SMTA International
Technical Conference October 14-18
2018

Modeling Temperature Cycle Fatigue Life of Select SAC Solders

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Acknowledgement

- Special thanks the INEMI Pb-Free Alternative Solder Alloy Team. In particular, Richard Coyle and Richard Parker for herding us cats.
- Thanks to the CALCE Electronics Products and Systems Consortium Members for funding testing and analysis provided in this presentation.

Evolution of Lead-free Solders

- Near-eutectic Sn-Ag-Cu (SAC) alloys were initially recommended by National Center for Manufacturing Center (NCMS) and International Electronics Manufacturing Initiative (iNEMI) as the primary solder replacements after the adoption of lead-free legislation [1,2].
- The move from near-eutectic SAC alloys towards a lower silver content alloy was partly motivated by the cost savings in reducing the amount of silver and to avoid intellectual property issues with Iowa State University [2,3].
- The formation of large Ag_3Sn platelets in the near-eutectic SAC alloys was believed to degrade their thermal fatigue resistance [2,4].
- The hypo-eutectic SAC305 alloy has excellent thermal cycling reliability due to the presence of silver and thereby became the de facto industry standard.

[1] E. Bastow and T. Jensen, "The Proliferation of Lead-free Alloys", SMTA International Conference, October, 2009.
[2] Henshall, G., Healey, R., Pandher, R., Sweatman, K., Howell, K., Coyle, R., Sack, T., Snugovsky, P. Tisdale, S., and Hua, F., "iNEMI Pb-Free Alloy Alternatives Project Report: State of the Industry", Proceedings SMTA International, Orlando, Florida, pp. 109, August, 2008.
[3] K. Sweatman et al., "iNEMI Pb-Free Alloy Characterization Project Report: Part III - Thermal Fatigue Results for Low-Ag Alloys", SMTA International Conference, Orlando, Florida, October 12, 2012.
[4] S. Kang et al., "Evaluation of Thermal Fatigue Life and Failure Mechanisms of Sn-Ag-Cu Solder Joints with Reduced Ag Contents", Electronic Components and technology Conference, pp. 661-667, June, 2004.

Lead-free Solders with Low Silver Content and Microalloy Additions

- While the presence of silver in SAC solder provided excellent temperature cycling durability, the silver in high silver SAC alloy also made the solders susceptible to failures under drop/shock loading.
- To improve the drop/shock reliability, the silver content in SAC alloys was reduced from three percent, to as low as no silver.
- Solder dopants, also known as microalloy additions, are elements (typically 0.1% or lower) other than the main constituents of the alloy that have been shown to improve solder performance [1].
- Commonly used microalloy additions include nickel (Ni), bismuth (Bi), manganese (Mn), and antimony (Sb).

[1] Henshall, G., Healey, R., Pandher, R., Sweatman, K., Howell, K., Coyle, R., Sack, T., Snugovsky, P. Tisdale, S., and Hua, F., "iNEMI Pb-Free Alloy Alternatives Project Report: State of the Industry", Proceedings SMTA International, Orlando, Florida, pp. 109, August, 2008.

Characterization of Pb-Free Alloy Alternatives Project

- Although the impact of lower silver and microalloy additions has been studied, a comprehensive data on the reliability of alternative solders benchmarked against SnPb and SAC305 is unavailable.
- To fill the gap in the thermal fatigue knowledge and data of these new solder alloys, iNEMI initiated the **Characterization of Pb-Free Alloy Alternatives** project in 2008 [1-2].
- The initial findings from one of the iNEMI test profiles is presented here and classified as following:
  - Effect of package size.
  - Effect of silver content.
  - Effect of microalloy addition.
  - Effect of aging.
- CALCE recommended the incorporation of a temperature cycling test with 120 minute dwell to study the impact of extended dwell time.

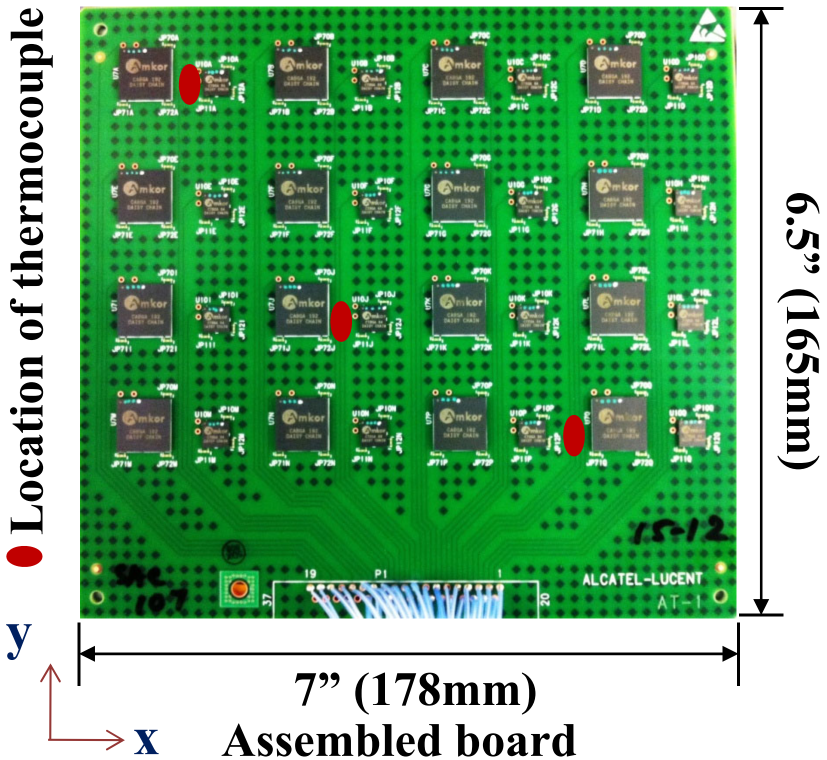
[1] Henshall, G., Healey, R., Pandher, R., Sweatman, K., Howell, K., Coyle, R., Sack, T., Snugovsky, P. Tisdale, S., and Hua, F., "iNEMI Pb-Free Alloy Alternatives Project Report: State of the Industry", Proceedings SMTA International, Orlando, Florida, pp. 109, August, 2008.

[2] G. Henshall et al., "iNEMI Pb-Free Alloy Characterization Project Report: Part I - Program Goals, Experimental Structure, Alloy Characterization, and Test Protocols for Accelerated Thermal Cycling", SMTA International Conference, Orlando, Florida, October 12, 2012.

Complete List of Solder Ball/Paste Compositions

No	Short Name	Composition	Paste	Note
1	SnPb	Sn37Pb	SnPb	Control
2	SN100C	Sn-0Ag-0.7Cu-0.05Ni-Ge	SN100C	0 Ag
3	SN100C	Sn-0Ag-0.7Cu-0.05Ni-Ge	SAC305	Low Ag
4	SAC0307	Sn-0.3Ag-0.7Cu	SAC305	Impact of Ag
5	SAC105	Sn-1.0Ag-0.5Cu	SAC305	Impact of Ag
6	SAC205	Sn-2.0Ag-0.5Cu	SAC305	Impact of Ag
7	SAC305	Sn-3.0Ag-0.5Cu	SAC305	Impact of Ag
8	SAC405	Sn-4.0Ag-0.5Cu	SAC305	Impact of Ag
9	SAC105+Ni	Sn-1.0Ag-0.5Cu+Ni	SAC305	Impact of Ni
10	SAC205+Ni	Sn-2.0Ag-0.5Cu+Ni	SAC305	Impact of Ni
11	SAC+Mn	Sn-1.0Ag-0.5Cu+Mn	SAC305	Impact of Mn
12	SACX	Sn-0.3Ag-0.7Cu +Bi+X	SAC305	Compare with SAC0307
13	SAC105+Aged	Sn-1.0Ag-0.5Cu	SAC305	10 days at 125oC
14	SAC305+Aged	Sn-3.0Ag-0.5Cu	SAC305	10 days at 125oC
15	SAC107	Sn-1.0Ag-0.7Cu	SAC305	Compare with SAC105
16	SACi	Sn-1.7Ag-0.64Cu+Sb	SAC305	Sb addition

Test Matrix



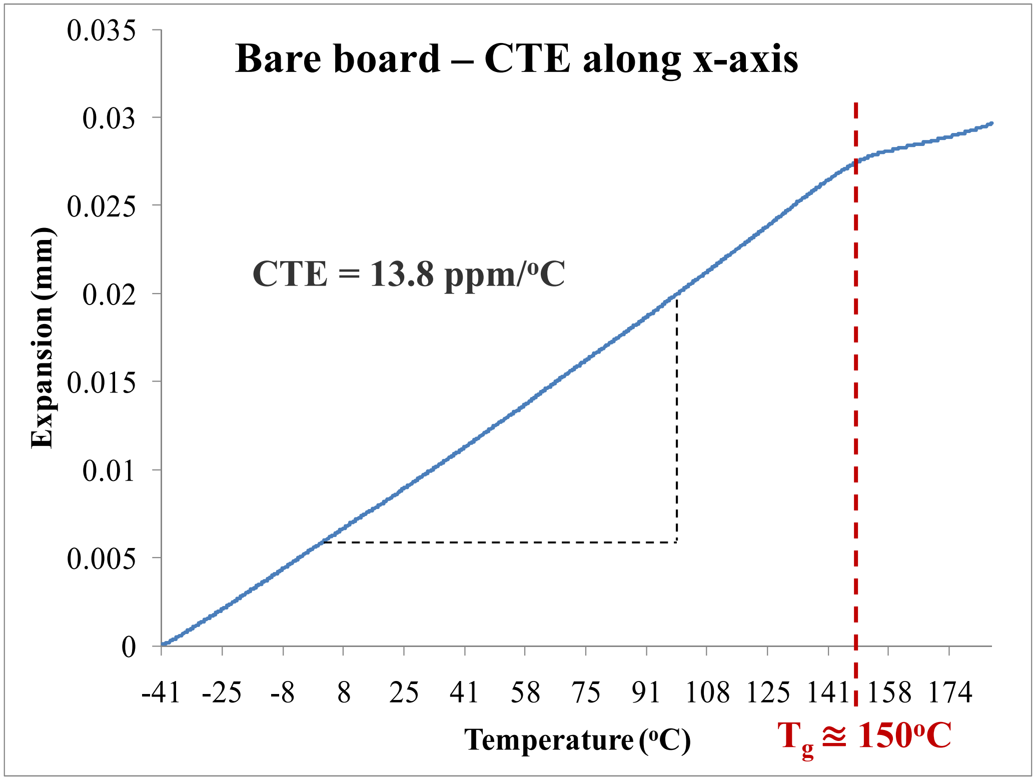
Assembled board

No	Solder ball	Solder paste	No	Solder ball	Solder paste
1	SnPb	SnPb	9	SAC105 + Ni	SAC305
2	SN100C	SN100C	10	SAC205 + Ni	SAC305
3	SN100C	SAC305	11	SAC-Mn	SAC305
4	SAC0307	SAC305	12	SACX	SAC305
5	SAC105	SAC305	13	SAC105-Aged*	SAC305
6	SAC205	SAC305	14	SAC305-Aged*	SAC305
7	SAC305	SAC305	15	SAC107	SAC305
8	SAC405	SAC305	16	SACi	SAC305

- The board was constructed with FR-4 laminate and is 0.093" (2.36mm) thick.
- Each board has sixteen 192 I/O CABGAs and sixteen 84 I/O CTBGAs.
- The glass transition temperature (T_g) of the board was approximately 150°C and CTE_x and CTE_y were 13.8 and 12.2 ppm/°C respectively.
- Package side and board side pad finishes were electrolytic Ni/Au and high temperature OSP.

***the boards were aged at 125°C for 10 days**

Properties of Board and Packages



- The properties of the board were measured using a thermo-mechanical analyzer (TMA)
- The glass transition temperature (T_g) of the board was approximately 150°C and CTE_x and CTE_y were 13.8 and 12.2 ppm/°C respectively.

iNEMI Ball Grid Array Packages

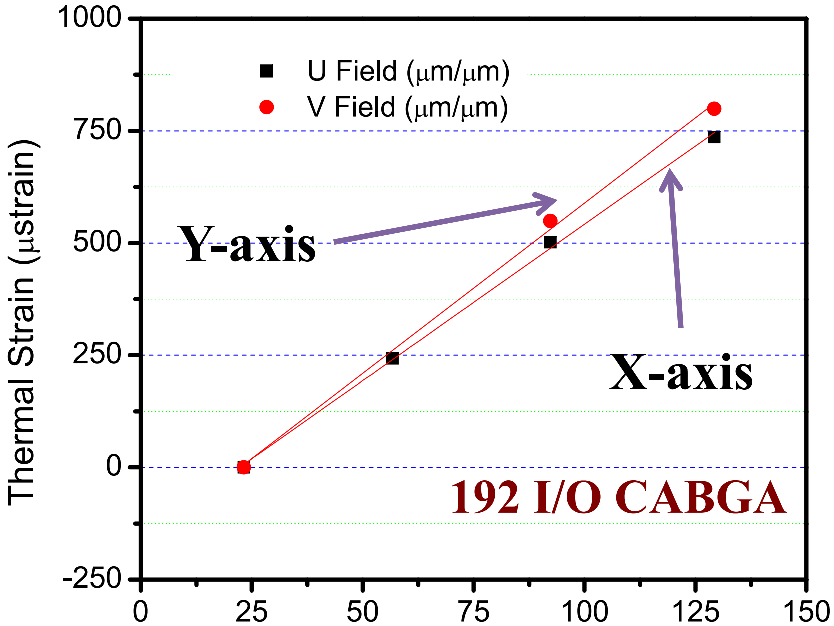
- Two BGA packages types were tested: 192 I/O CABGA (ChipArray® BGA) and 84 I/O CTBGA (Thin ChipArray ® BGA).
- Each board had sixteen 192 I/O CABGAs and sixteen 84 I/O CTBGAs.
- Each package was connected by 1 daisy chain net.

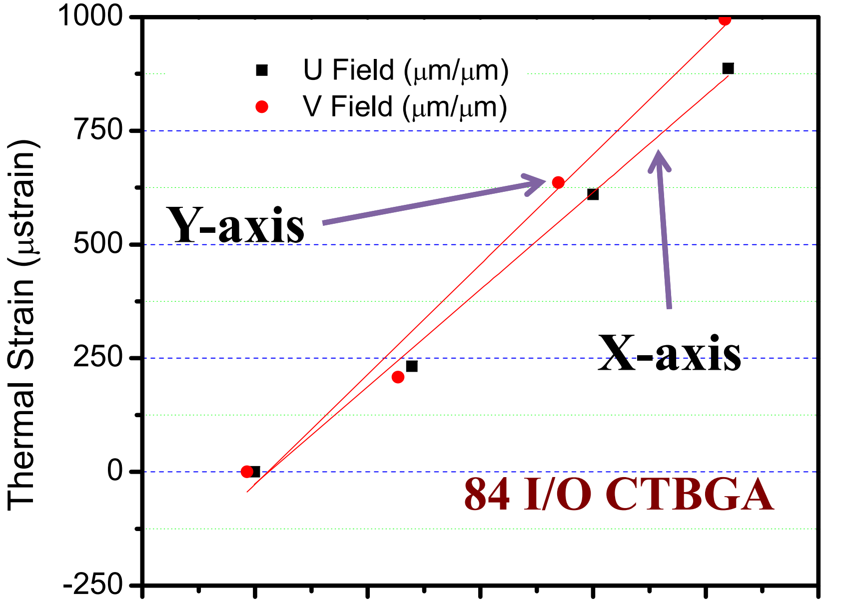
Package Type	192 I/O CABGA	84 I/O CTBGA
Pitch	0.8 mm	0.5 mm
Dimension	14 mm X 14 mm	7 mm X 7 mm
Die dimension	12.07 mm X 12.07 mm	5.08 mm X 5.08 mm
Die thickness	0.26 mm	0.22 mm
Solder ball size	0.46 mm	0.3 mm

Package CTE from Moire Interferometry

The packages were tested at temperatures of 25ºC, 55ºC, 90ºC, and 130ºC.

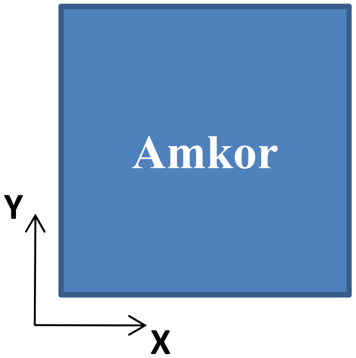
Strains and linear regression curves





CTE of 192 I/O CABGA by linear regression:

- X-axis = 7.0 ppm/°C
- Y-axis = 7.6 ppm/°C

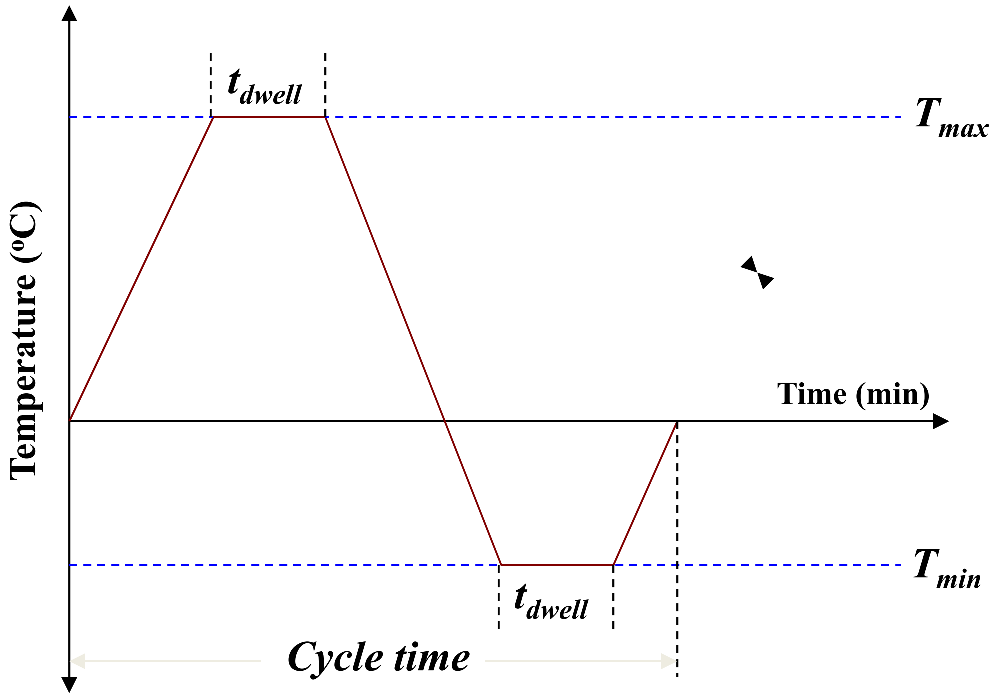


Specimen Orientation

CTE of 84 I/O CTBGA by linear regression:

- X-axis = 8.5 ppm/°C
- Y-axis = 9.6 ppm/°C

Temperature Cycling Test Matrix

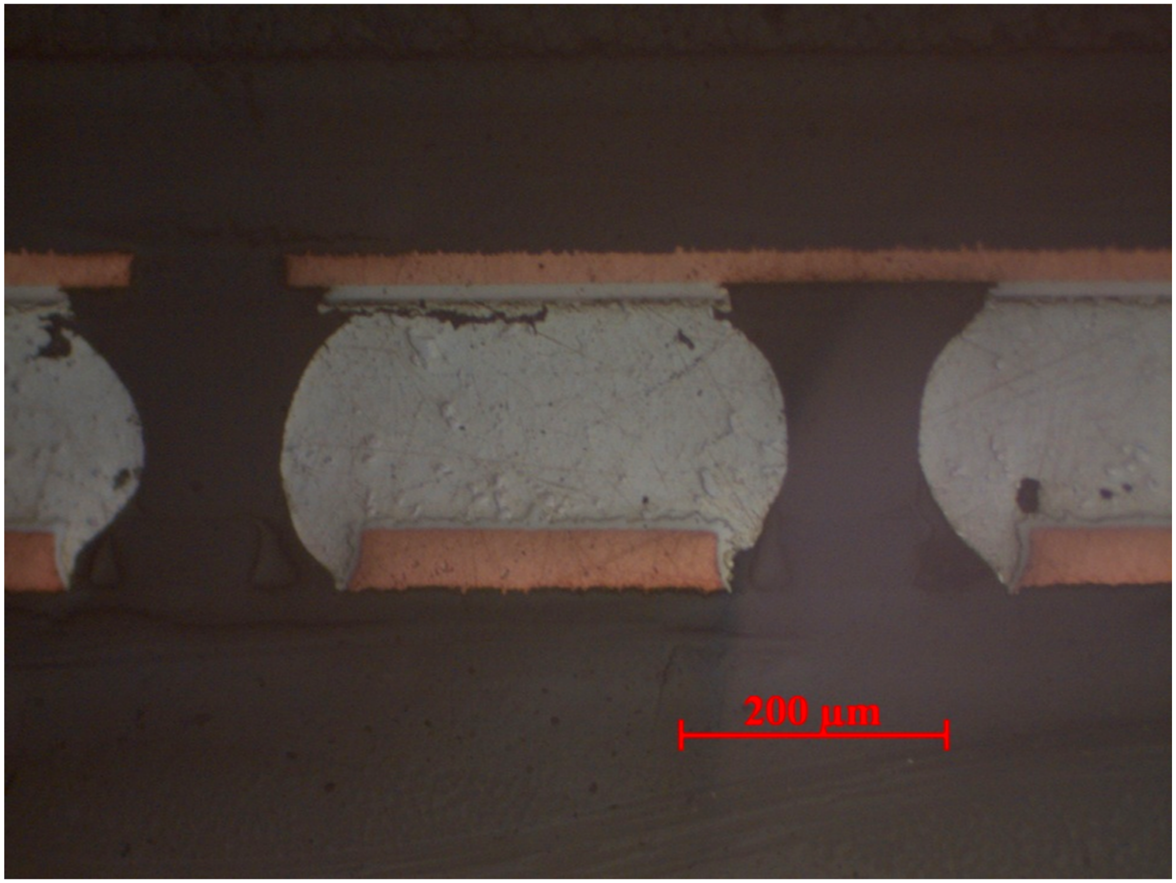


T_{min} (°C)	T_{max} (°C)	t_{dwell} (min)
0	100	10
0	100	60
25	125	10
25	125	60
-15	125	10
-15	125	60
-40	100	10
-40	100	60
-40	100	120
-40	125	10

- The ramp rate during heating and cooling was 7°C/min.
- Failure criterion was defined as the occurrence of resistance value greater than 1000Ω confirmed by 9 additional interruptions within an additional 10% of the cyclic life.

Failure Analysis

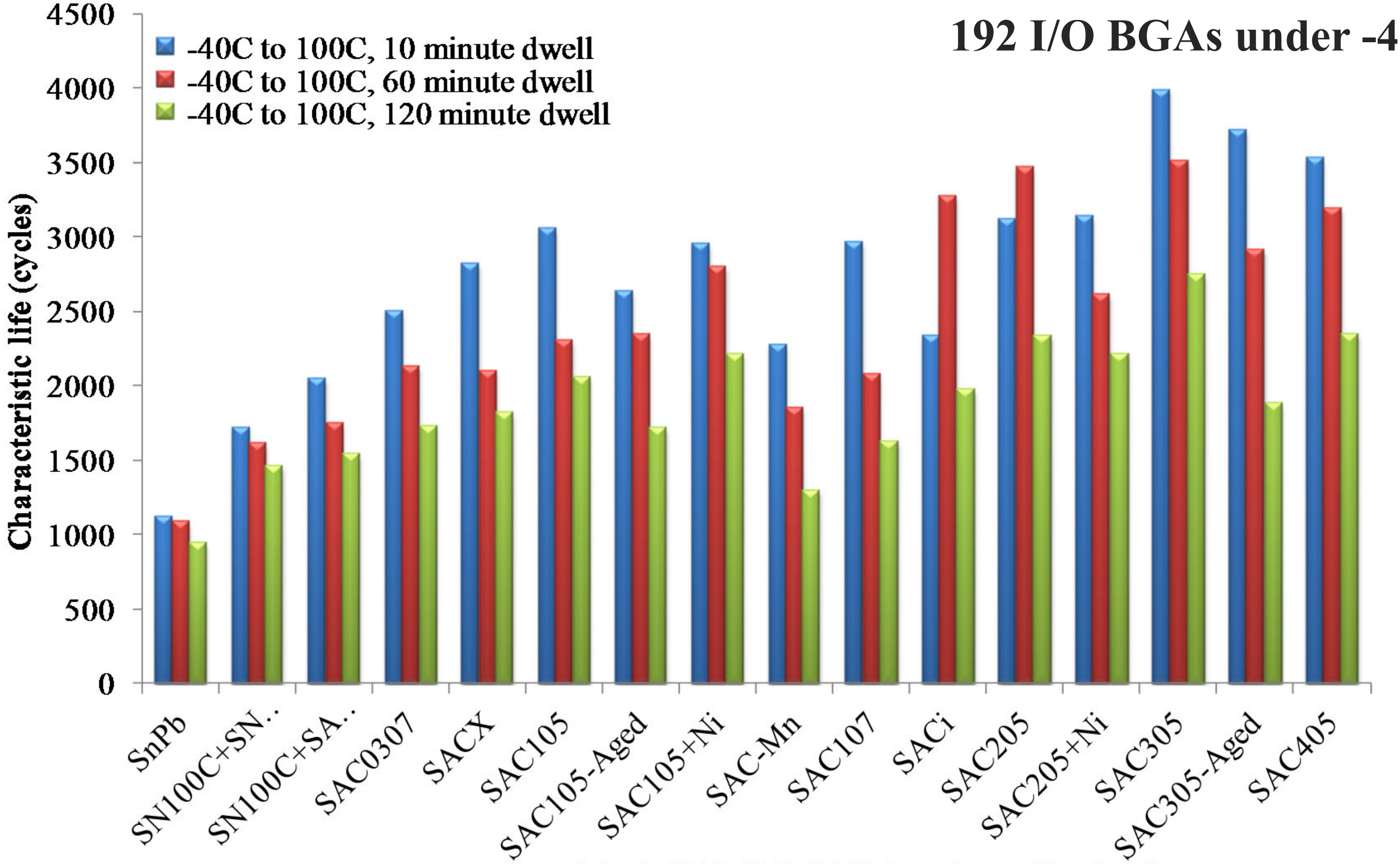
Failure analysis has been initiated to verify source of detected electrical discontinuity. To date, electrical and sectional analysis indicates solder failure.



Section of a 192 IO CABGA with SAC305 solder sphere attached with SAC305 solder. Removed after 4257 cycles under -15 to 125°C, 60 minute dwells.

Effect of Extended Dwell Time

- The extended dwell time resulted in decrease in characteristic lives in all lead-free solders except SACi and SAC205.
- The percentage decrease in the characteristic life with increase in dwell time is less significant for SnPb and SN100C solders.

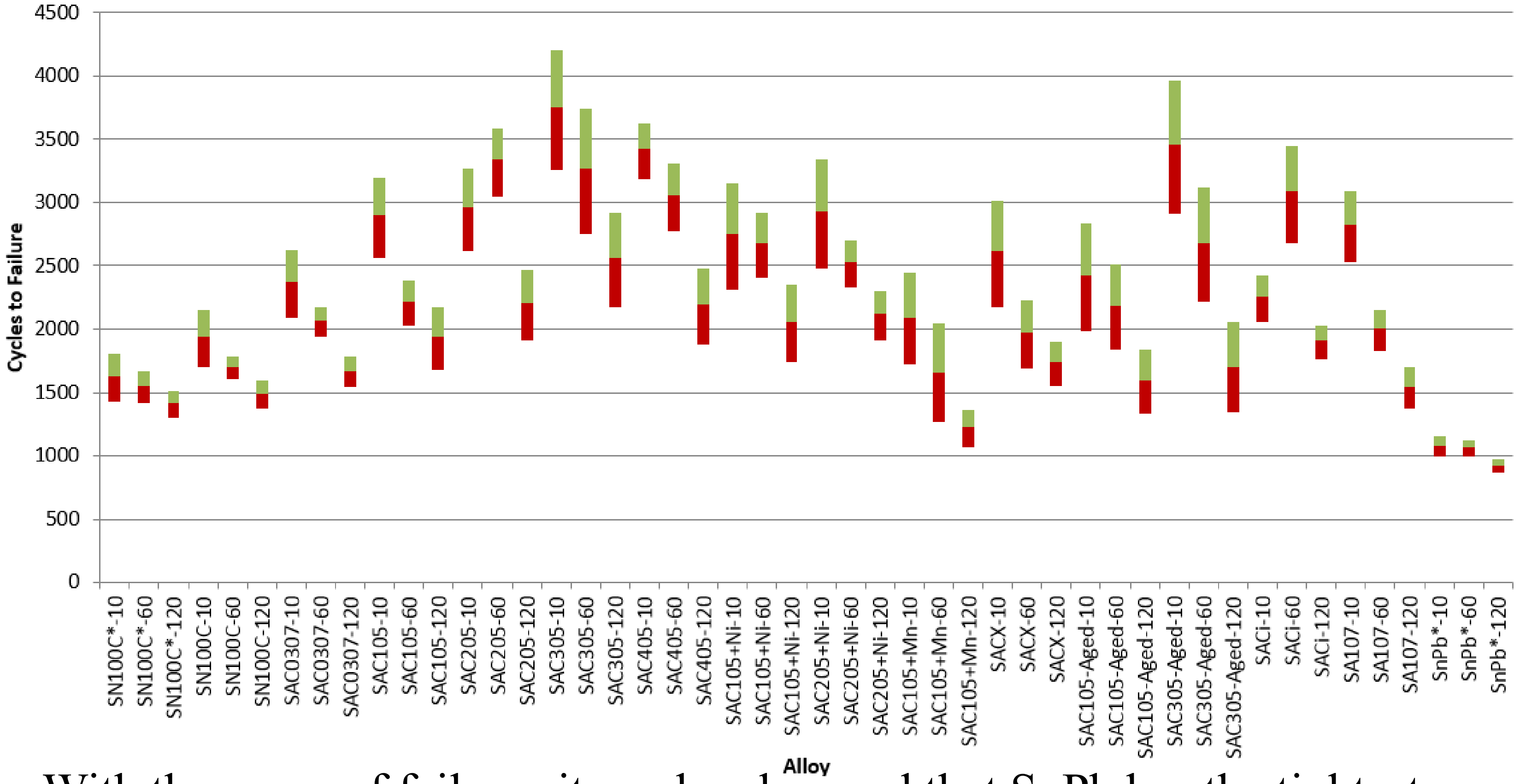


192 I/O BGAs under -40°C to 100°C tests

192 I/O BGA

25th to 75th Percentile

-40 to 100°C Test Condition



With the range of failures it can be observed that SnPb has the tightest distribution while the Aged SAC305 and SAC305 have some of the widest distributions

Model Constants and Curve Fitting

To determine the model constants for fatigue models, a curve fitting analysis may be used to calculated the model constants and provide statistical analysis of the individual parameters.

For this analysis, we examined two common models, Engelmaier Thermal Fatigue Life Model and the Norris-Landzberg Acceleration model. To facilitate the analysis, a commercial product called DataFit was used.

http://www.oakdaleengr.com/datafit.htm

Norris- Landzberg Acceleration Factors

$$AF = \frac{N_{use}}{N_{test}}$$

Norris – Landzberg Acceleration Factor Model for Collapsed Bump Solder Interconnects

$$AF = \left(\frac{f_f}{f_t}\right)^m \left(\frac{\Delta T_f}{\Delta T_t}\right)^n \exp^{\frac{E_a}{K}\left(\frac{1}{T_f} - \frac{1}{T_t}\right)}$$

SnPb solder, C4, m=0.33, n=-1.9, Ea/K=1414 [1]
SAC solder, BGA, CSP, TSOP, m=0.132 (here f is replaced with dwell time), n=-2.65, Ea/K=2185 [2]
SAC solder, m=0.33, n=-1.9, Ea/K=1414 [3]

[1] K. C. Norris and A. H. Landzberg, "Reliability of controlled collapse interconnections", IBM J. Res. Develop., May 1969, pp. 266-271,
[2] N. Pan et al, "An Acceleration Model for Sn-Ag-Cu Solder Joint Reliability under Various Thermal Cycle Conditions", Proc. SMTA, 2005, pp. 876-883
[3] V. Vasudevan and X. Fan, An Acceleration Model for Lead-Free (SAC) Solder Joint Reliability under Thermal Cycling, 2008 ECTC, May 2008, pp. 139-145.

Fitted Norris- Landzberg Parameters

$$AF = \left(\frac{f_f}{f_t}\right)^m \left(\frac{\Delta T_f}{\Delta T_t}\right)^n \exp^{\frac{E_a}{K}\left(\frac{1}{T_f}-\frac{1}{T_t}\right)}$$

Composition	Ea/K	n	m	R^2
SnPb	32	-1.752	0.078	0.329
SAC305	1602	-2.728	0.345	0.591
SAC405	2234	-3.380	0.352	0.780
SAC205	1888	-2.974	0.274	0.742
SAC105	1883	-3.292	0.309	0.514
SAC0307	1926	-3.094	0.230	0.597
SN100C	1766	-3.126	0.215	0.499
SN100C-SAC305	1379	-2.833	0.240	0.707
SAC105-Ni	1287	-2.517	0.302	0.300
SAC107	2078	-2.738	0.341	0.834

T – cyclic mean temperature was used for these fitted parameters.

Example use of Norris Landzberg Model

Consider you conduct 0 to 100C test with 24 cycles per day and you find your product survives 1000 cycles. Is this sufficient for a 10 year use condition of 20 to 60 with 1 cycle per day.

$$AF = \left(\frac{fu}{ft}\right)^{0.345} \left(\frac{\Delta Tu}{\Delta Tt}\right)^{-2.728} exp\left(1602\left(\frac{1}{273+Tu} - \frac{1}{273+Tt}\right)\right)$$

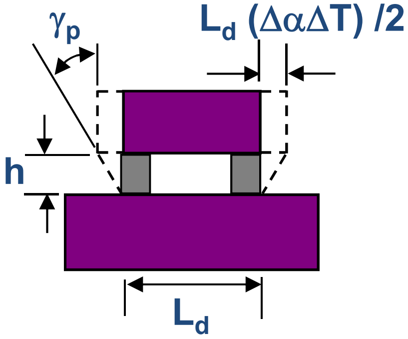
$$AF = \left(\frac{1}{24}\right)^{0.345} \left(\frac{40}{100}\right)^{-2.728} exp\left(1602\left(\frac{1}{273+40} - \frac{1}{273+50}\right)\right)$$

$$AF = \frac{Nu}{Nt} = 4.77$$

Nu =4.77(1000) = 4770 cycle per day = 12.8 years

Strain Range Based Solder Fatigue Rapid Assessment Model

$$N_f = \frac{1}{2}\left(\frac{\Delta D}{2\varepsilon_f}\right)^{\frac{1}{c}}$$



Leadless

$$\Delta D = \frac{f L_d \Delta\alpha\Delta T}{2h}$$

Leaded

$$\Delta D = \frac{fK\left(L_d \Delta\alpha\Delta T\right)^2}{200Ah}$$

- ε_f = Constant
- $c = c_0 + c_1 T_{sj} + c_2 \ln\left(1 + freq\right)$

- N_f : mean number of cycles to failure
- $\Delta\gamma_p$: inelastic strain range, g (package type, geometry, dimension, material property, load profile)
- K lead stiffness
- f model calibration factor assumed 1
- ε_f = material constant, fatigue ductility coefficient
- c = material constant, fatigue ductility exponent, h (load profile)
- T_{sj}: mean cyclic temp. (°C)
- freq: cycle frequency (cycles per day).

This model is preferred since it provides a physical relationship between the temperature cycle load and failure and it has a quick solution time.

Engelmaier, W., "Fatigue Life of Leadless Chip Carrier Solder Joints During Power Cycling,", Components, Hybrids, and Manufacturing Technology, IEEE Transactions on, Volume: 6 Issue: 3 , Sep 1983, pp. 232 -237

Strain Range Estimate

$$\Delta D = \frac{L\Delta\alpha}{2h}\Delta T = \frac{\left|\sqrt{\left(L_x\alpha_{cx}\right)^2 + \left(L_y\alpha_{cy}\right)^2} - \sqrt{\left(L_x\alpha_{bx}\right)^2 + \left(L_y\alpha_{by}\right)^2}\right|}{4h}\Delta T$$

192 IO BGA
L_x = 12 mm
L_y= 12 mm
h = 0.322 mm
a_{cx}= 7.0 ppm/^{o}C
a_{cy} = 7.6 ppm/^{o}C
a_{bx}= 13.8 ppm/^{o}C
a_{by}= 12.2 ppm/^{o}C

L$\Delta\alpha$/2h = 1.056e-4mm/mm/^{o}C

84 IO BGA
L_x = 5.5 mm
L_y= 5.5 mm
h = 0.18 mm
a_{cx}= 8.5 ppm/^{o}C
a_{cy} = 9.6 ppm/^{o}C
a_{bx}= 13.8 ppm/^{o}C
a_{by}= 12.2 ppm/^{o}C

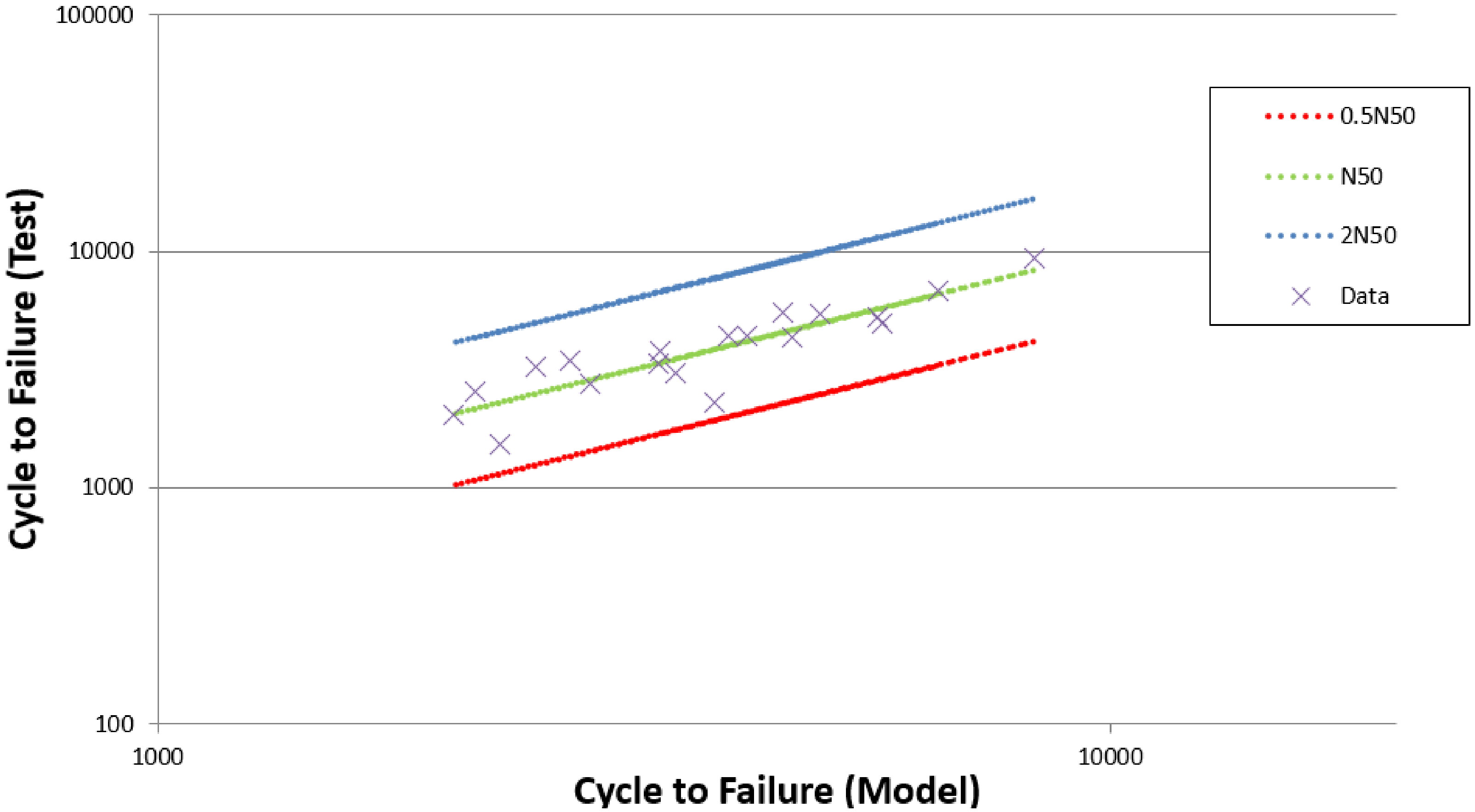
L$\Delta\alpha$/2h = 7.422e-5 mm/mm/^{o}C

Fitted Engelmaier Parameters For Leadless Formulation

Composition	c0	c1	c2	ef	R^2
SAC405	-0.5107	-7.43E-04	1.72E-02	0.939	0.861
SAC305	-0.7311	-6.74E-04	2.55E-02	5.391	0.789
SAC205	-0.6010	-6.77E-04	1.67E-02	1.959	0.836
SAC105	-0.6393	-6.15E-04	2.03E-02	2.177	0.742
SAC0307	-0.5842	-6.83E-04	1.42E-02	1.502	0.817
SAC107	-0.6092	-8.18E-04	2.17E-02	1.760	0.860
SAC105-Ni	-0.6604	-6.47E-04	2.37E-02	2.709	0.768
SnPb	-0.8569	-4.14E-05	1.12E-02	7.608	0.815
SN100C	-0.5344	-6.30E-04	1.13E-02	0.935	0.818

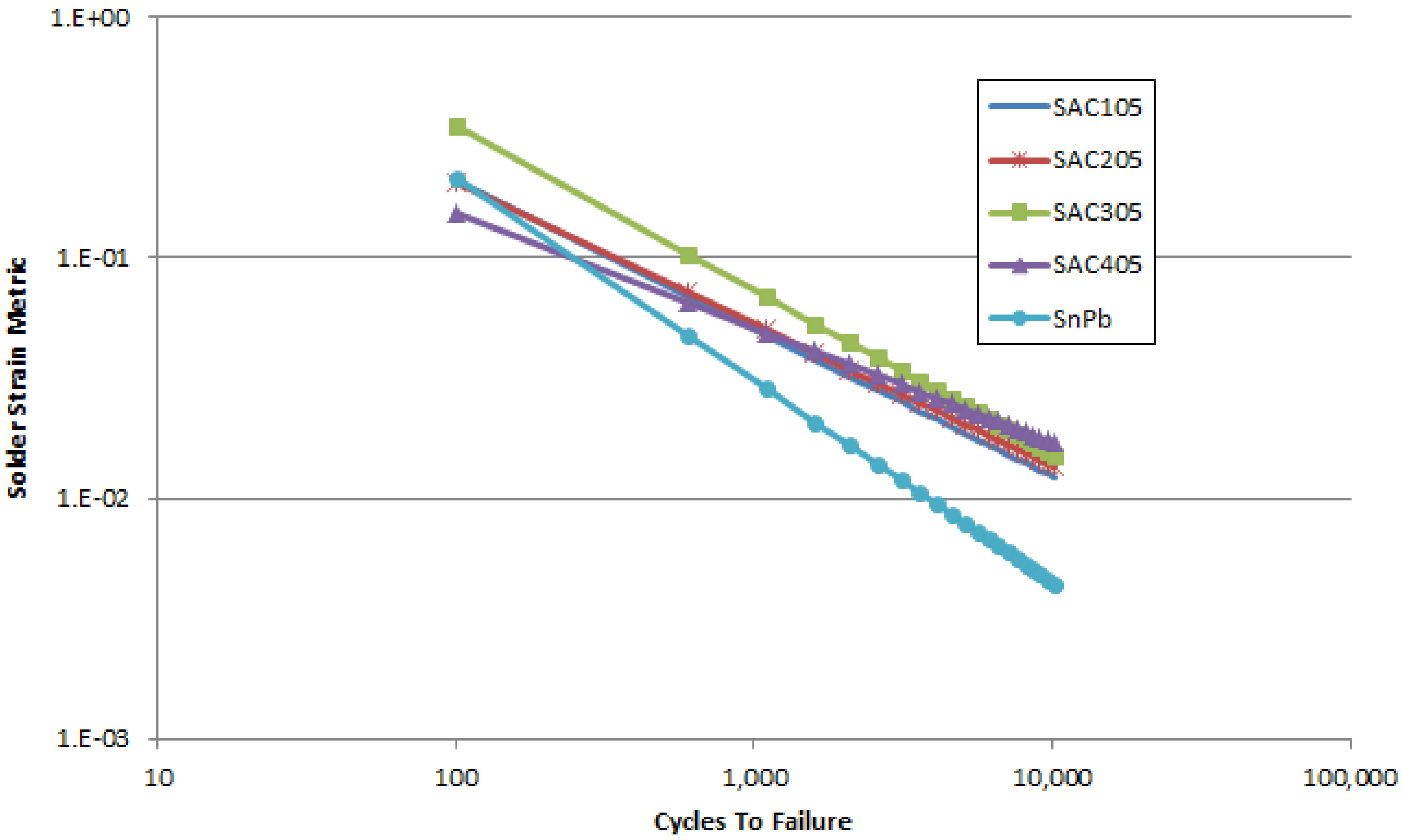
Analysis indicates data can be modeled using the Engelmaier formulation. However, the exponent constants are higher that those regressed from thermal fatigue testing of leadless parts.

Model Vs Test for SAC305



The fatigue life is bound between half and twice the predicted values.

Comparison of SAC solders



SAC305 appears to be better at higher damage metrics but cross with lower silver content SAC solder as damage metric reduces. SnPb solder gets better as damage metric increases.

Example of Life Assessment

Consider the 192 IO BGA subject to a temperature cycle that consist of 20C to 60C that occurs 1 time per day.

$$N_f = 0.5\left(\frac{\Delta D}{2\varepsilon_f}\right)^{\frac{1}{\left(c_0+c_1T_m+c_2 ln(1+CPD)\right)}}$$

$$N_f = 0.5\left(\frac{(1.056e-4)(40)}{5.391}\right)^{\frac{1}{\left(-0.73-0.00067(40)+0.025 ln(1+1)\right)}}$$

$N_f = 7837$ cycles to failure

Conclusions

- As has been noted in the past work, the reduction of silver results in a reduction temperature cycle fatigue life of SAC solders.
- The Engelmaier model formulated with frequency provides a reasonable representation of the data. However, the low correlation values for some materials points to an issue with applying this model to this test data.
- The Norris Landzberg model does not provide a very good fit the test data. As a result, the usefulness of this model is questionable. In particular, the SnPb does not correlate with prior work.

Questions?