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Solder Creep-Fatigue Model Parameters for SAC & SnAg Lead-Free Solder Joint Reliability Estimation

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Abstract
For many of the Pb-free solders required under the European RoHS directive, there is now sufficient information, primarily in the form of the results of accelerated thermal cycling of various levels of severity, to develop acceleration models for the creep-fatigue of these solders. In this paper the parameters for the SAC405/305, SAC205, SAC105 and SnAg to replace the parameters for eutectic SnPb in the well-established Engelmaier-Wild solder creep-fatigue model.

1. Introduction
Unfortunately, nobody has endeavored to repeat Roger Wild's classical work [Ref. 1] for SnPb solders for any of the Pb-free solders. Absent that, one is left with results from accelerated thermal cycling programs from various sources, obtained under widely varying conditions, on a large variety of different components, and all too often inadequately documented. However, at this time, there has accumulated sufficient data to combine the results from these test programs with physical insights and develop, albeit tentatively, accelerated reliability models for at least some of these Pb-free solders. The reason for having such a model allows (1) the outright estimation of solder joint reliability for a given product in its use environment, (2) the development of acceleration factors to extrapolate the results from accelerated reliability tests to use conditions, and (3) the specification of reliability standards like IPC- 9701 [Ref. 2].

2. Data Base
Looking at the Weibull graphs of the results from accelerated creep-fatigue thermal cycling tests, it is evident that the accelerated test results for the SAC405/305 are no more than a factor of two (2) away from the results for SnPb solder joints. This is illustrated in Figures 1 through 6.

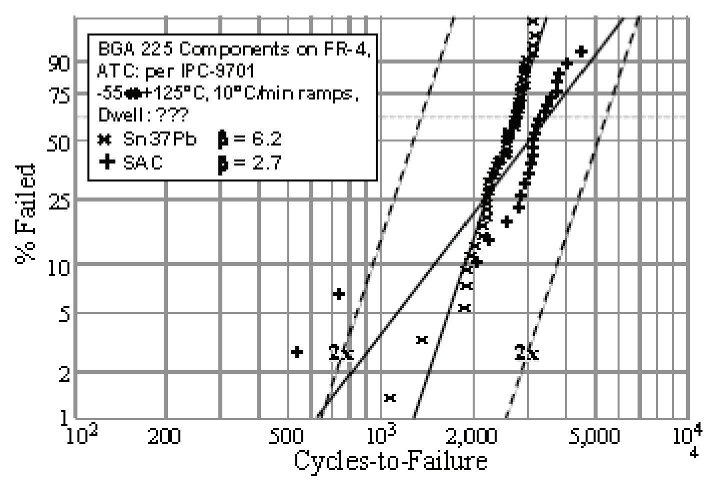

Figure 1— Weibull plots for Sn37Pb and SAC405 solder joints for severe thermal cycling showing significantly lower life and wider failure distribution for SAC405. [Source: Dave Hillman, Rockwell Collins, USA].

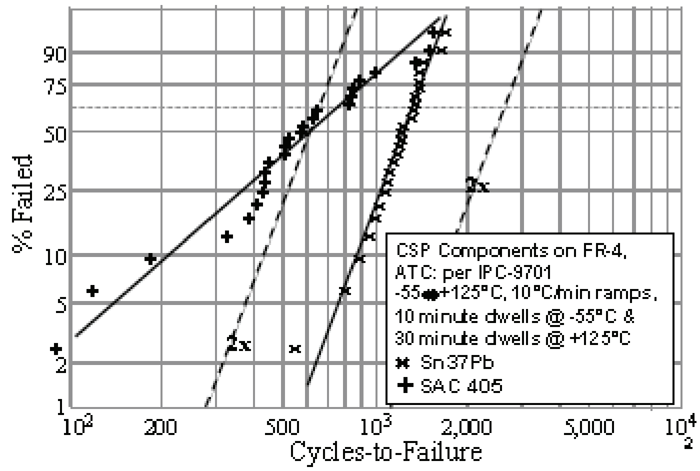

Figure 2— Weibull plots for Sn37Pb and SAC solder joints for severe thermal cycling showing comparable life but wider failure distribution for the SAC solder. [Source: Dave Hillman, Rockwell Collins, USA].

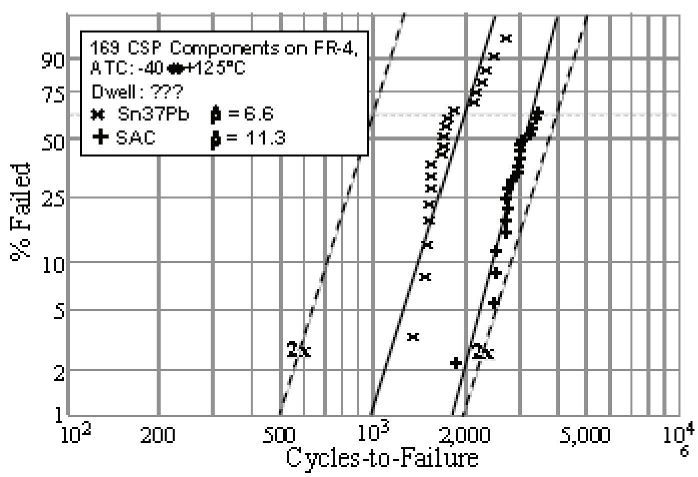

Figure 3— Weibull plots for Sn37Pb and SAC solder joints for severe thermal cycling showing longer life and narrower failure distribution for the SAC solder. [Source: iNEMI Consortium, USA].

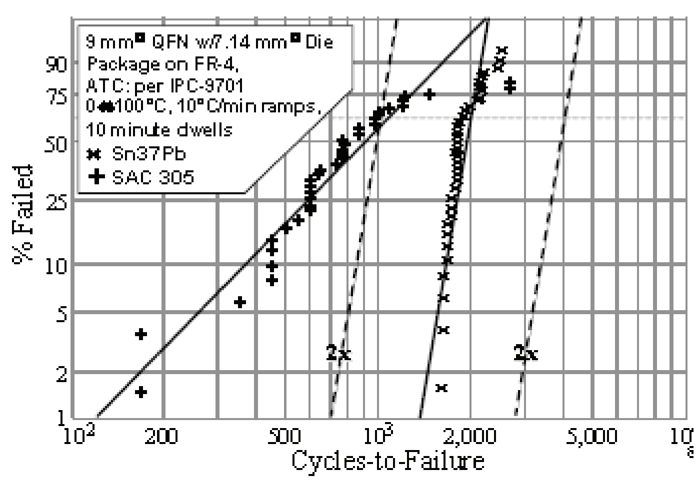

Figure 4— Weibull plots for Sn37Pb and SAC405 solder joints for benign thermal cycling showing essentially identical results for SAC405. [Source: Alex Chan, Alcatel-Lucent, Canada, Aman Khan, Int. Rectifier, USA, and Robert Kinvaniui, Sanmina-SCI, USA].

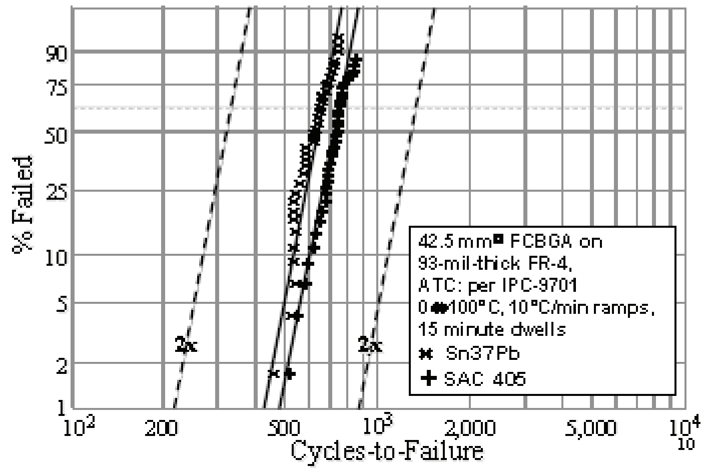

Figure 5— Weibull plots for Sn37Pb and SAC305 solder joints for benign thermal cycling showing essentially identical results for SAC305. [Source: J. Radhakrishnan, Intel, USA].

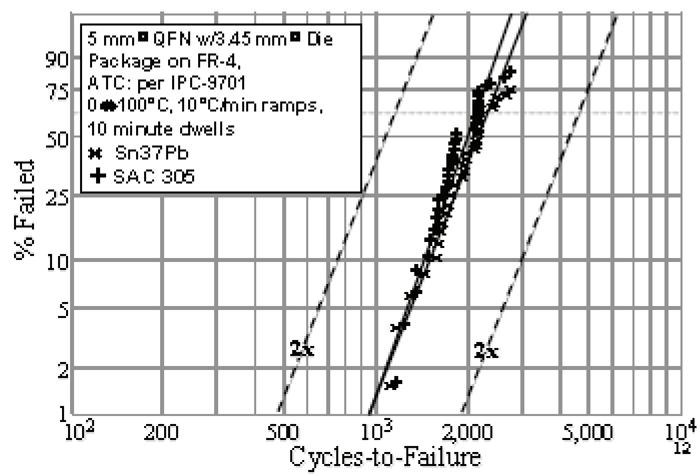

Figure 6— Weibull plots for Sn37Pb and SAC305 solder joints for benign thermal cycling showing essentially identical results for SAC305. [Source: Alex Chan, Alcatel-Lucent, Canada, Aman Khan, Int. Rectifier, USA, and Robert Kinvaniui, Sanmina-SCI, USA].

Additional data and analyses were published showing that for results coming from the same testing environment, a certain consistency and commonality can be shown. Figure 7 shows the results of an analysis of some of the JCAA/JGPP/ NASA No-Lead Solder Project data [Ref. 3] by CALCE at the University of Maryland [Ref. 4]. The analysis is based on the Engelmaier-Wild model (see Refs. 1 & 2), with four of the parameters changed by regression analysis and data fitting without consideration of the solder properties or the creep-fatigue behavior, other than the accelerated test results.

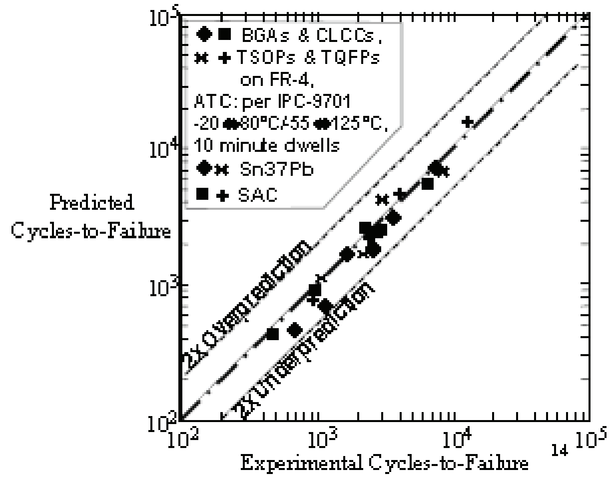

Figure 7— Plot of comparisons of predicted and experimentally determined accelerated cycles-to-failure for Sn37Pb and SAC solder joints for leadless and stiff-leaded components. [Source: Ref. 4].

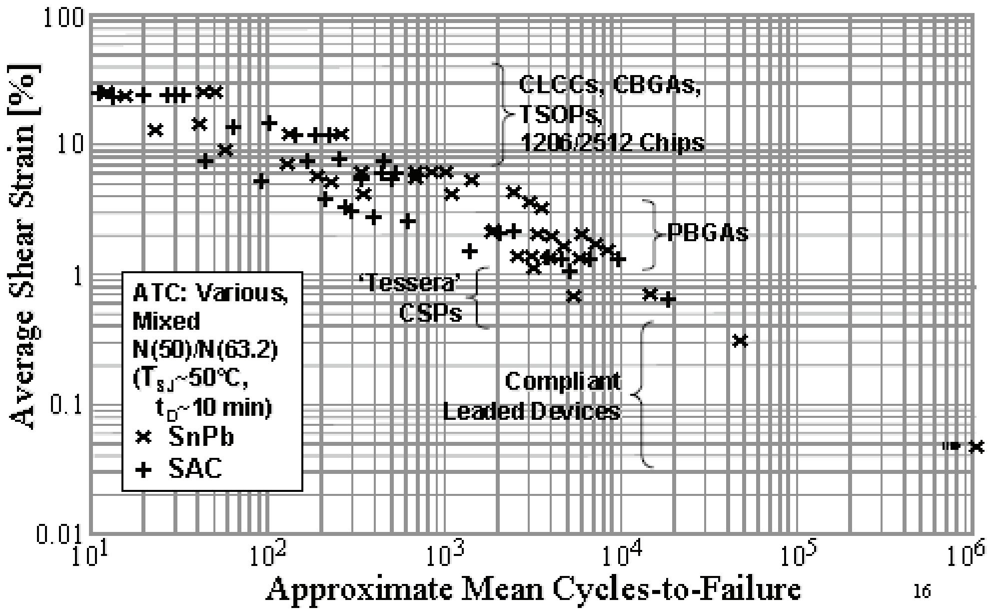

Figure 8— Manson-Coffin plot of SnPb and SAC solder joint accelerated creep fatigue test results. [Sources: Jean-Paul Clech, EPSI Inc.; Ref. 4; Bell Telephone Laboratories data base, others].

The analysis in Reference 4 initially analyzed the leaded components, TSOPs and TQFPs, as compliant-leaded in violation of 'Caveat 5' in IPC-D-279 [Ref. 5] which dictates that the leaded analysis be used only for component with leads sufficiently compliant to reduce the cyclic stress range to stress levels below the yield strength of the solder. When these components were properly analyzed as leadless, the predicted results and the experimental results were within a factor of 2 of each other, which is well within the experimental variation to be expected.

This experimental variation is fully evident in Figure 8 which is based on an analysis of Jean-Paul Clech of available industry data (see Ref. 6, Fig. 14), however with a significant addition of data.

For other Pb-free solders, the data base is much less developed. Furthermore, much in terms of the test details is missing.

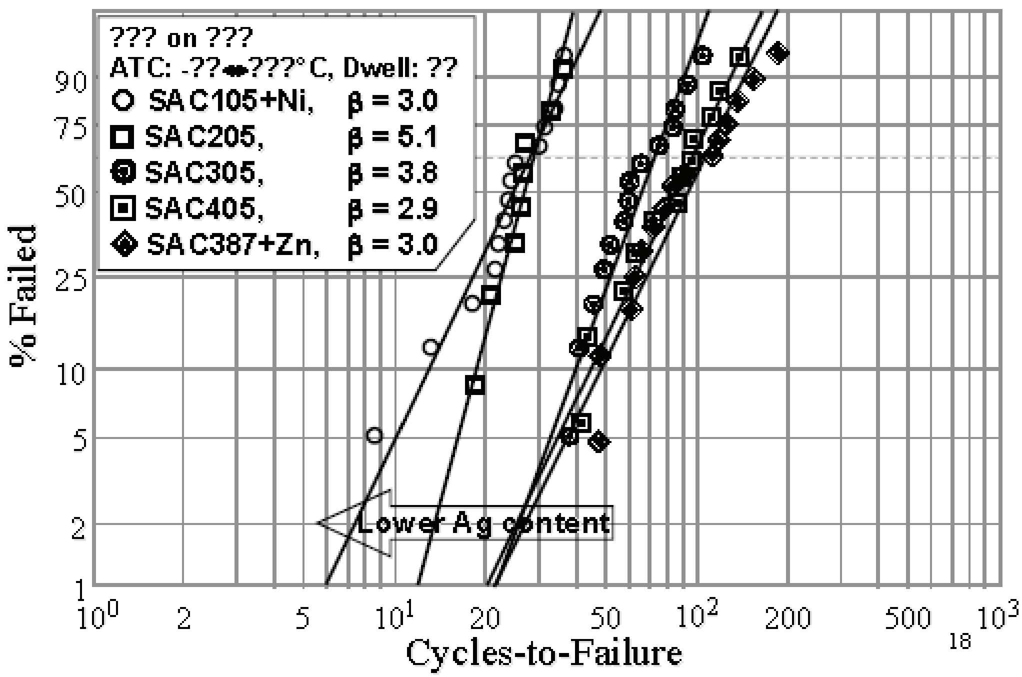

Figure 9— Manson-Coffin plot of SnPb and SAC solder joint accelerated creep fatigue test results. [Sources: Linda Scala, Celestica, USA].

3. Solder Creep-Fatigue Model and Results

From these and other data and the physical insights gained, the model parameters in the Engelmaier-Wild solder creep-fatigue model can be modified for some of the Pb-free solders.

The Engelmaier-Wild model is shown in Equations 1 and 2 with the parameters that change for different solder alloys.

$$N_f(50\%) = \frac{1}{2}\left[\frac{2\varepsilon_f'}{\Delta D}\right]^m \quad \text{Eq. 1}$$

where

$$\frac{1}{m} = c_0 + c_1\overline{T}_{SJ} + c_2 \ell n\left(1 + \frac{t_0}{t_D}\right) \quad \text{Eq. 2}$$

Five parameters are different for different solder alloys as shown in Table I. It is likely, that these parameters will see slight adjustments once data showing the independent influences of temperature and creep time on creep-fatigue life are available. The National Physical Laboratory, UK, and perhaps others are working on developing these data.

Table I. Parameters for Solder Creep-Fatigue Model

Solder	Model Parameters				
	ε_f'	c_0	c_1	c_2	t_0
Engelmaier-Wild Creep-Fatigue Model for SnPb Solders					
SnPb	0.325	0.442	6.00e-04	-1.74e-02	360
Tentative Creep-Fatigue Model Parameters for Pb-Free Solders					
SAC405/305	0.425	0.480	9.30e-04	-1.92e-02	500
SAC205	0.250	0.480	9.30e-04	-1.92e-02	500
SAC105	0.225	0.480	9.30e-04	-1.92e-02	500
SnAg	0.275	0.430	6.30e-04	-1.82e-02	400

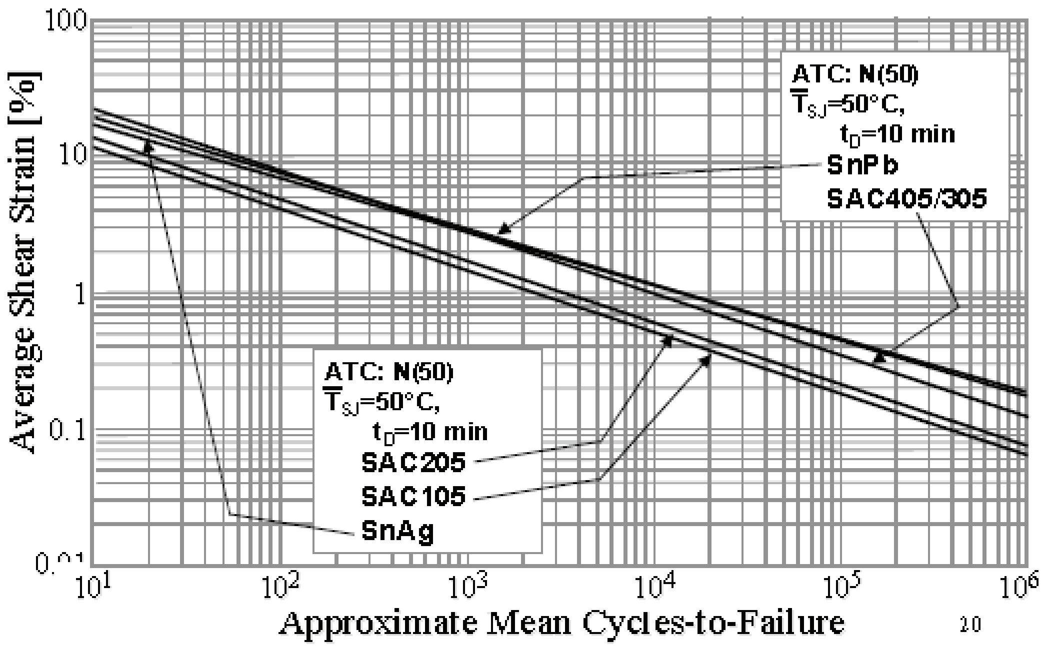

Figure 10— Manson-Coffin plot of SnPb and Pb-free solder joint accelerated creep-fatigue model results.

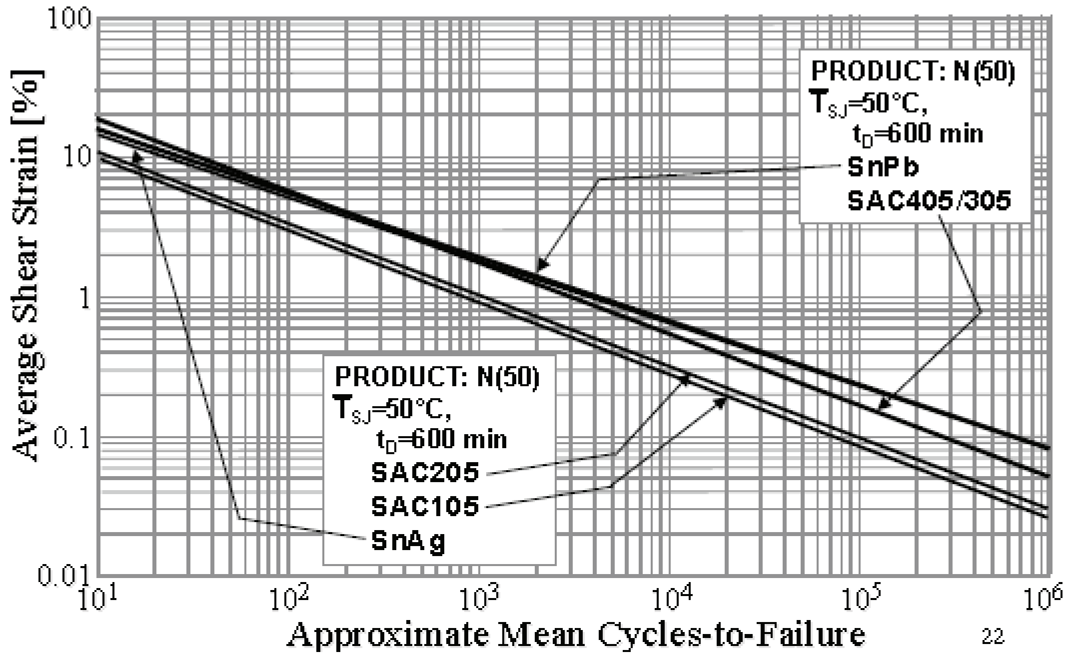

Figure 11— Manson-Coffin plot of SnPb and Pb-free solder joint product creep fatigue model results.

In Figure 10 the results of model predictions for the various solders are shown in a Manson-Coffin plot. The predictions are for an accelerated test with a cyclic dwell time of 10 minutes; in Figure 11 similar results are shown for a product operational cycle with a dwell time of 600 minutes. In all cases the cyclic mean temperature is 50°C.

4. Discussion And Conclusions

The solder alloys listed in Table I are far from all that are in use today; however, there is not enough information as yet for other Pb-free solders to propose model parameters.

Both the data base of the results of accelerated reliability tests as well as the model predictions shown for accelerated reliability testing in Figure 10 and a typical product operational environment in Figure 11 show relatively insignificant differences in the solder creep-fatigue for SnPb and SnAg solders; for benign loading conditions SAC 405/305 solders show a reduced life of up to a factor of 3.

SAC solders with reduced silver contents show a marked decline their mean cycles-to-failure relative to the other solder alloys in Table I.

References:

[1] Wild, R. N., "Some Fatigue Properties of Solders and Solder Joints," IBM Tech. Rep. 73Z000421, January 1973.

[2] IPC-9701, Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments. IPC—Association Connecting Electronics Industries, January 2002/IPC-9701A, February 2006.

[3] Hillman, D., and R. Wilcoxon, "-55ºC to +125ºC Thermal Cycle Testing," JCAA/JG-PP No-Lead Solder Project, Final Report, March 15, 2006.

[4] Osterman, M., A. Dasgupta and B. Han, "A Strain Range Based Model for Life Assessment of Pb-free SAC Solder Interconnects," Proc. 56th ECTC, May-June 2006, pp. 884-890.

[5] Engelmaier, W. in IPC-D-279, Design Guidelines for Reliable Surface Mount Technology Printed Board Assemblies. IPC—Association Connecting Electronics Industries, July 1996.

[6] Engelmaier, W., "Update on Lead-Free Solder Joint Reliability," Global SMT & Packaging, Vol. 8, No. 8, August 2008, pp. 46-49.

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