SMTAI 2006 LEAD-FREE SYMPOSIUM SOL4

Applicability of Various Pb-free Solder Joint Acceleration Models

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Presentation Outline

- Motivation & Objective
- AF Model Descriptions
- Case Studies
- Conclusions

Motivation & Objective

- AF models provide a quick way to access solder joint reliability in combination with test failure data;
- A variety of AF models have been proposed for SAC assemblies. However, the error bounds of those models are rarely spelled out - neither are conditions of applicability;
- This work attempts to assess both the accuracy and the applicability of AF models;
- SAC387/396 are considered

Scope of Investigation

- Algebraic Model (AM)
- Compact Strain Energy Model (CSEM)
- Finite Element Modeling (FEM)

AF Model Descriptions: AM

- A first attempt at fitting a Norris-Landzberg type of equation to accelerated thermal cycling results for SAC assemblies:

$$AF \equiv \frac{N_o}{N_t} = \left(\frac{\Delta T_t}{\Delta T_o}\right)^{2.65} \left(\frac{t_t}{t_o}\right)^{0.136} \exp\left[2185\left(\frac{1}{T_{\max,\,o}} - \frac{1}{T_{\max,\,t}}\right)\right]$$

- The three constants were obtained by curve-fitting failure data covering different component types, temperature extremes, dwell times and characteristic lives;
- Errors for AFs were estimated in the range of -25% to +50%. They tend to be higher in cold temperatures, possibly indicating change in failure mechanism

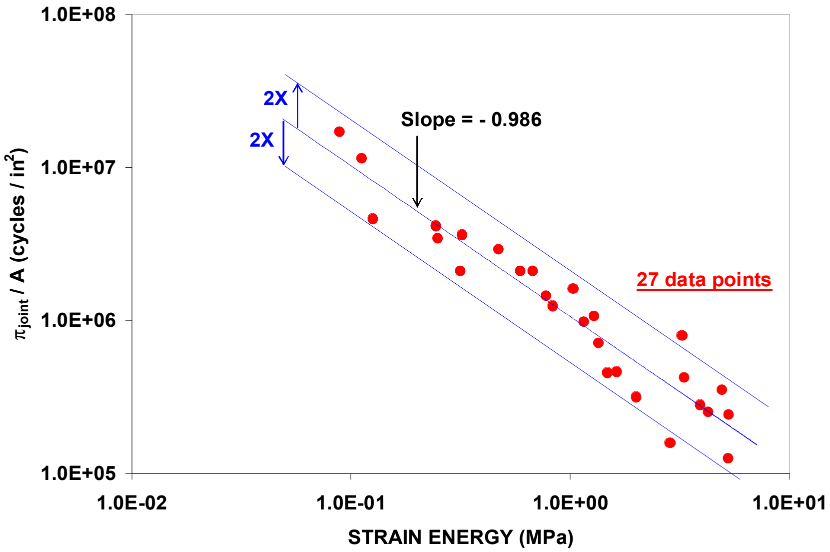
AF Model Descriptions: CSEM

- One-dimensional model where cyclic strain energy is represented by the area of stabilized hysteresis loops;
- Both global CTE mismatch (shear deformations - component vs. board) and local CTE mismatches (normal stresses and strains - solder vs. interconnected parts) are captured;
- Constitutive equations for creep rates:

$$\overset{\circ}{\varepsilon}(/\sec) = 5.0\cdot 10^{-9}\sigma^{5.56}\cdot\exp\left[-\frac{3544}{T(K)}\left(1-\frac{\sigma}{1280}\right)\right] + 6802\sigma^{3.02}\cdot\exp\left[-\frac{11050}{T(K)}\left(1-\frac{\sigma}{181}\right)\right]$$

$$\overset{\circ}{\gamma}(/\sec) = \sqrt{3}\times \left\{ 5.0\times 10^{-9}\left(\tau\sqrt{3}\right)^{5.56}\cdot\exp\left[-\frac{3544}{T(K)}\left(1-\frac{\tau\sqrt{3}}{1280}\right)\right] + 6802\left(\tau\sqrt{3}\right)^{3.02}\cdot\exp\left[-\frac{11050}{T(K)}\left(1-\frac{\tau\sqrt{3}}{181}\right)\right]\right\}$$

AF Model Descriptions: CSEM



$$\frac{\alpha_{JOINT}}{A} = \frac{C}{\Delta W^m}$$

$$AF \equiv \frac{N_f(field)}{N_f(test)} = \frac{\Delta W(test)}{\Delta W(field)}$$

- $\alpha_{JOINT:}$ characteristic life on a per joint basis
- A: solder joint load bearing or crack area
- C : constant
- ΔW: cyclic strain energy density obtained from the area of stress / strain hysteresis loops
- m: slope. close to 1 (0.986)

AF Model Descriptions: FEM

- 3-D model where cyclic strain energy is represented by the delta between two stabilized consecutive cycles;
- All CTE mismatches are captured. Full-field equations are solved to provide strain energy information in all solder joints in one run;
- Constitutive equation (Anand type):

$$\dot{\varepsilon}_p = A \exp\left(-\frac{Q}{RT}\right)\left[\sinh\left(\xi\frac{\sigma}{s}\right)\right]^{1/m}$$

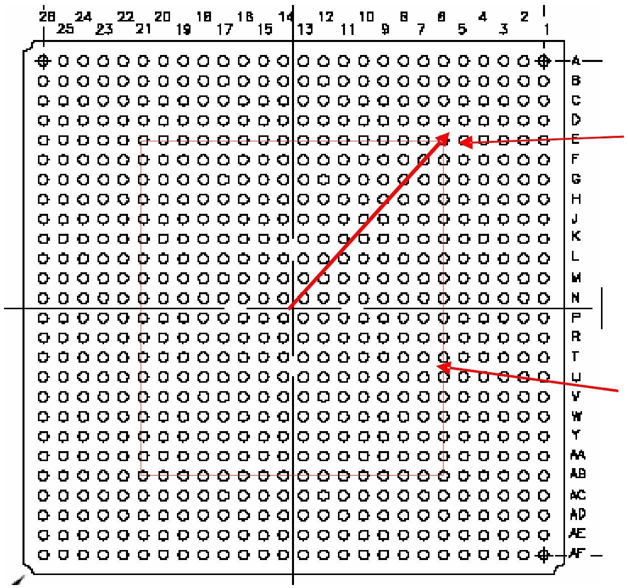
- Anand equation consists of 9 constants, which are curve fitted from tests

Case Studies

Case #	Package Type	Conditions	Comparison
1	Plastic BGA	Two test conditions, with test results available.	Model (AM, CSEM, FEM) vs. test AF
2	Ceramic BGA	Three test conditions, with test results available.	Model (AM, CSEM, FEM) vs. two test AFs
3	HiCTE Ceramic FC-BGA	One test condition, two use conditions (main and mini-cycles)	Two AFs predicted by three models (AM, CSEM, FEM)

Case # 1: PBGA Assembly

- 676 I/O PGBA, 16.96x16.96 mm die, 27x27x0.33 mm substrate, 2.36mm (93 mil) thick FR-4 board;

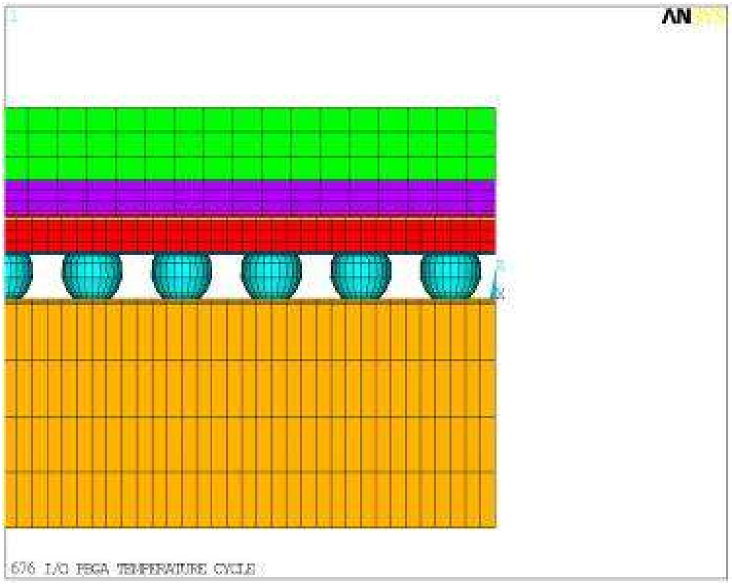


At corner joint nearest to die corner:

$DNP_{die\ corner}$
= 8.5 mm x sqrt(2)
= 12.0208 mm
= 0.47326”

Die shadow:
16.96 x 16.96 mm

Pitch = P = 1 mm = 39.37 mil



Package and die foot prints

Assembly cross-section

Case # 1: PBGA Assembly

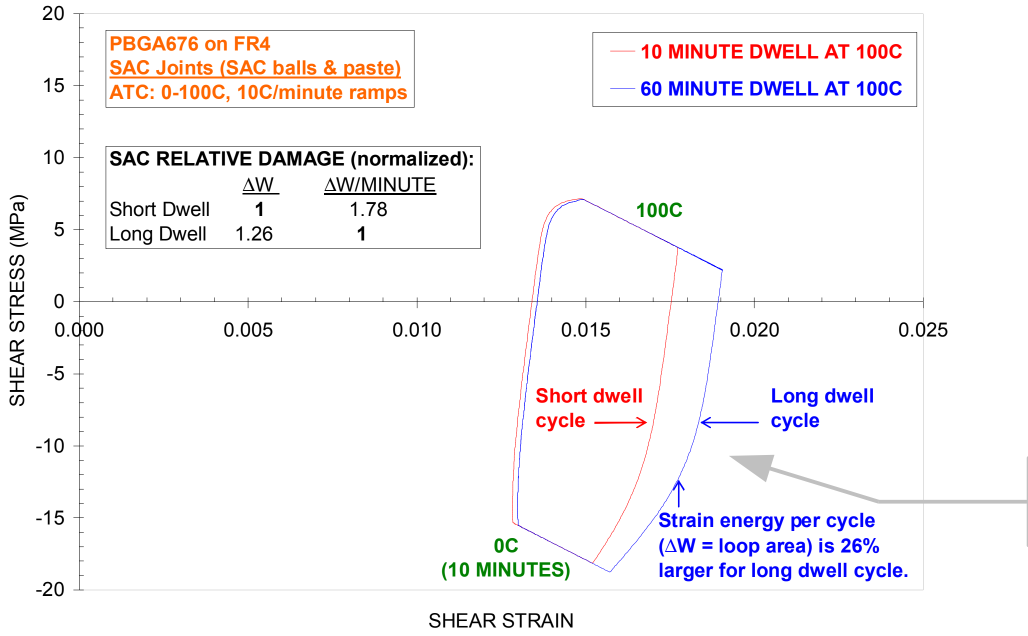
- ATC conditions
  - Short cycle: 0ºC/ 100ºC, 10 min ramps, 10 min dwells at 0ºC/100ºC
  - Long cycle: Same as above except 60 min dwell at 100ºC

Case # 1: PBGA Assembly

- AM:

$$AF \equiv \frac{N_o}{N_t} = \left(\frac{t_t}{t_o}\right)^{0.136} = \left(\frac{60}{10}\right)^{0.136} = 1.276$$

- CSEM:



PBGA676 on FR4
SAC Joints (SAC balls & paste)
ATC: 0-100C, 10C/minute ramps

SAC RELATIVE DAMAGE (normalized):

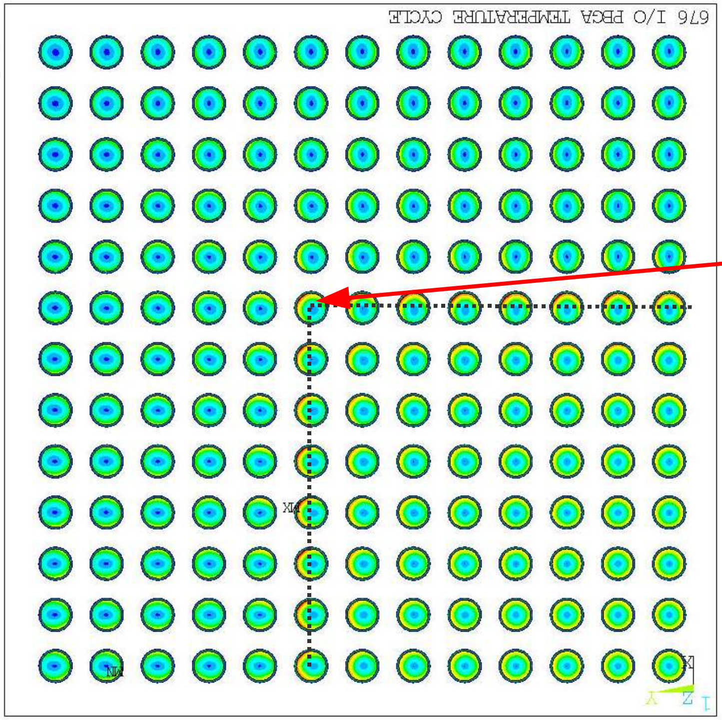
	ΔW	ΔW/MINUTE
Short Dwell	**1**	1.78
Long Dwell	1.26	**1**

Strain energy per cycle (ΔW = loop area) is 26% larger for long dwell cycle.

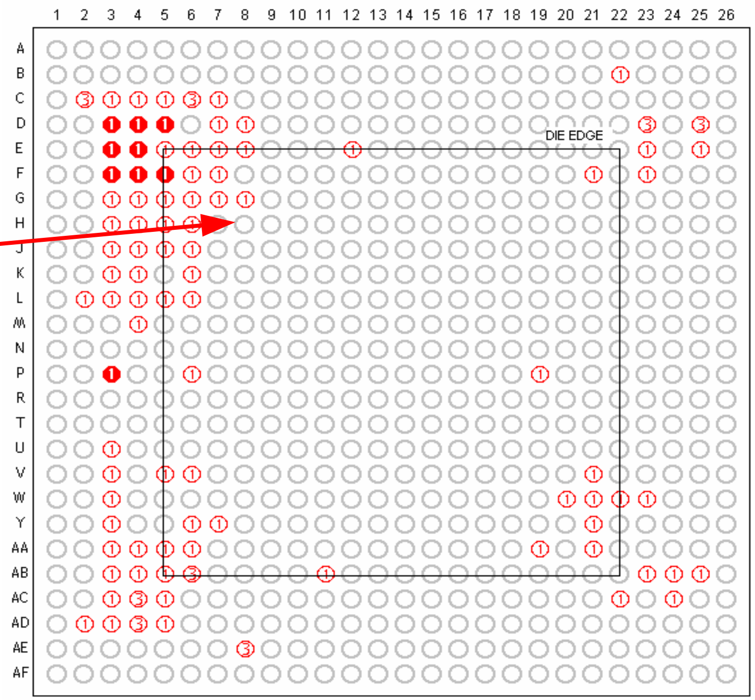
AF=1.26

Case # 1: PBGA Assembly

- FEM:



Strain energy contour plot (Quarter model)



●	1.3%	Complete Fracture at Package/Solder Interface
①	11.4%	Partial Fracture at Package/Solder Interface
③	1.2%	Partial Fracture at PCB/Solder Interface
○	86.1%	No Pre-existing Cracks (no red dye)

Dye & pry test results from [13]

Case # 1: PBGA Assembly

- Comparisons

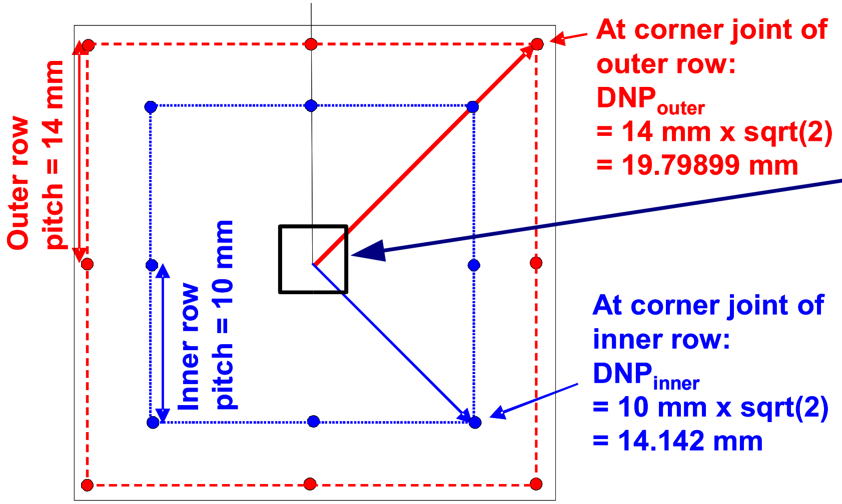
TEST	AF	AF Calculation Method
	1.24	Calculated as ratio of cycles to 1% failure in test (2P Weibull)
	1.39	Calculated as ratio of cycles to 63.2% failure in test (2P Weibull).
	1.288	Calculated as ratio of failure-free cycles in test (3P Weibull, not shown).
	1.282	Ratio of cycles to first failure
Test_avg	1.300	Average of above four AFs in test.

Model	Predicted AF	Error
AM	1.276	-2%
CSEM	1.26	-3%
FEM	1.13	-13%
Test	1.30	N/A

- All models predict AFs within 15%

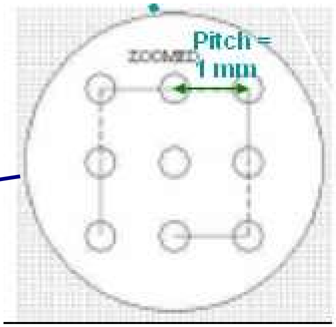
Case # 2: CBGA Assembly

- 17 I/O CBGA, 30x30x1 mm substrate, 2 mm (78.75 mil) thick FR-4 board;

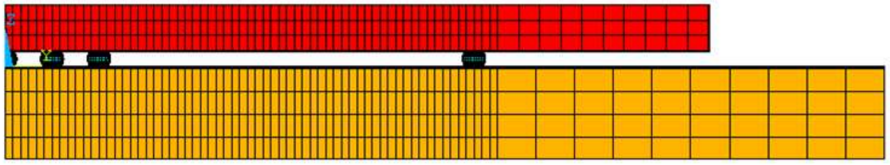


At corner joint of outer row:
DNP_{outer}
= 14 mm x sqrt(2)
= 19.79899 mm

At corner joint of inner row:
DNP_{inner}
= 10 mm x sqrt(2)
= 14.142 mm



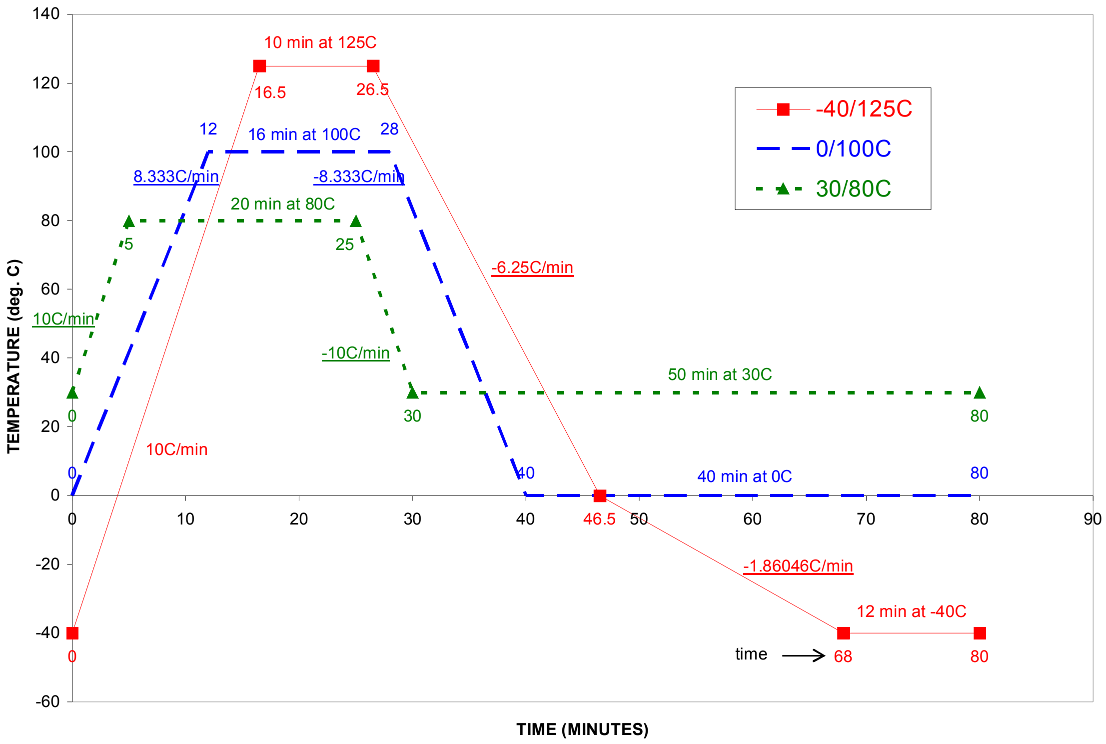
Inner and Outer Rows



Assembly Cross-section (Inner Row)

Case # 2: CBGA Assembly

- ATC conditions: -40/125ºC, 0/100ºC and 30/80ºC



Case # 2: CBGA Assembly

- AM:

EXAMPLE: Ceramic "BGA" prototype after Salmela et al., SMTA Journal, Vol. 18, No. 2, 2005, pp. 15-21; conditions: ATC3 = -40/125C and ATC1 = 30/80C

AF is defined as: N(30/80C) / N(-40/125C),
thus: "30/80C" = "o" condition and "-40/125C"= "t" condition

	"t" condition -40/125C = "ATC3"	"o" condition 30/80C = "ATC1"		AF	
Tmax (deg.C)	125	80	term 3:	2.01	Arrhenius term
Tmin (deg. C)	-40	30			
Dwell (min.)	10	20	term 2:	0.91	Dwell time factor
ΔT (deg. C)	165	50	term 1:	23.66	Delta T factor
AF_Predicted = term3 x term2 x term1				43.36	

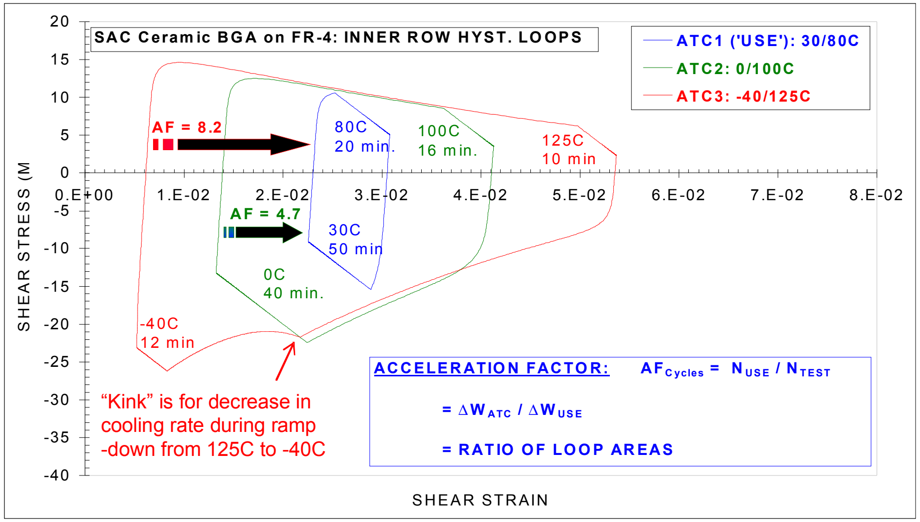
EXAMPLE: Ceramic "BGA" prototype after Salmela et al., SMTA Journal, Vol. 18, No. 2, 2005, pp. 15-21; conditions: ATC2 = 0/100C and ATC1 = 30/80C

AF is defined as: N(30/80C) / N(0/100C),
thus: "30/80C" = "o" condition and "0/100C"= "t" condition

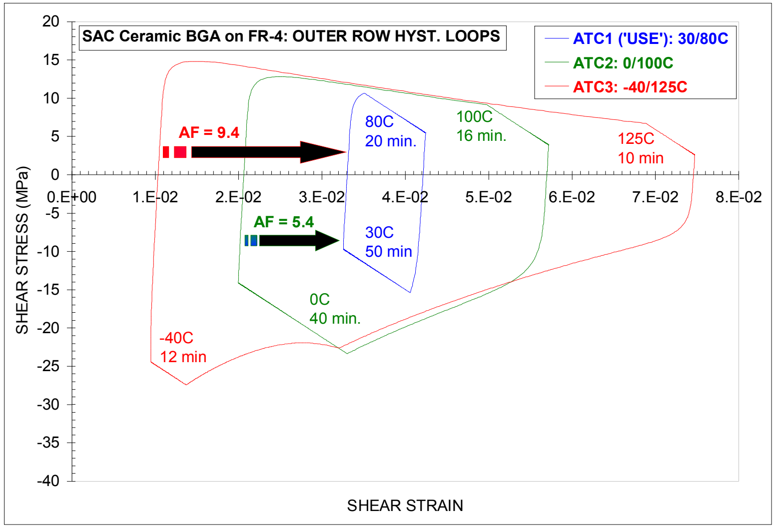
	"t" condition 0/100C = "ATC2"	"o" condition 30/80C = "ATC1"		AF	
Tmax (deg.C)	100	80	term 3:	1.39	Arrhenius term
Tmin (deg. C)	0	30			
Dwell (min.)	16	20	term 2:	0.97	Dwell time factor
ΔT (deg. C)	100	50	term 1:	6.28	Delta T factor
AF_Predicted = term3 x term2 x term1				8.49	

Case # 2: CBGA Assembly

- CSEM:



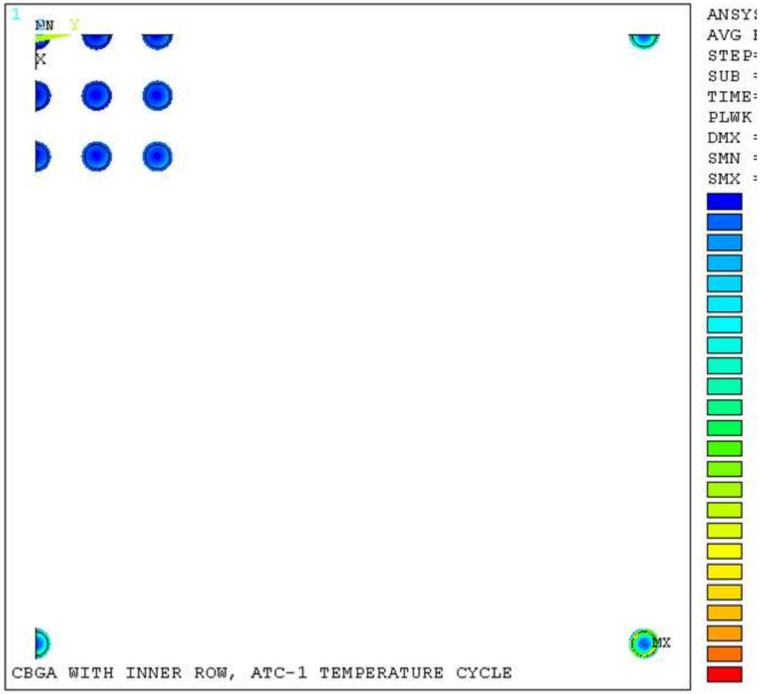
Inner row results



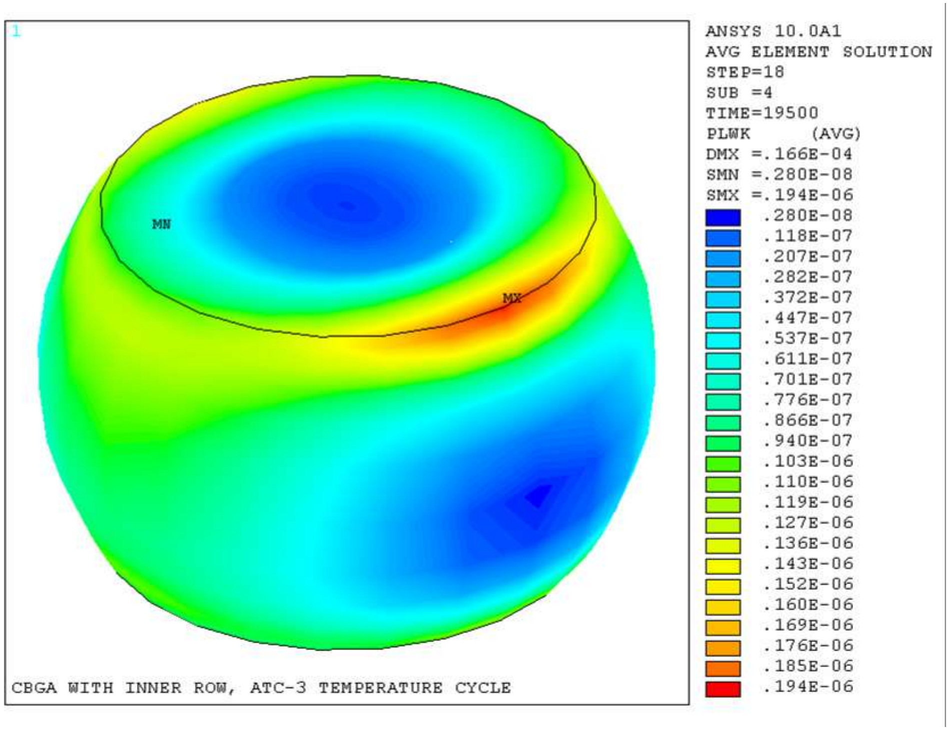
Outer row results

Case # 2: CBGA Assembly

- FEM:



Strain energy contour plot



Maximum strain energy at package interface

Case # 2: CBGA Assembly

- Comparisons

Inner Row, AF=N(30/80C)/N(0/100C)

Model	Predicted AF	Error
AM	8.49	131%
CSEM	4.7	13%
FEM	2.74	-34%
Test	3.68	N/A

Outer Row, AF=N(30/80C)/N(0/100C)

Model	Predicted AF	Error
AM	8.49	104%
CSEM	5.4	30%
FEM	2.89	-31%
Test	4.16	N/A

Inner Row, AF=N(30/80C)/N(-40/125C)

Model	Predicted AF	Error
AM	43.36	334%
CSEM	8.2	-18%
FEM	5.44	-46%
Test	10	N/A

Outer Row, AF=N(30/80C)/N(-40/125C)

Model	Predicted AF	Error
AM	43.36	224%
CSEM	9.4	-30%
FEM	5.82	-57%
Test	13.39	N/A

Case # 2: CBGA Assembly

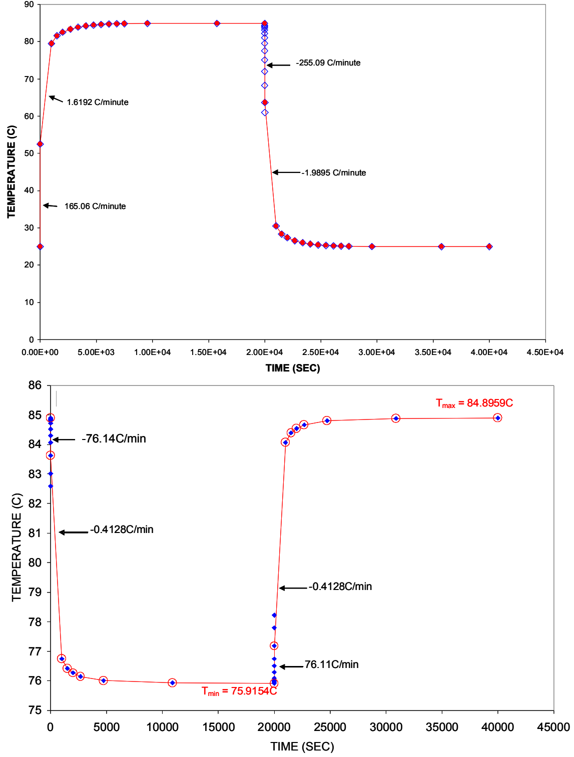
- The AM approach over-predicts the AFs by about 2 times for the 0/100ºC test and about three to four times for the -40/125ºC test;
- For both test conditions (-40/125ºC and 0/100ºC) the CSEM approach predicts AFs within +/-30%;
- The FEM approach appears to be on the conservative side since it predicts AF values within -25 to -30% (0/100ºC test) or -46 to -57% (-40/125ºC test) of the experimental AFs. The larger error for the -40/125ºC test conditions is attributed to the constitutive model used as the SAC mechanical data is only valid above room temperature;
- DNP effect: The DNP effect on AFs is not negligible since the effect is from 13% to 34% between the inner and outer rows.

Case # 3: FC-BGA Assembly

- 43x43 array I/O FC-BGA, 45x45x2 mm substrate, 2.36 mm (93 mil) thick FR-4 board;
- ATC conditions: 0/100ºC, 25/85ºC (main cycle) and 75/85ºC (mini cycle)

Cross section of FC-BGA assembly

Main and mini cycles



Case # 3: FC-BGA Assembly

- AM:

Main-Cycle AF Calculations

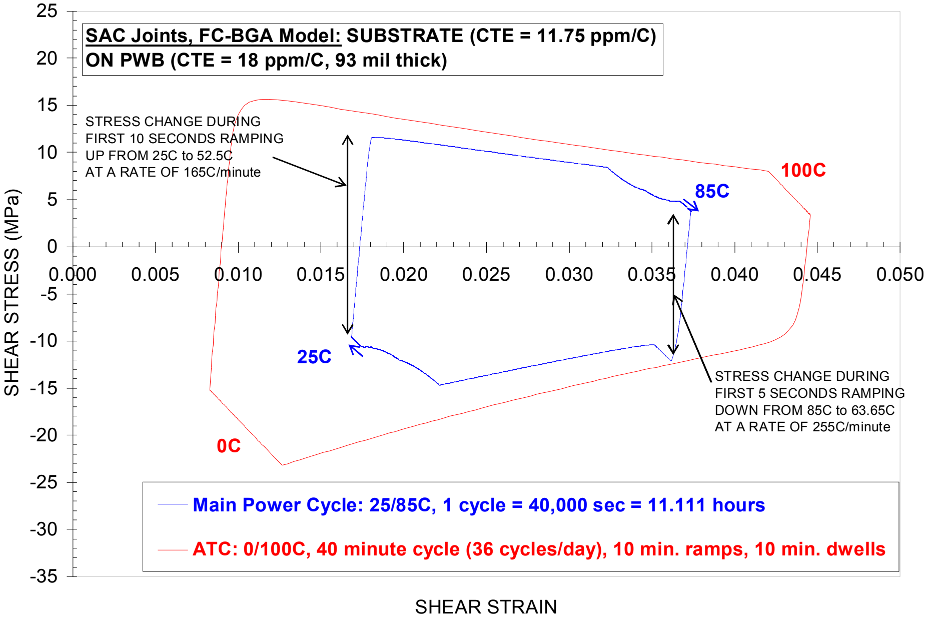
	USE	TEST		AF	
Tmax (deg.C)	85	100	term 3:	1.28	= Arrhenius term
Tmin (deg.C)	25	0			
Dwell (min.)	228 (~ 3.8 hours)	10	term 2:	0.65	= dwell time factor
DT	60	100	term1:	3.87	= ΔT factor
AF_Predicted = term1 x term2 x term3				**3.23**	

Mini-Cycle AF Calculations

	USE	TEST		AF	
Tmax (deg.C)	84.8959	100	term 3:	1.28	= Arrhenius term
Tmin (deg.C)	75.9154	0			
Dwell (min.)	308.3 (~ 5.14 hours)	10	term 2:	0.63	= dwell time factor
ΔT	8.9805	100	term1:	593.96	= ΔT factor
AF_Predicted = term1 x term2 x term3				**477.11**	

Case # 3: FC-BGA Assembly

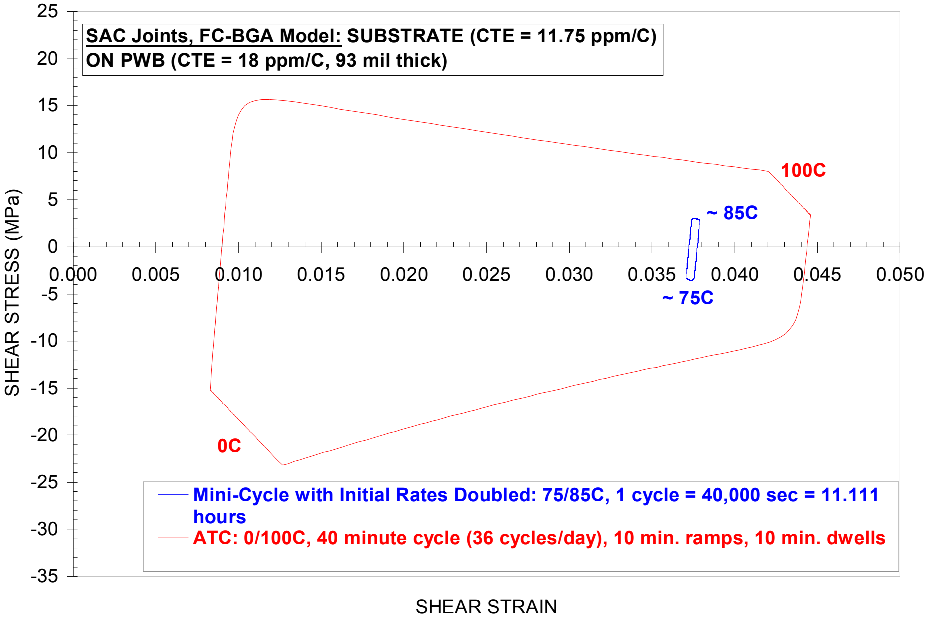
- CSEM:



SAC Joints, FC-BGA Model: SUBSTRATE (CTE = 11.75 ppm/C) ON PWB (CTE = 18 ppm/C, 93 mil thick)

STRESS CHANGE DURING FIRST 10 SECONDS RAMPING UP FROM 25C to 52.5C AT A RATE OF 165C/minute

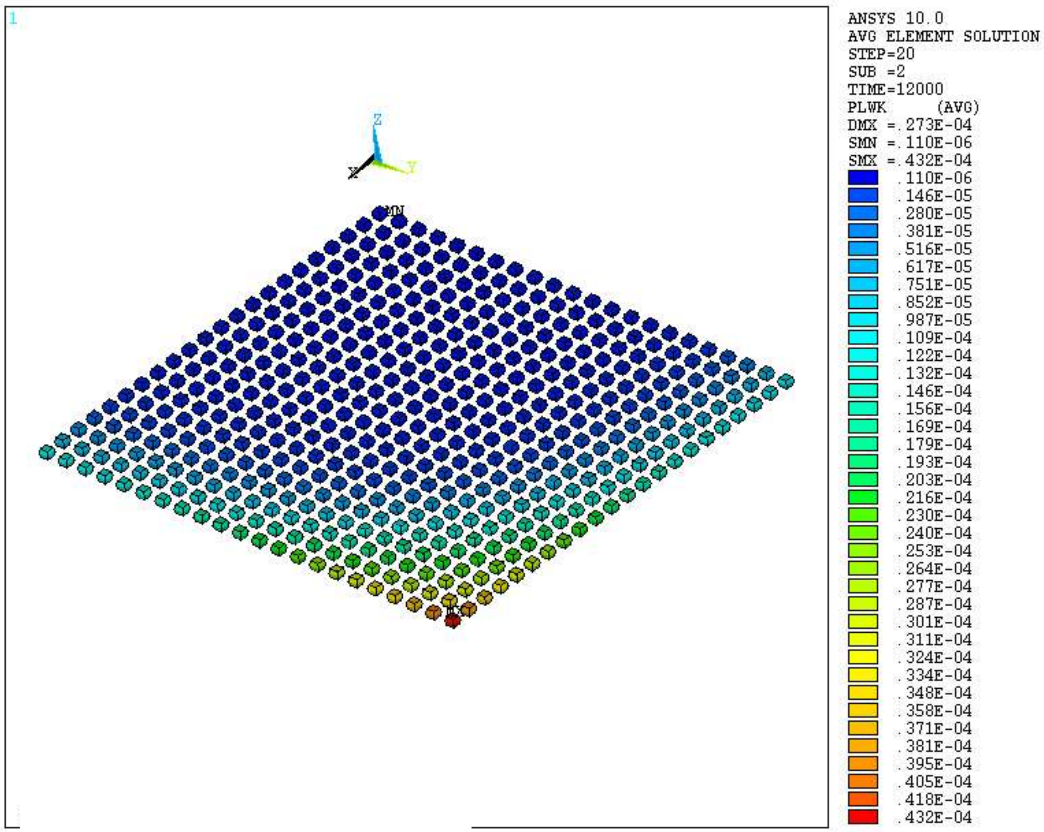
STRESS CHANGE DURING FIRST 5 SECONDS RAMPING DOWN FROM 85C to 63.65C AT A RATE OF 255C/minute



SAC Joints, FC-BGA Model: SUBSTRATE (CTE = 11.75 ppm/C) ON PWB (CTE = 18 ppm/C, 93 mil thick)

Case # 3: FC-BGA Assembly

- FEM:



```
ANSYS 10.0
AVG ELEMENT SOLUTION
STEP=20
SUB =2
TIME=12000
PLWK      (AVG)
DMX =.273E-04
SMN =.110E-06
SMX =.432E-04
 .110E-06
 .146E-05
 .280E-05
 .381E-05
 .516E-05
 .617E-05
 .751E-05
 .852E-05
 .987E-05
 .109E-04
 .122E-04
 .132E-04
 .146E-04
 .156E-04
 .169E-04
 .179E-04
 .193E-04
 .203E-04
 .216E-04
 .230E-04
 .240E-04
 .253E-04
 .264E-04
 .277E-04
 .287E-04
 .301E-04
 .311E-04
 .324E-04
 .334E-04
 .348E-04
 .358E-04
 .371E-04
 .381E-04
 .395E-04
 .405E-04
 .418E-04
 .432E-04
```

Strain energy contour plot

Case # 3: FC-BGA Assembly

- Comparisons

MAIN TEMPERATURE CYCLE: AF COMPARISONS		
MODEL	**AF**	AF Ratio = AM Model/ Other AF
AM	3.23	1
FEM	2.23	1.448
CSEM	2.345	1.377

MINI-TEMPERATURE CYCLE: AF COMPARISONS		
MODEL	**AF**	AF Ratio = AM Model/ Other AF
AM	477.11	1
FEM	322.47	1.480
CSEM	300.004	1.590

- AFs for mini-cycles are much larger than for the main cycles, by over two orders of magnitude;
- CSEM and FEM results are within 10% for both main and mini cycles;
- AM results are 37% to 59% larger

Conclusions

- AM is easier to use but tends to predict higher AFs, which could overestimate solder joint fatigue performance and lead to weak designs that may not survive field conditions;
- CSEM and FEM approaches predict AFs more in line with test data. Since both approaches take geometry and material properties into consideration, it requires more upfront work;
- FEM yields more conservative AFs with the particular Anand constants used in this paper. Further work is required to characterize SAC solders below room temperature to improve FEM prediction accuracy;

Conclusions

- The CBGA case yielded largest errors between models and test data. Uncertainty of the failure data could be a contributing factor;
- An error margin of about 30% on AFs appears as a reasonable and feasible goal, which should prove to be a effective tool in the design stage;
- In general, it is worthwhile to exercise several approaches to better gauge the accuracy of AF results.

Acknowledgments

- Keith Newman, Sun Microsystems
- Gregory Henshall, HP

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