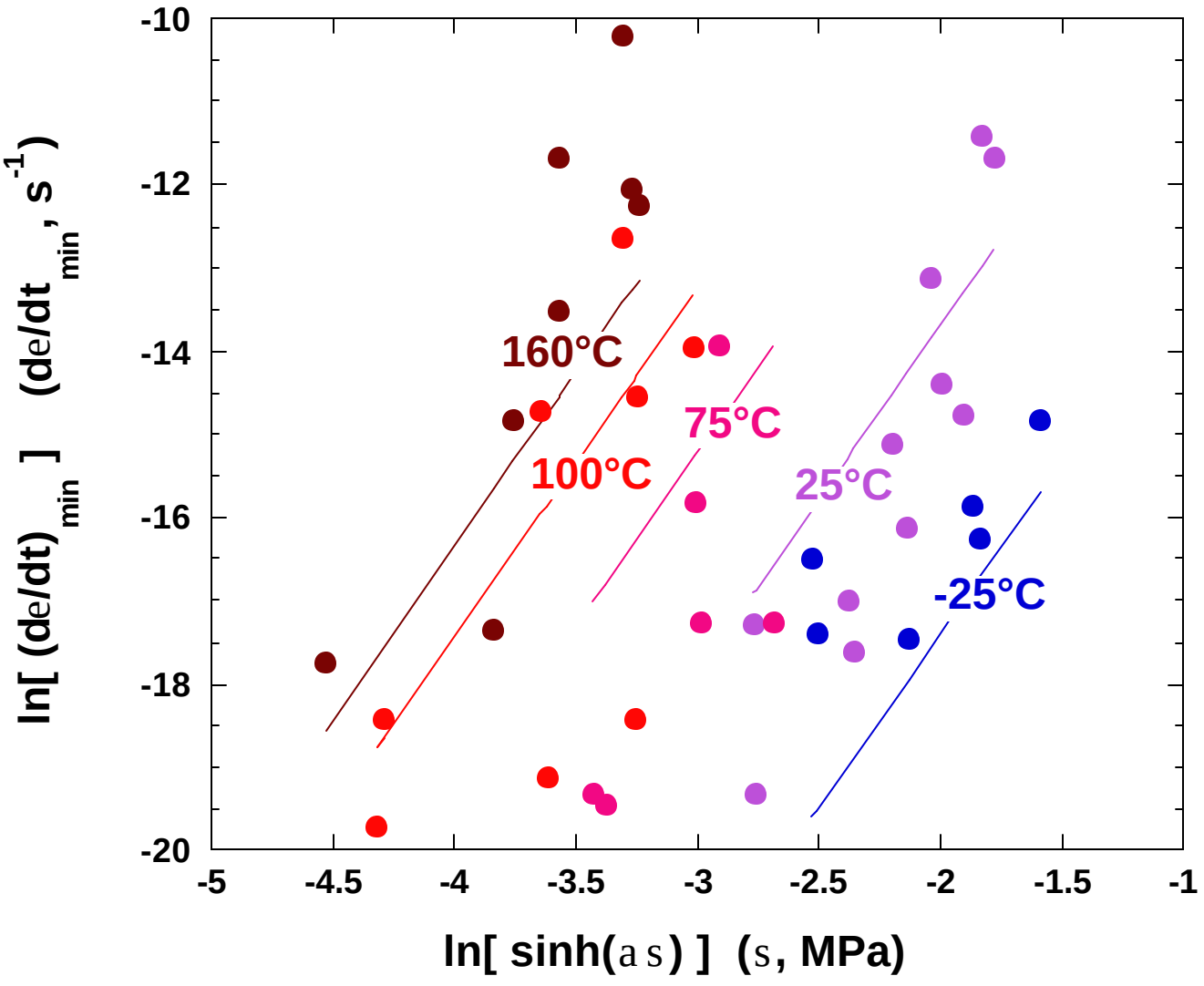
Lau, J., W. Dauksher, and P. Vianco, "Acceleration Models, Constitutive Equations and Reliability of Lead-Free Solders and Joints," *IEEE Electronic Components and Technology Conference Proceedings*, New Orleans, Louisiana, June 2003, pp. 229-236.

Viance, P., J. Rejent, and A. Kilgo, "Creep Behavior of the Ternary 95.5Sn-3.9Ag-0.6Cu Solder: Part I – As-Cast Condition", sent to *Journal of Electronics Material* for publication.

Schubert, A., R. Dudek, H. Walter, E. Jung, A. Gollhardt, B. Michel, and H. Reichl, 2002, "Reliability Assessment of Flip-Chip Assemblies with Lead-Free Solder Alloys," *IEEE Electronic Components and Technology Conference Proceedings*, San Diego, CA, May 2002, pp. 1246-1255.

Schubert, A., R. Dudek, E. Auerswald, A. Gollhardt, B. Michel, and H. Reichl, "Fatigue Life Models for SnAgCu and SnPb Solder Joints Evaluated by Experiments and Simulation," *IEEE Electronic Components and Technology Conference Proceedings*, New Orleans, Louisiana, June 2003, pp. 603-610.

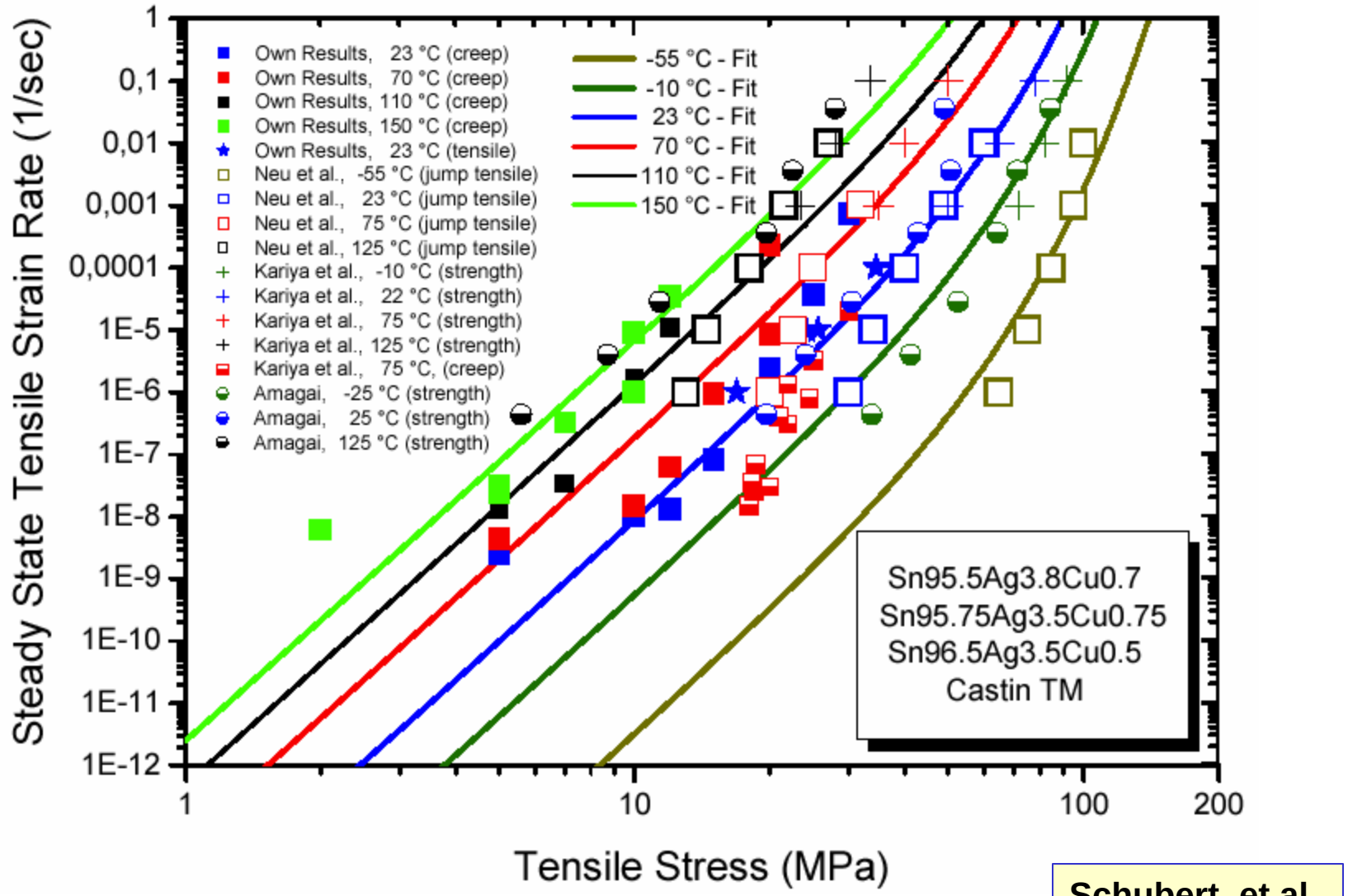
95.5Sn-3.9Ag-0.6Cu Creep Test Data



Sandia

Lau, Dauksher, and Vianco, "Acceleration Models, Constitutive Equations, and Reliability of Lead-Free Solders And Joints", *IEEE Electronic Components and Technology Conference*, June 2003, pp. 229-234.

Creep of SnAgCu Solders Based on 108 Data Points (IZM)



Schubert, et.al.

Lead-Free Solder Creep Constitutive Equation

Solder alloys	C_1 (1/sec)	C_2 (1/Pa)	C_3	C_4 (°K)
95.5Sn-3.9Ag-0.6Cu	441000	5×10^{-9}	4.2	5412
63Sn-37Pb	926(508 - T)/T	1/(37.78x106 - 74414T)	3.3	6360
IZM's LF	277984	24.47×10^{-9}	6.41	6504

$$\frac{\partial e}{\partial t} = C_1 [\sinh(C_2 s)]^{C_3} \exp\left(\frac{-C_4}{T}\right)$$

C_1 , C_2, C_3, C_4 are the input constants for ANSYS finite element program. The stress unit is Pa.

Lau, Dauksher, and Vianco, "Acceleration Models, Constitutive Equations, and Reliability of Lead-Free Solders And Joints", *IEEE Electronic Components and Technology Conference*, June 2003, pp. 229-234.

Schubert, A., R. Dudek, H. Walter, E. Jung, A. Gollhardt, B. Michel, and H. Reichl, 2002, "Reliability Assessment of Flip-Chip Assemblies with Lead-Free Solder Alloys," *IEEE Electronic Components and Technology Conference Proceedings*, San Diego, CA, May 2002, pp. 1246-1255.

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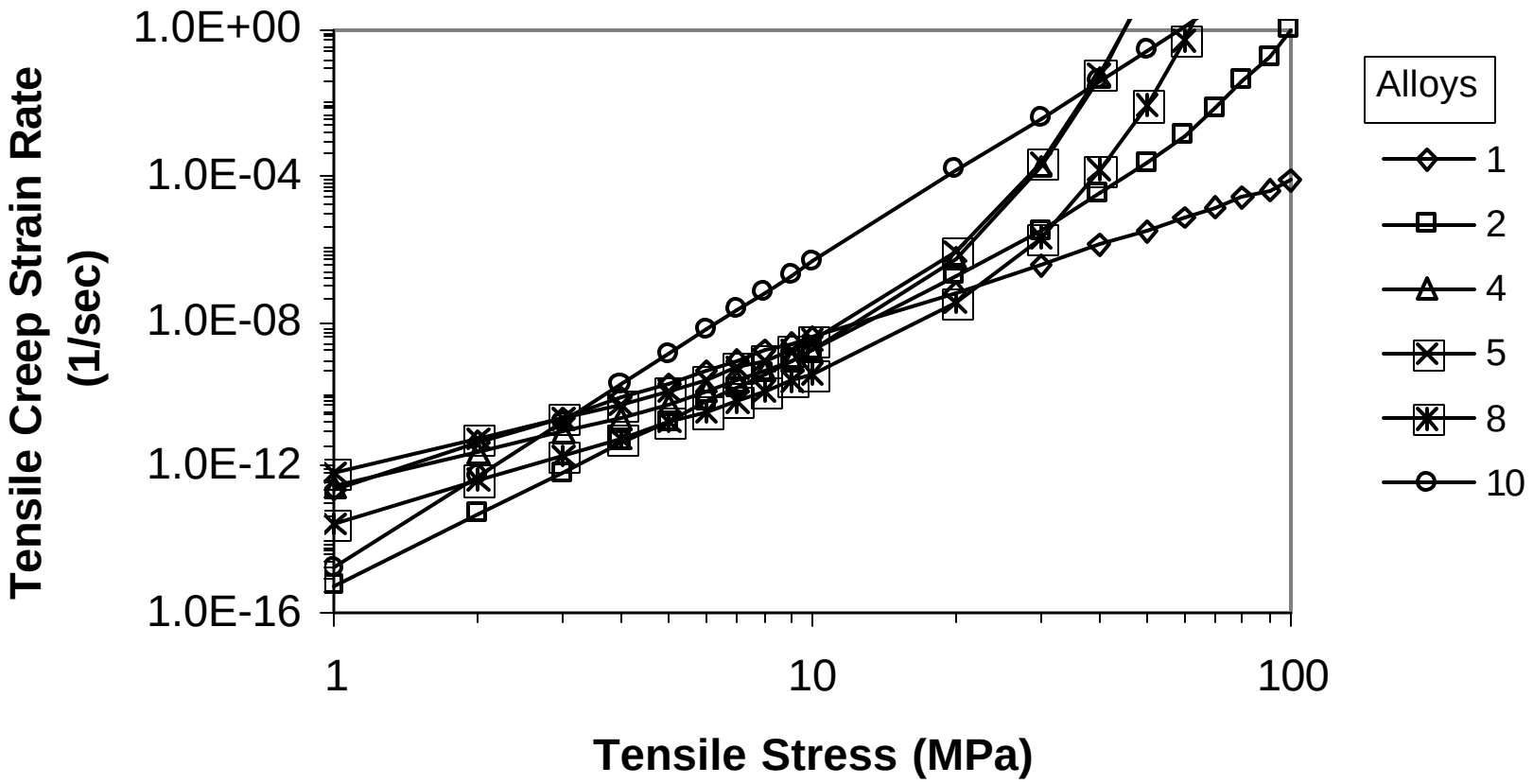
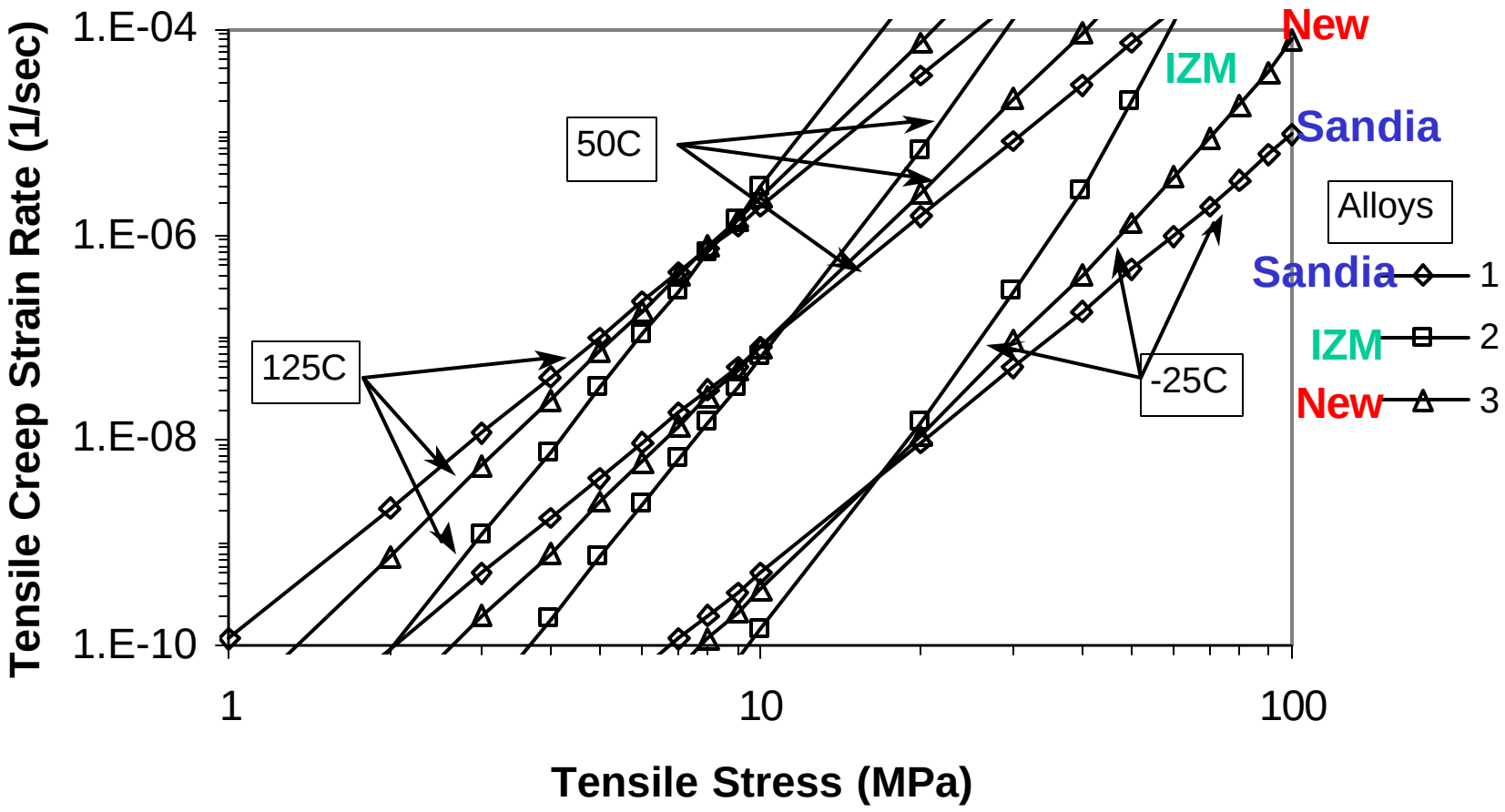
Table 1 – Material properties

Alloy No.	Alloy compositions	$E=E_0+E_1*T(C)$ (GPa)		$\alpha=\alpha_0+\alpha_1*T(C)$ (ppm/ºC)		ν	C_1 (sec^{-1}) or (sec^{-1} Mpa^{-C3})	C_2 (MPa^{-1})	C_3	C_4 (eV)	Lab	Comments
		E_0	E_1	α_0	α_1							
1	Sn-3.9Ag-0.6Cu	53	-0.08	21.301	0.017	0.34	441000	.005	4.2	0.466	Sandia	Refs 1, 2, bulk sample, compression, strain rate=$4.2x10^{-5}$, and TMA, -25ºC to 160ºC
2	Sn-3.8Ag-0.7Cu Sn-3.5Ag-0.75Cu Sn-3.5Ag-0.5Cu Castin™	45.056	-0.0574	20		0.36	277984	0.02447	6.41	0.56	Fraunhofer Institute & Dresden U. Tech.	Ref 7, various specimens types, fit to numerous researchers results, -55ºC to 150ºC
3	Sn-(3.5-3.9)Ag-(0.5-0.8)Cu	49	-0.07	21.301	0.017	0.35	500000	0.01	5	0.5	Agilent Recommended	Average of values for solder alloys in 1 and 2
4	Sn-3.8Ag-0.7Cu						~0.5	0.1878	3.07	0.545	Fraunhofer Institute & Dresden U. Tech.	Ref 6, bulk, tension, C_1 obtained by inspection, 23ºC to 150ºC
5	Sn-3.8Ag-1Cu						0.0026	0.185	3	0.401	Fraunhofer Institute & Dresden U. Tech.	Ref 8, bulk, tension, 20ºC to 180ºC
6	Sn-3.8Ag-0.7Cu			14.9	0.018						Fraunhofer Institute & Dresden U. Tech.	Ref 8, bulk, TMA, 20ºC to 150ºC, calculated at 100ºC and 150ºC
7	Sn-4Ag-0.5Cu	41.75	-0.075				$2 x10^{-21}$	1	18	0.861	Fraunhofer Institute & Dresden U. Tech.	Ref 9, flip chip bumps, shear, 5ºC and 50ºC
8	Sn-3.9Ag-0.6Cu	18.596	-0.0206				143.41	0.10854	3.7884	0.652	CALCE	Ref 3, thin disk, shear, 25ºC, 75ºC, 125ºC
9	Sn-3.8Ag-0.7Cu	56.571	-0.25								Nanyang Tech. U.	Ref 4, bulk-dog bone, tension, bulk, 25ºC, 75ºC, 125ºC, strain rate=$5.6x10^{-3}$ /sec
10	Sn-4Ag-0.5Cu						$2.474 x10^{-14}$	-	8.36	0.062	Ford	Ref 5, shear, 40ºC to 140ºC
11	Sn-3Ag-0.5Cu							6.6 to 10.7		0.776 to 0.983	U.C. Berkley/Intel	Refs 10, 11, BGA-like, 60ºC to 130ºC, anomalous creep behavior
12	Sn-3Ag-0.5Cu	54									Nagaoka U.	Ref 12, bulk–ASTM E606, tension, strain rate=$4x10^{-2}$ /sec, 20ºC
13	Sn-3.9Ag-0.6Cu					0.34					NIST/Sandia	Ref 13
14	Sn-Pb	34.4	-0.152	24.5			926(508-T(K))/T(K)	1/(37.8-.07*T(K)	3.3	0.548		Ref 14
15	Sn	44.3		21.743	0.0139	0.33					Textbook Sn	Refs 15, 16

Creep Rate vs. Stress of Lead-Free Solders (0ºC)



New Creep Equation (from the Average of Sandia and IZM Creep Equations)



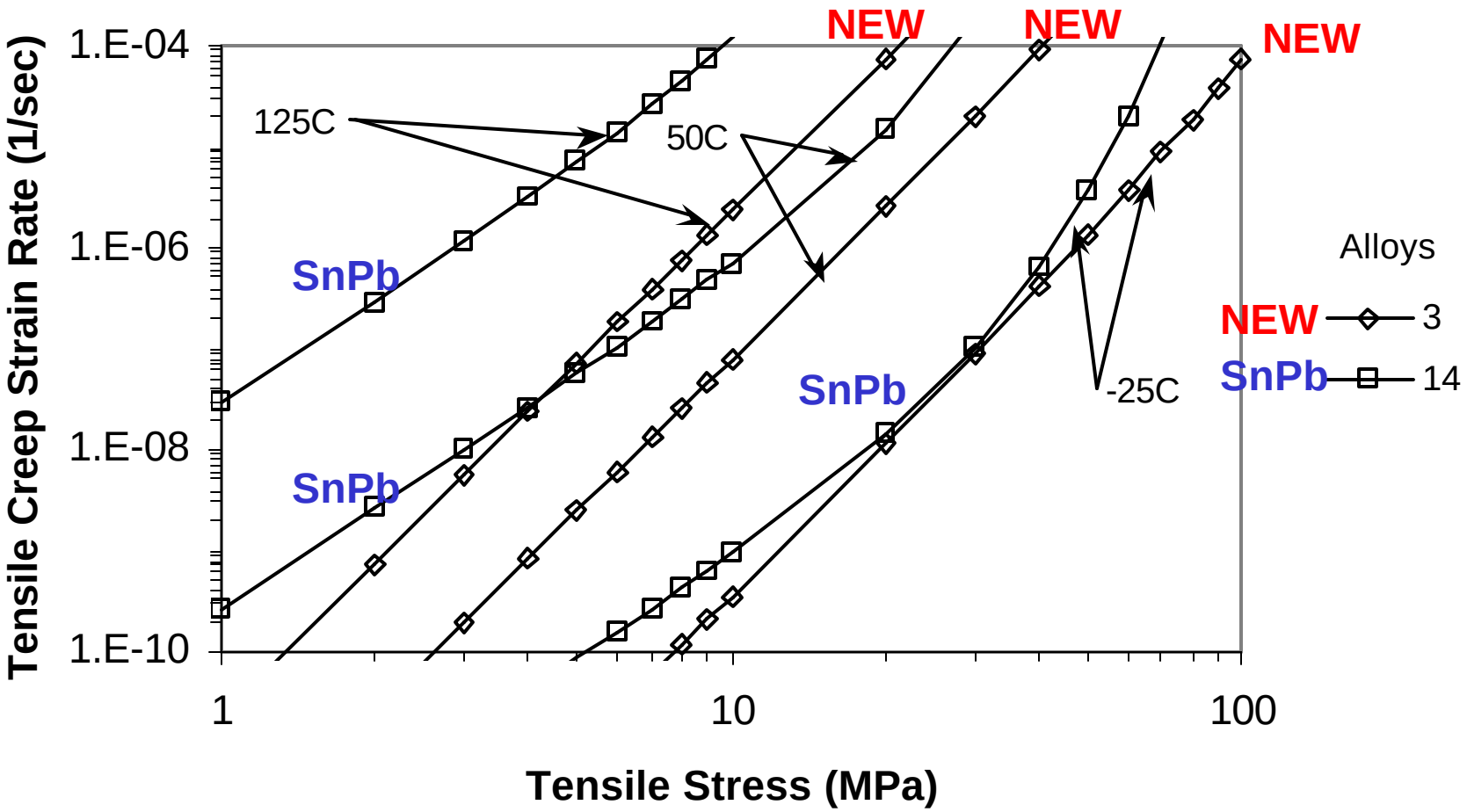
Lead-Free Solder Creep Constitutive Equation

Solder alloys	C_1 (1/sec)	C_2 (1/Pa)	C_3	C_4 (°K)
95.5Sn-3.9Ag-0.6Cu	441000	5×10^{-9}	4.2	5412
Sn(3.5-3.9)Ag(.5-.8)Cu	500000	10×10^{-9}	5.0	5807
Fraunhofer's LF	277984	24.47×10^{-9}	6.41	6504

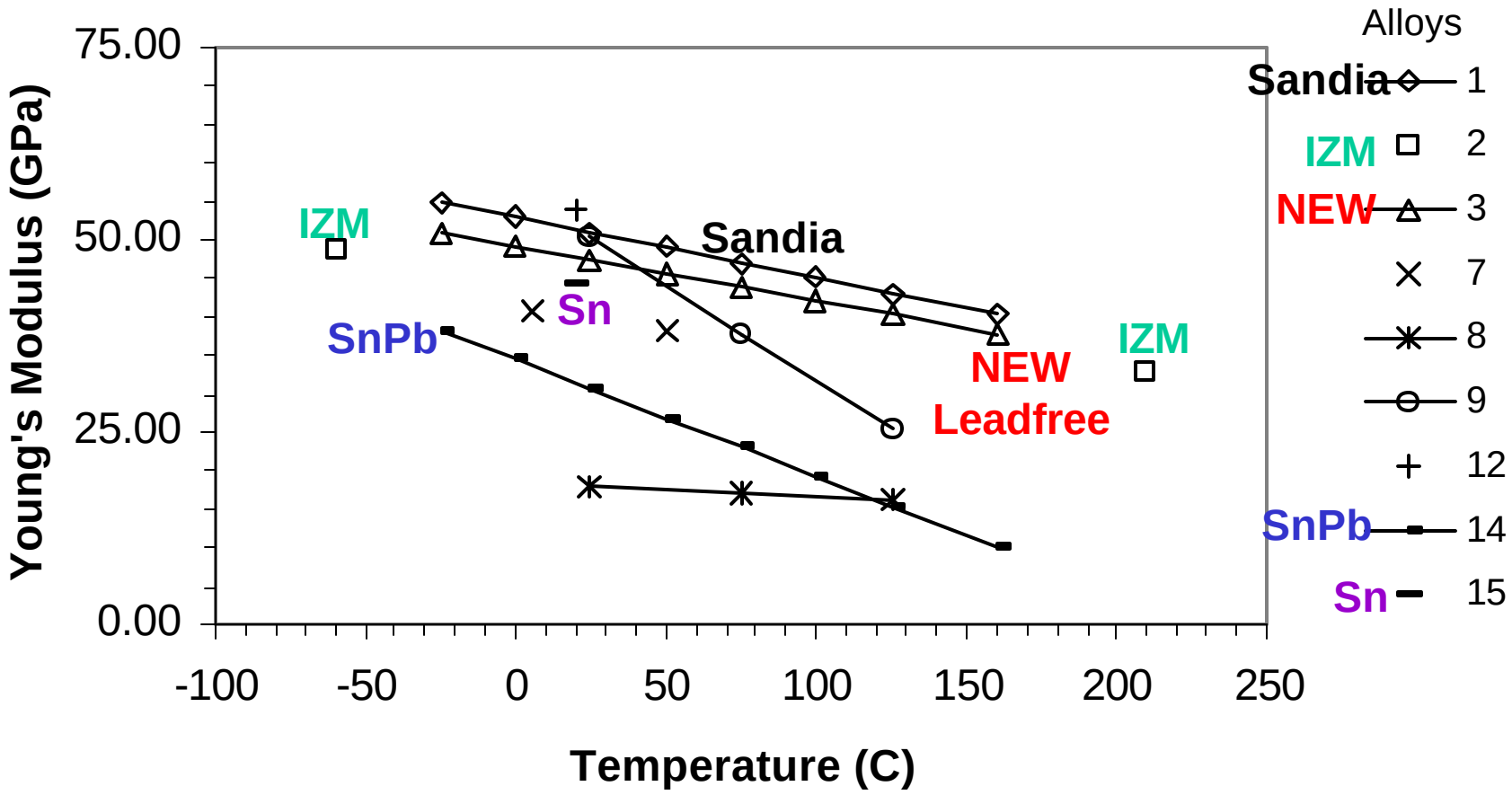
$$\frac{\partial e}{\partial t} = C_1 [\sinh(C_2 s)]^{C_3} \exp\left(\frac{-C_4}{T}\right)$$

C_1 , C_2, C_3, C_4 are the input constants for ANSYS finite element program. The stress unit is Pa.

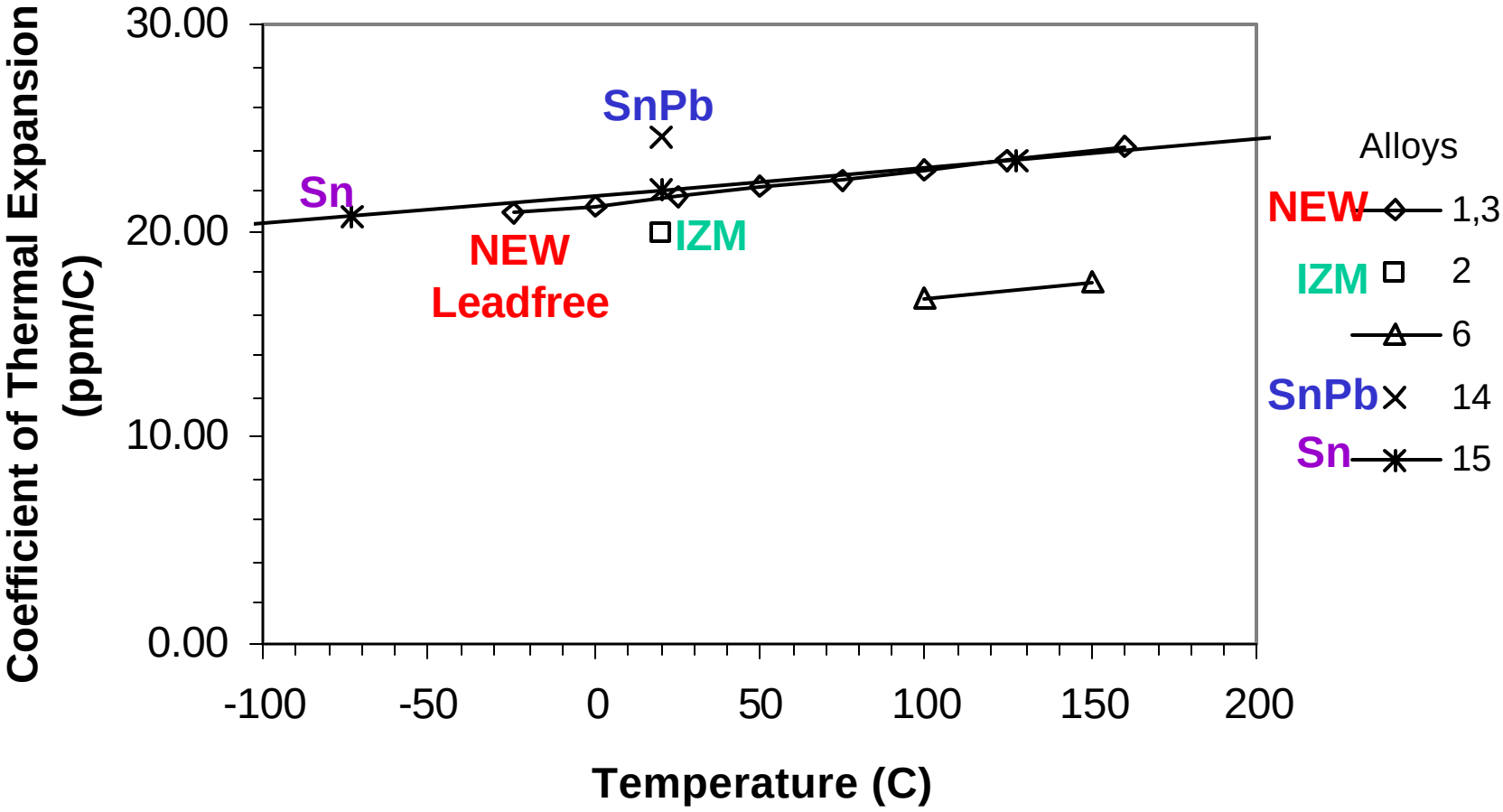
New Sn(3.5-3.9)Ag(.5-.8)Cu Creep Equation vs. Sn37Pb Creep Equation



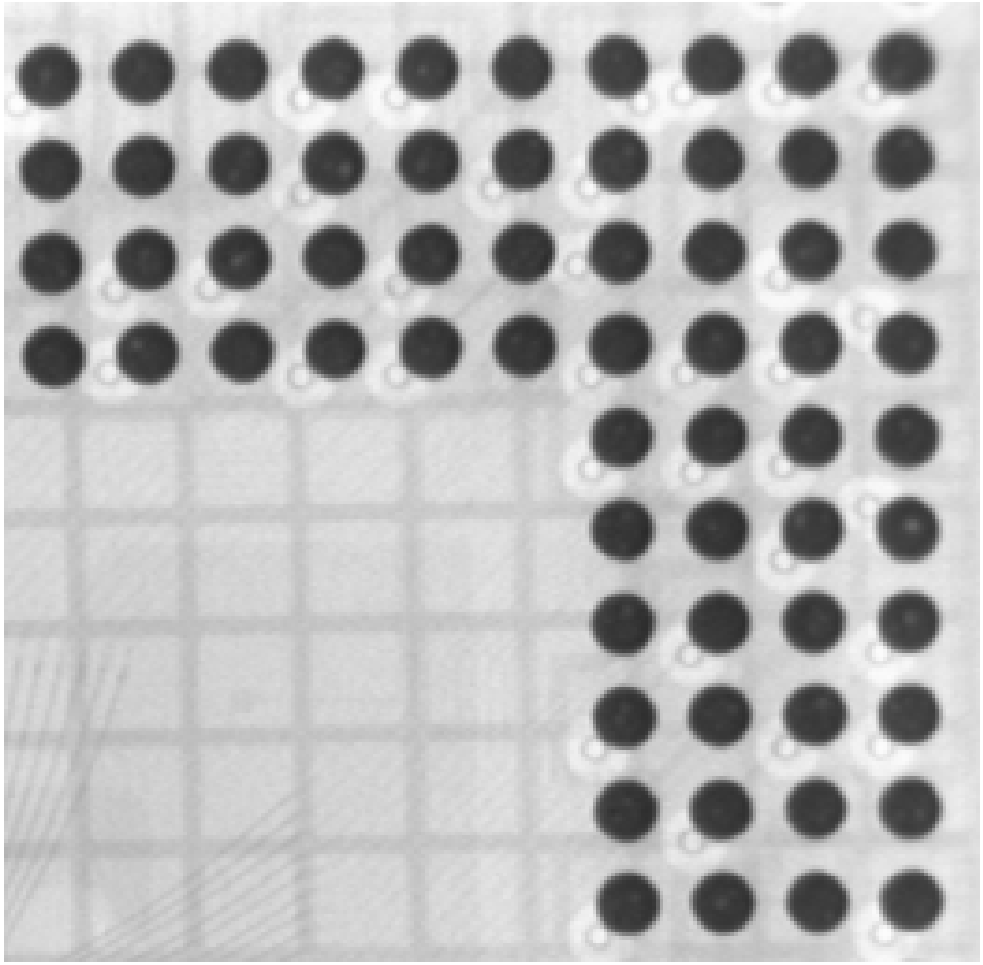
Young's Modulus of Lead-Free Solders



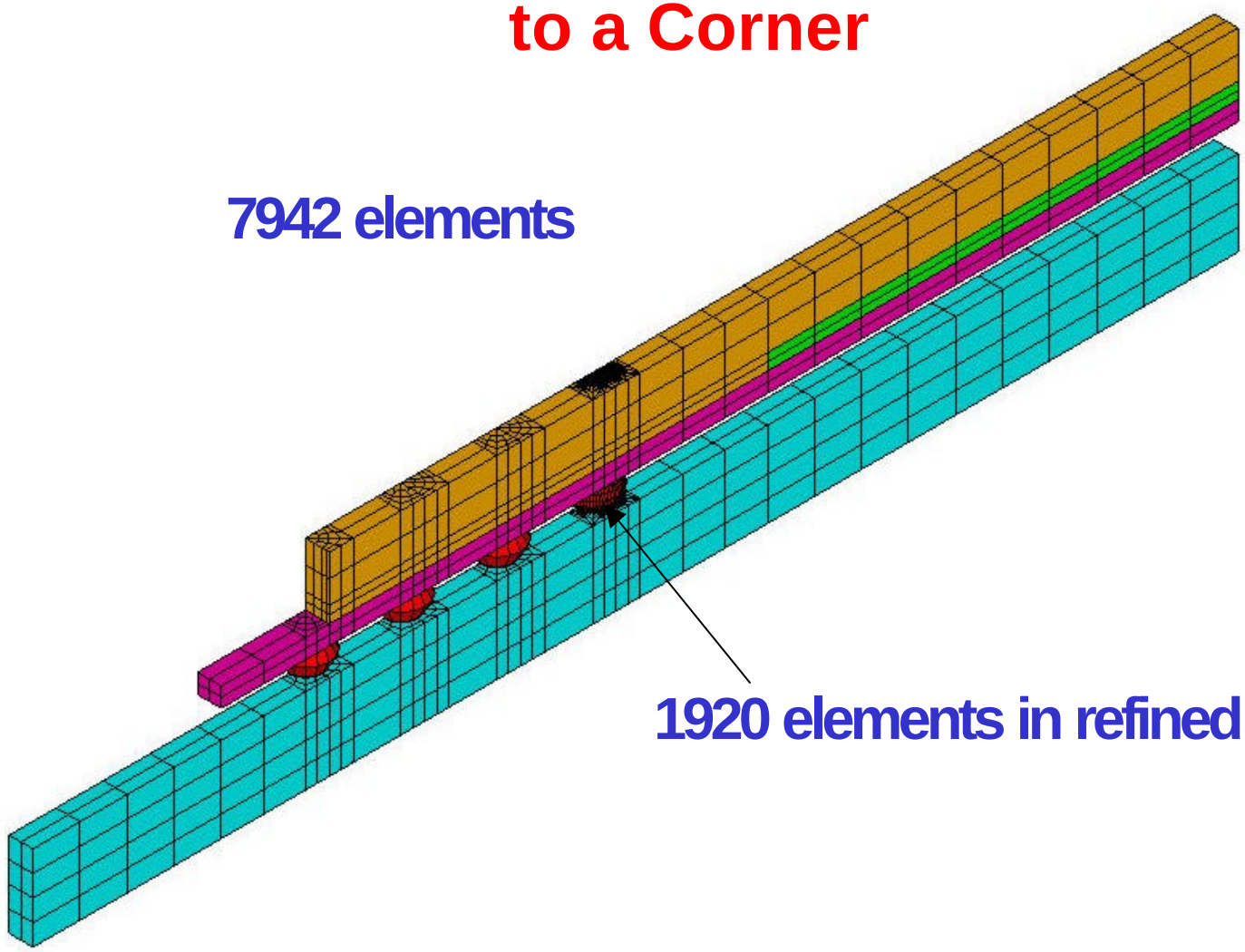
Coefficient of Thermal Expansion of Lead-Free Solders



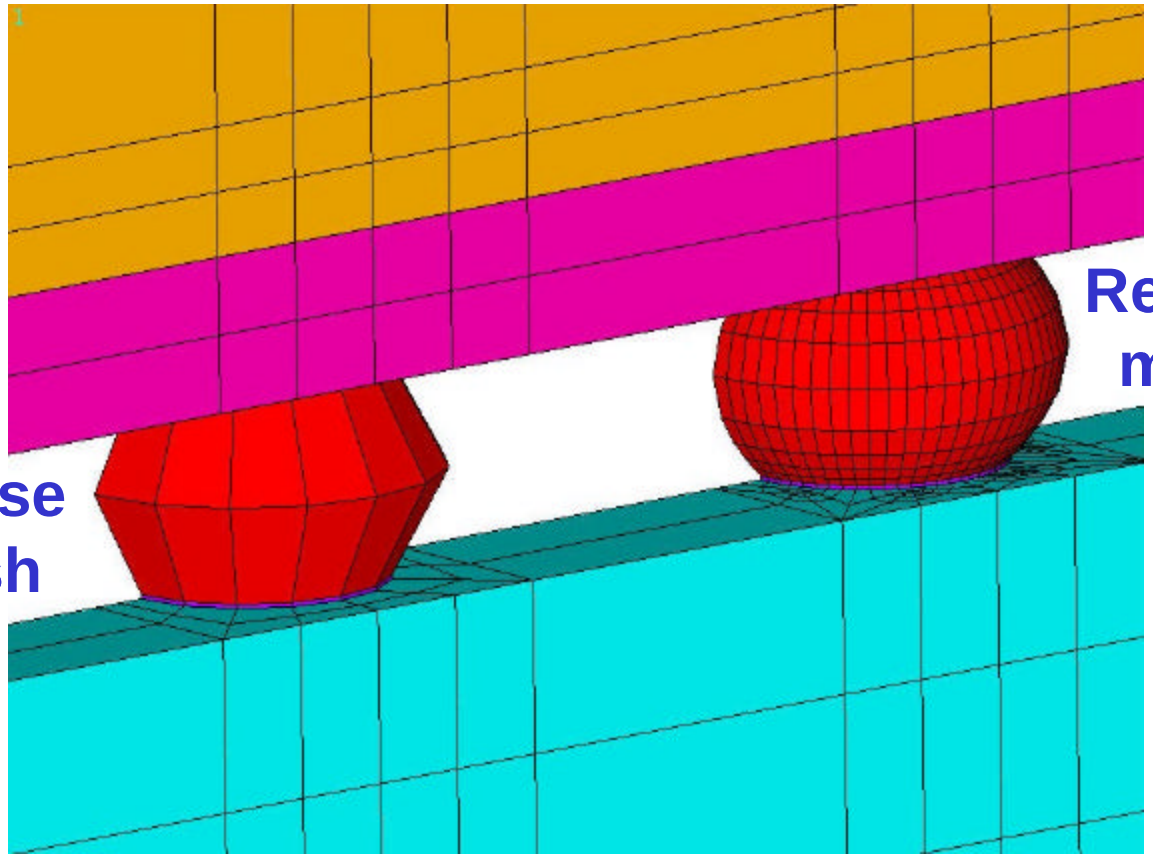
X-ray Image of One Quarter of a 256-pin PBGA PCB Assembly



Finite Element Model along a Diagonal Strip from the 256-pin PBGA's Geometric Center to a Corner



Details of the Refined and Coarse Ball Meshes in the PBGA Packages



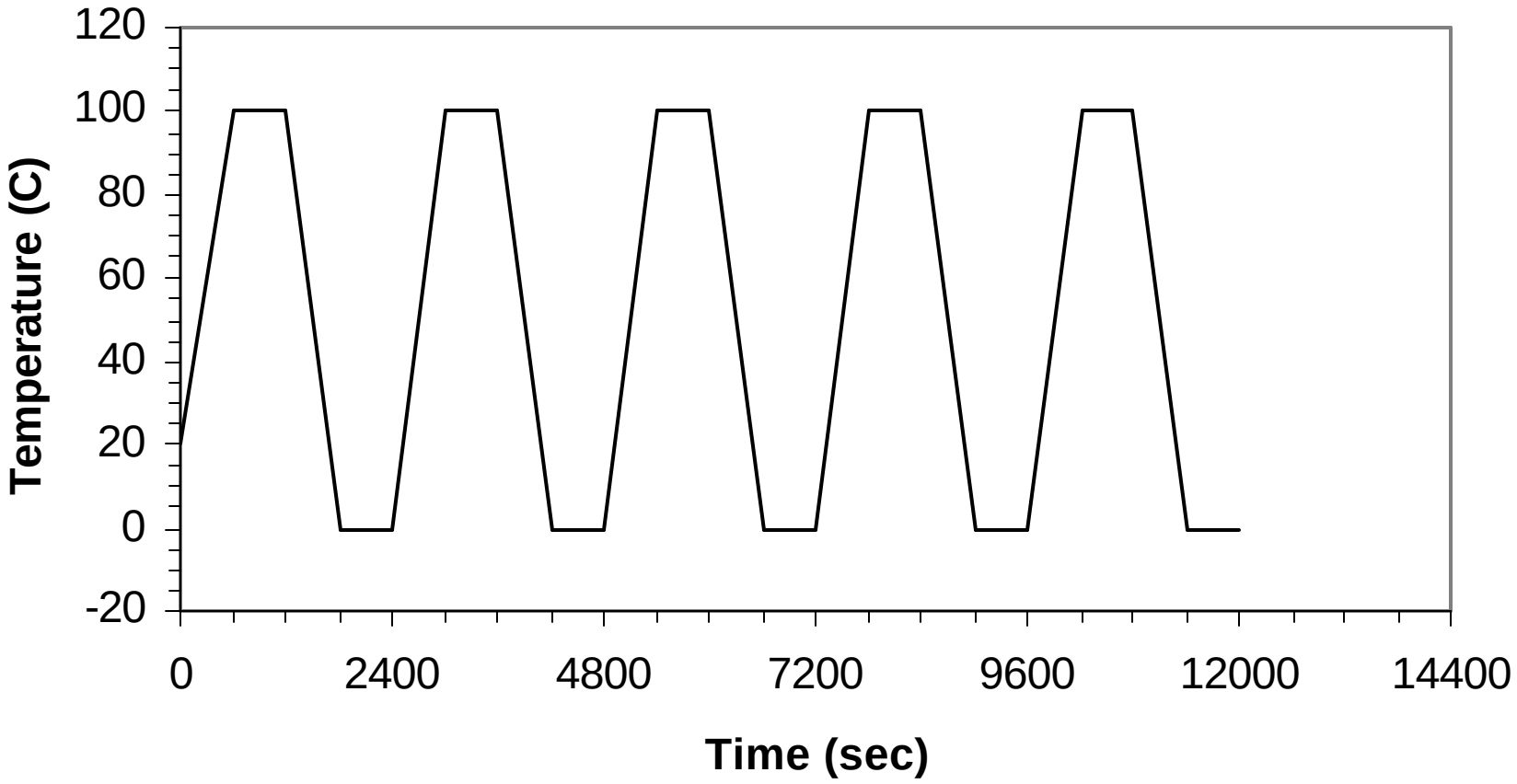
Material Properties of the Lead-Free 256PBGA PCB Assembly

Table 2 - Properties of the 256 PBGA assembly

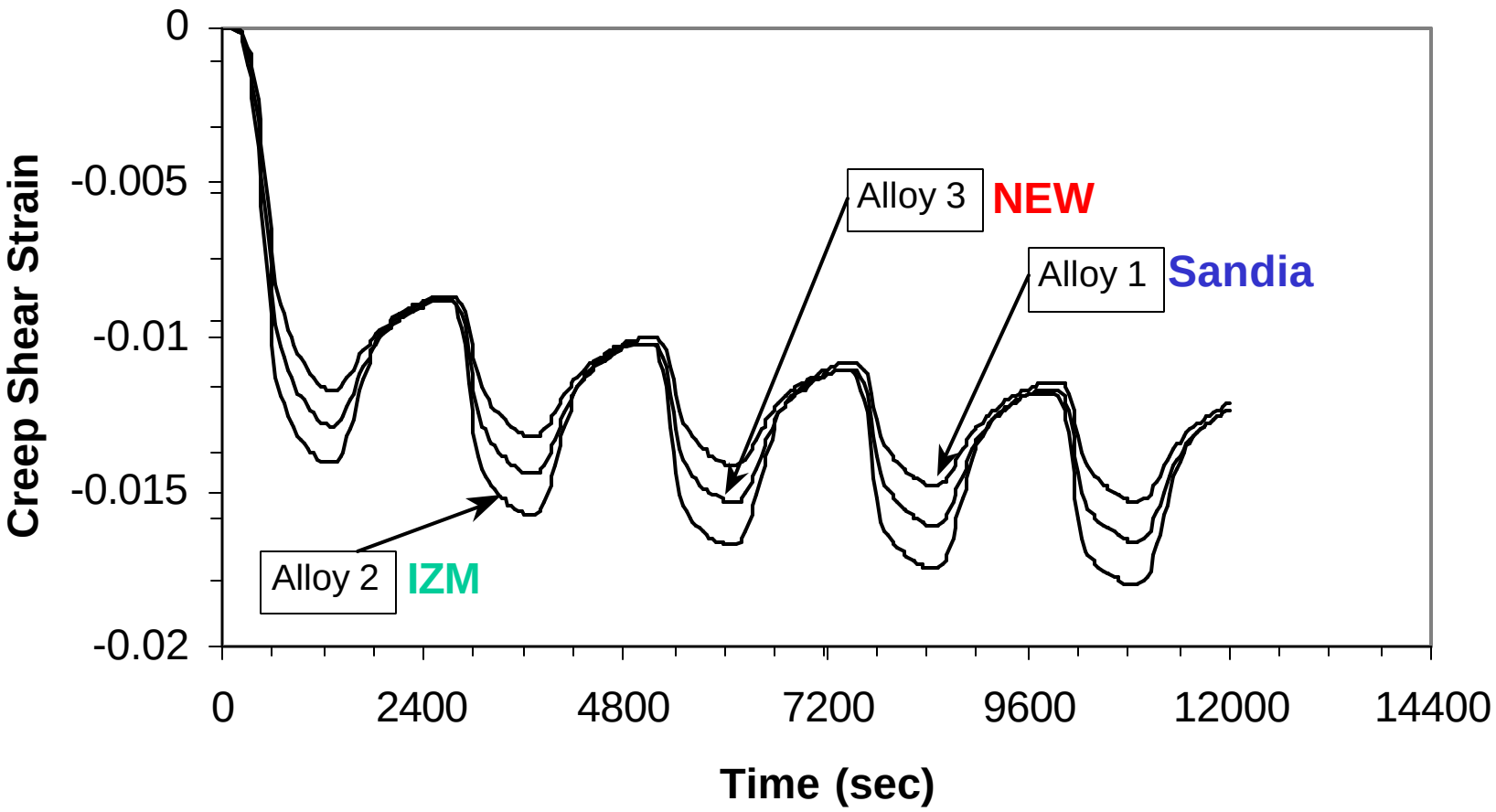
Component	E (GPa)	α (ppm/ºC)	ν	C_1 (sec^{-1})	C_2 (MPa^{-1})	C_3	C_4 (eV)
PC board	27	18	0.39	-	-	-	-
Copper pads	76	17	0.35	-	-	-	-
Laminate substrate	27	18	0.39	-	-	-	-
Die	167	2.54	0.28	-	-	-	-
Overmold	13	15	0.3	-	-	-	-
Alloy 1	49-0.07T	21.301+0.017T	0.35	441000	.005	4.2	0.466
Alloy 2	49-0.07T	21.301+0.017T	0.35	277984	0.02447	6.41	0.56
Alloy 3	49-0.07T	21.301+0.017T	0.35	500000	0.01	5	0.5

Note: All temperatures are in ºC

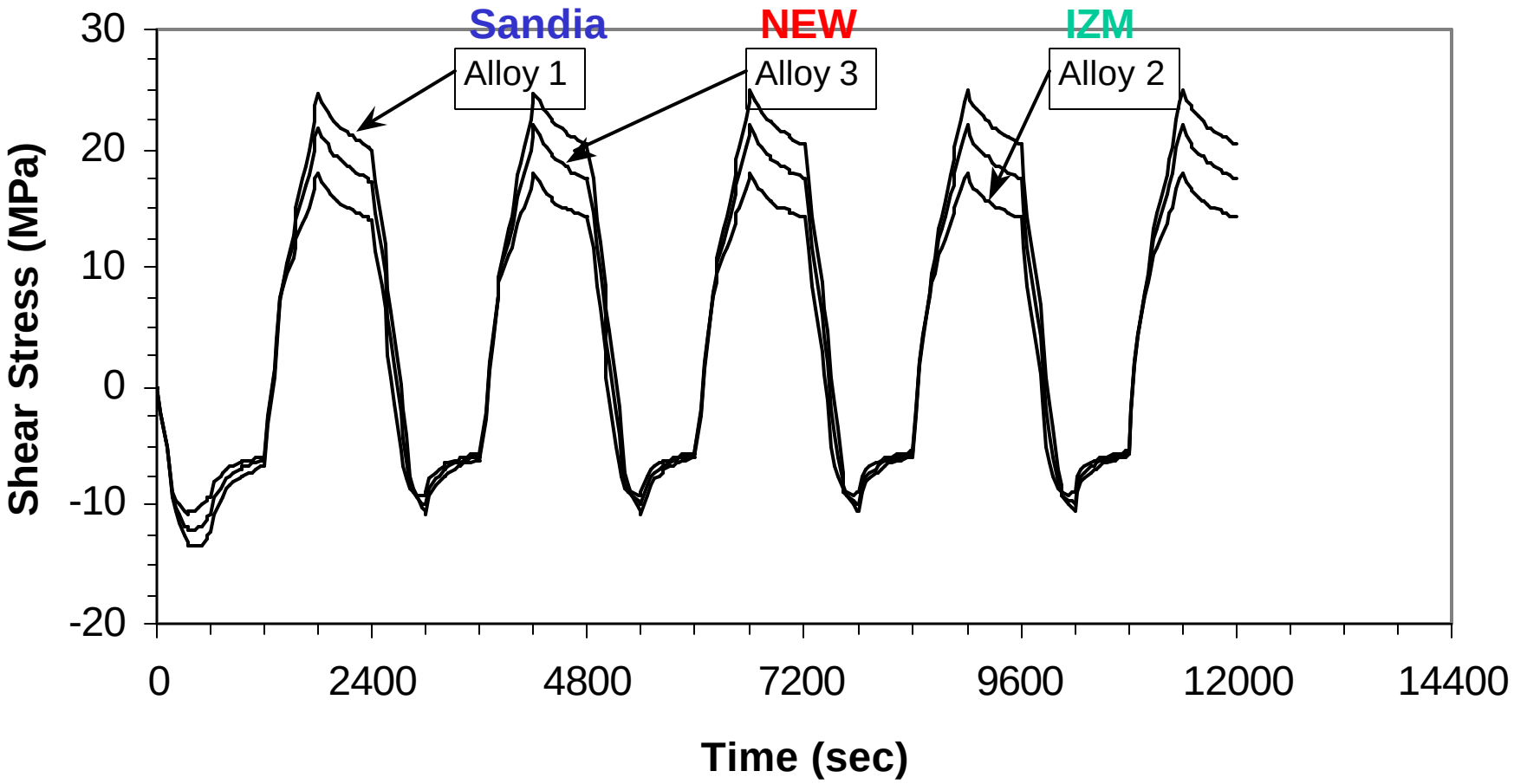
Input: Temperature vs. Time



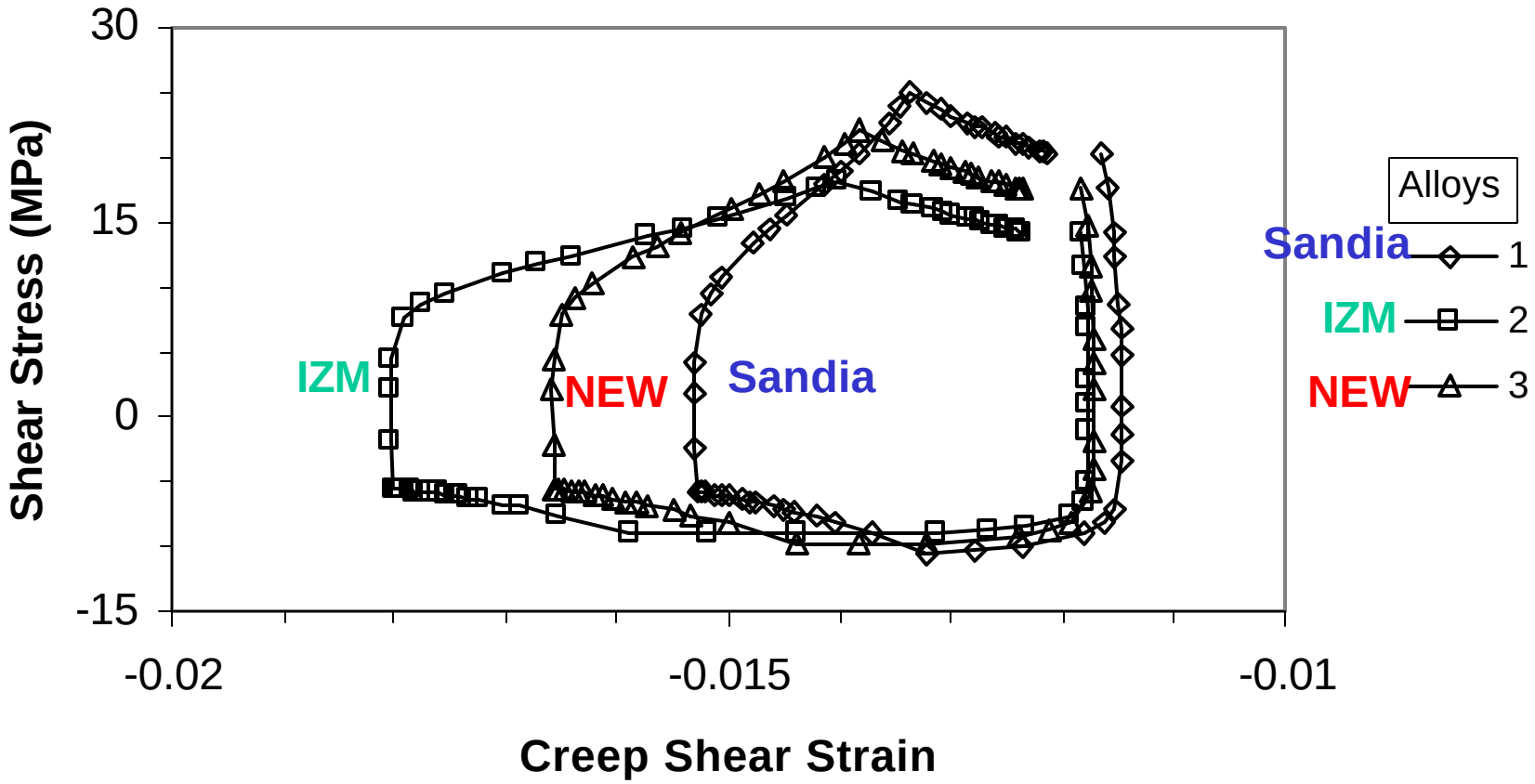
Creep Shear Strain Time-History



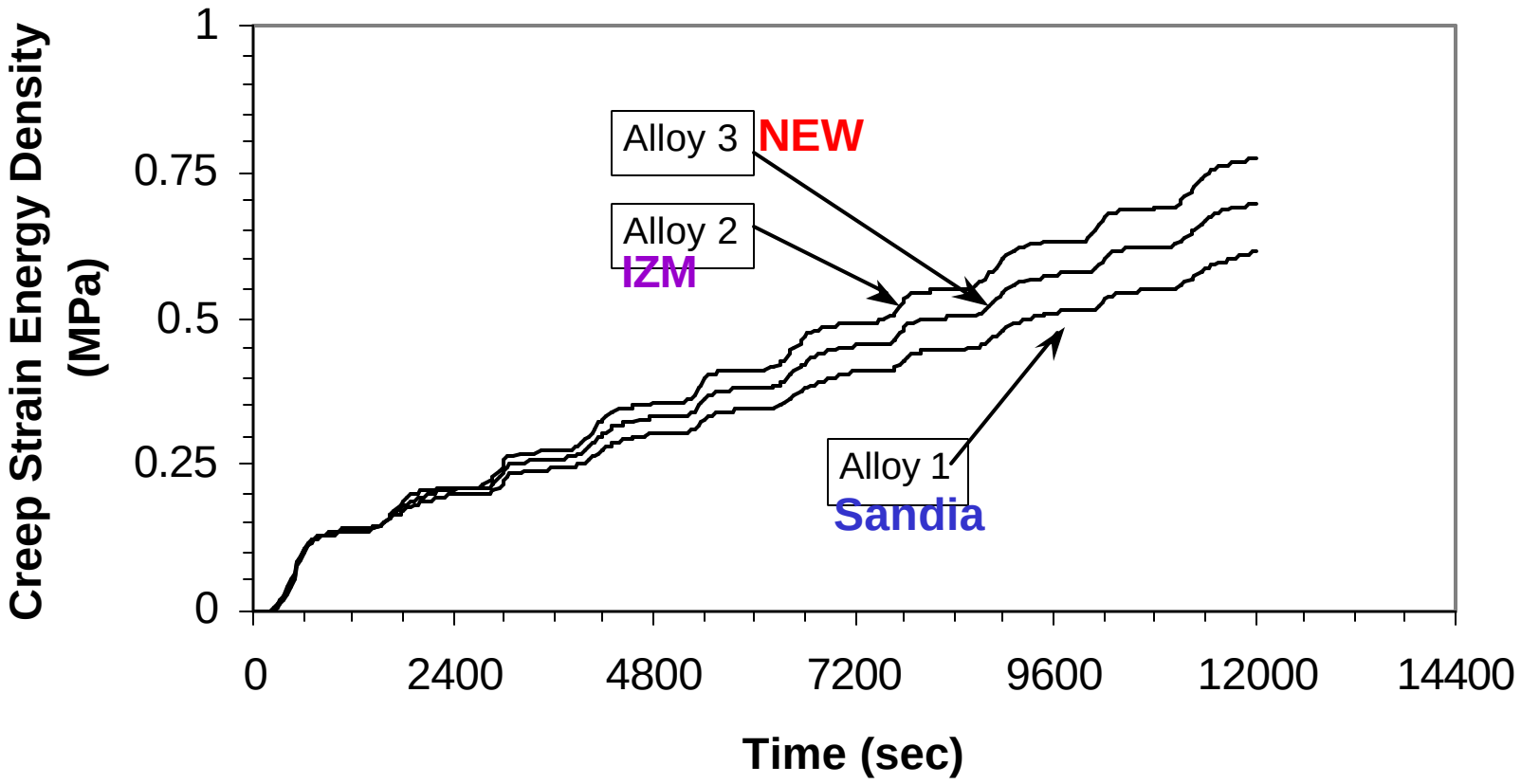
Shear Stress Time-History



The 5th Creep Hysteresis Loop



Creep Strain Energy Density Time-History



Thermal-Fatigue Life of Solder Joints

Based on a material constitutive equation, the creep strain energy density per cycle (*?W*) can be determined by the area within one of the hysteresis loops, which is determined by creep analysis of the structure (IC package, solder joints, and PCB) subjected to the specified temperture conditions.

Thermal fatigue life of solder joints (dominated by creep responses) may be predicted by the following equation.

$$N_f = y\left(\Delta W\right)^j$$

N_f is the number of cycle-to-failure of the solder joints

? (always positive) and *f* (always negative) are constants for the solder joints, and are usually determined by isothermal fatigue tests of the real solder-joint.

Summary and Recommendations

Based on the data by Schubert and Vianco, a new set of constitutive equations has been proposed for Sn(3.5-3.9)wt%Ag(0.5-0.8)wt%Cu lead-free solder alloys. Some important results are summarized in the following:

For all the temperatures, comparing with Schubert's data, Vianco's data tend to predict faster creep rates at lower stresses and slower creep rates at higher stresses. Vianco's data predicts a larger Young's modulus.

The creep shear strain range in the critical solder joint of the 256PBGA assembly predicted by Schubert's material model is larger than that by Vianco's.

The shear stress range in the critical solder joint of the 256PBGA assembly predicted by Schubert's material model is smaller than that using Vianco's model.

As expected, the responses predicted by the present material model, Alloy No. 3, are between those using the Vianco and Schubert models, since Alloy No. 3 is obtained by averaging theirs.

The isothermal fatigue test data of real solder joints are desperately needed in order to make quantitative solder-joint thermal-fatigue life prediction.

Acknowledgements

The authors would like to thank Ted Lancaster and Pete Woodhouse of Agilent for their strong supports on the Lead-Free Program.

Thank you very much for your attentions!