DPAM/DPAF Solder Joint Reliability under Thermal Cycling Conditions

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SUMMARY

The attachment reliability of SnPb and SAC DPAM/DPAF assemblies was estimated under mild to moderate field conditions: 25C to 45C and 25C to 55C thermal cycling at a frequency of 6 cycles/day. Reliability estimates were obtained by extrapolation of test failure cycles under Accelerated Thermal Cycling (ATC): 0C to 100C (10C/min ramp rates, 15 minute dwells) to field conditions, using strain-energy-based acceleration factors for both SnPb and SAC assemblies.

Assuming good quality solder joints, i.e. assembly as per common workmanship requirements, the SAC DPAM/DPAF assemblies are predicted to have a longer life than SnPb DPAM/DPAF assemblies. Under the above stated service conditions, solder joints of SAC DPAM/DPAF assemblies are predicted to have less than 1 ppm failures at 20 years of field use.

The solder joint reliability projections are specific to DPAM / DPAF assemblies on 92 mil thick FR-4 boards with similar properties as the test boards. Fraction failed at 20 years will also change under other application-dependent thermal conditions and will increase under harsher use conditions than those used in this study.

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INTRODUCTION

Accelerated test results for SAMTEC's DPAM/DPAF assemblies are extrapolated to mild and moderate use conditions using strain-energy based acceleration factors for SAC and SnPb solder joints under thermal cycling conditions. This report presents failure statistics from ATC testing, input data that was used to derive acceleration factors - including critical geometric parameters and material properties, and thermal cycling profiles – stress/strain analysis results (hysteresis loops) as well as predicted failure rates in the field. Acceleration factors for both SnPb and SAC assemblies are based on the ratio of cyclic strain energy (= area of stress/strain hysteresis loops) under test and use conditions.

FAILURE STATISTICS

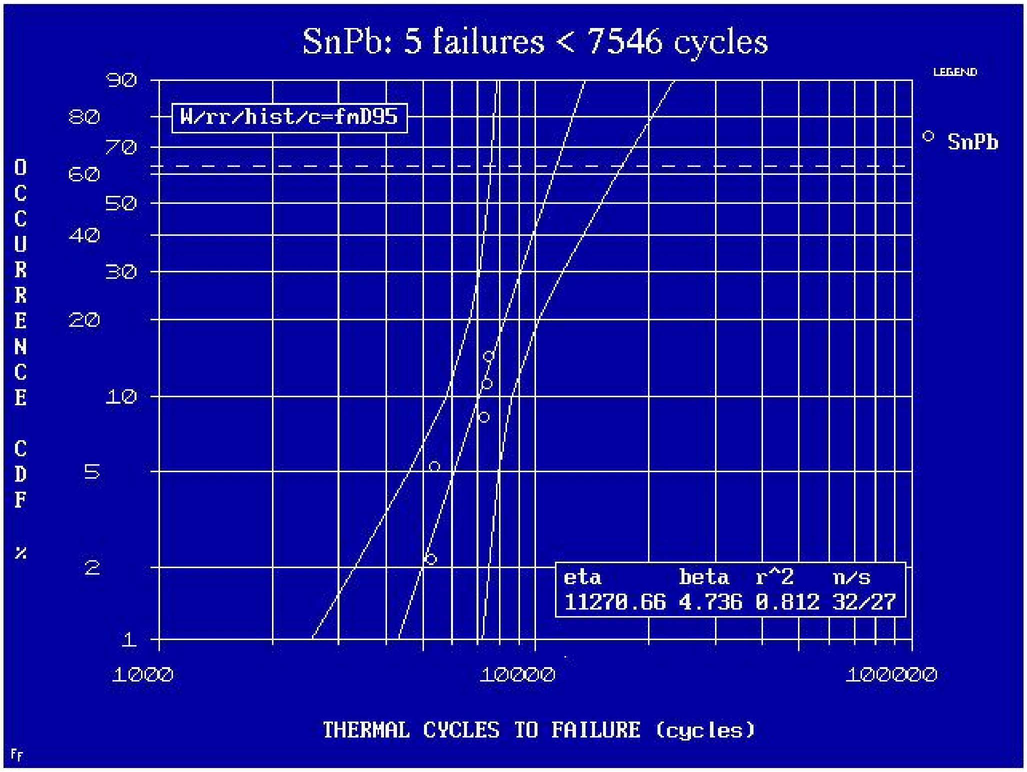

Figure 1: Two-parameter Weibull fit of SnPb ATC failure data.

For both SAC and SnPb assemblies, sample size was 32 connectors each (mated assemblies).

For SnPb, 5 failures were recorded within a test period of 7546 ATC cycles. Failure cycles are: 5240, 5363, 7281, 7416 and 7466 cycles. As shown in Figure 1, the two-parameter Weibull analysis of failure cycles gives a characteristic life: α = Cycles to 63.2% Failures = 11270 cycles and a shape parameter (slope of Weibull distribution): $\beta = 4.736$. For comparison purposes, an "average" value of β for SnPb surface mount assemblies is about 6.

For SAC assemblies, a single failure was recorded at 6917 cycles. For the shape parameter of the SAC failure distribution, assume the same β as for SnPb assembly, i.e. $\beta = 4.736$. The characteristic life is then estimated by back-solving the two-parameter Weibull equation for α, as shown here after:

$$\% \text{ Fail at 1st failure} = 1/32 = 1-\exp[-(6917 / \alpha)^{4.736}]$$

which gives α = 14,331. The SAC characteristic life is 14,331 / 11270 = 1.27 times larger than that of SnPb assemblies.

The end goal of this analysis is to extrapolate the ATC test results to specific field conditions.

THERMAL CONDITIONS

Accelerated Thermal Cycling Conditions

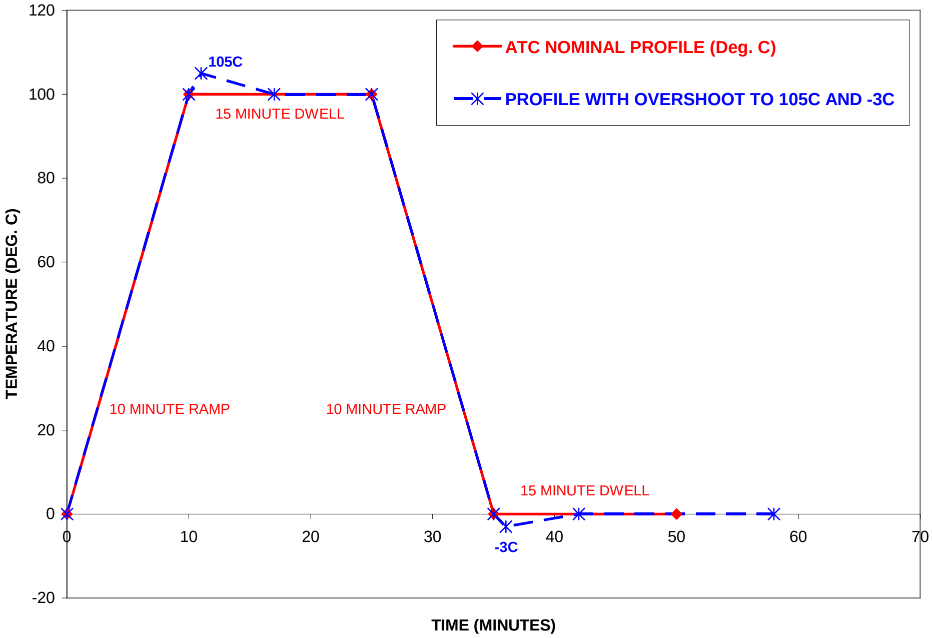

Figure 2: Accelerated thermal cycling profile.

Accelerated thermal cycling conditions are given as a temperature swing between 0°C and 100°C with ramp rates of 10ºC/minutes and dwell times of 15 minutes. The cycle duration is 50 minutes and the test frequency is 28.8 cycles per day. A temperature profile measured on a test board is shown in Figure 2. The slight temperature overshoots: 105ºC on the hot side and -3ºC on the cold side, were neglected in the solder joint stress/strain analysis, which makes the acceleration factors slightly conservative.

Use Conditions

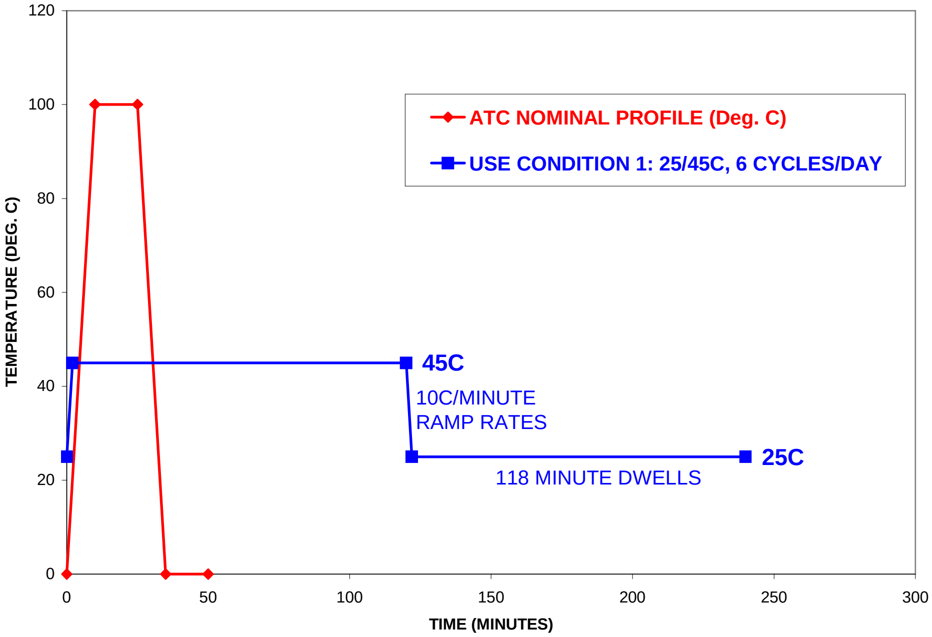

Figure 3a: Use thermal cycle profile # 1: 25/45ºC, 10ºC/min. ramps, 6 cycles/day (1 cycle = 4 hours).

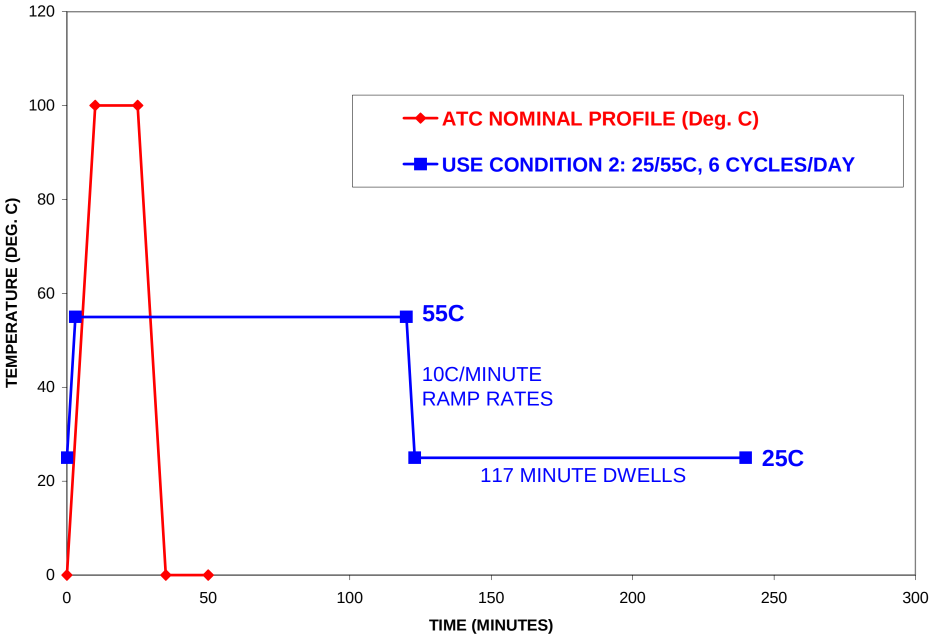

Figure 3b: Use thermal cycle profile # 2: 25/55ºC, 10C/min. ramps, 6 cycles/day (1 cycle = 4 hours).

Thermal profiles, and their descriptive parameters, are shown in Figures 3a & b for two sets of use conditions that were selected for field reliability projections. The cycles are from 25ºC to 45ºC (ΔT = 20ºC), and 25ºC to 55ºC (ΔT = 30ºC) at a frequency of 6 cycles/day. Reliability projections will differ for other field conditions.

DPAM / DPAF GEOMETRY AND MATERIAL PROPERTIES

Maximum Distance to Neutral Point

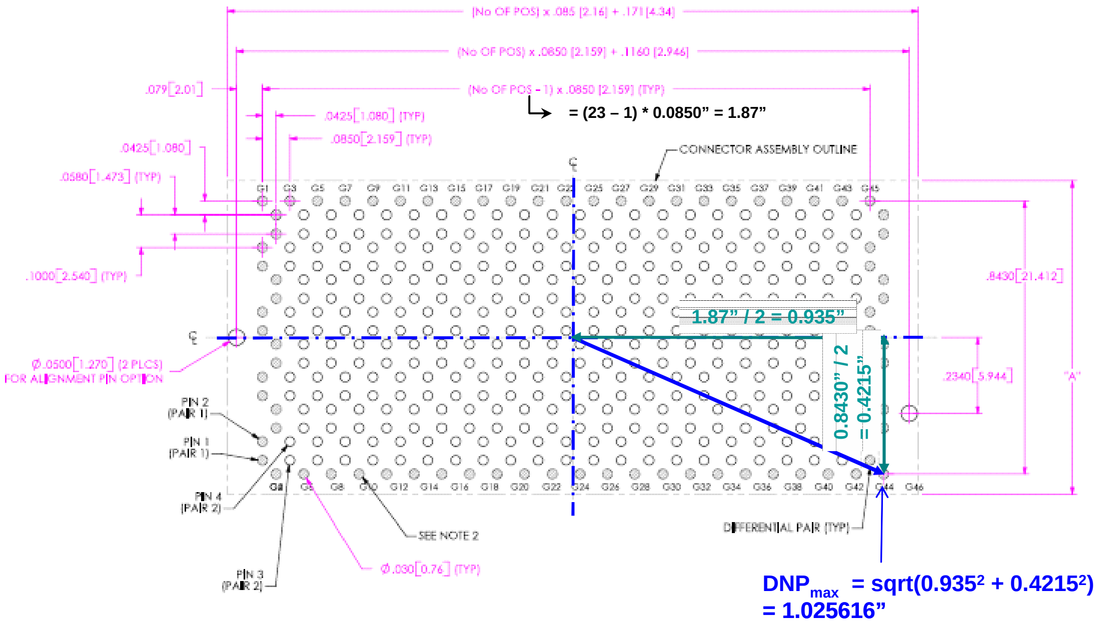

Figure 4: Footprint layout and maximum Distance to Neutral Point (DNP_{max})

Based on the footprint layout (Figure 4), the maximum Distance to Neutral Point (DNP_{max}) at the outermost corner joints is 1.025". The subsequent stress/strain, hysteresis loop analysis is done at outermost corner joints.

Component Effective CTE in Diagonal Direction of DPAM / DPAFs

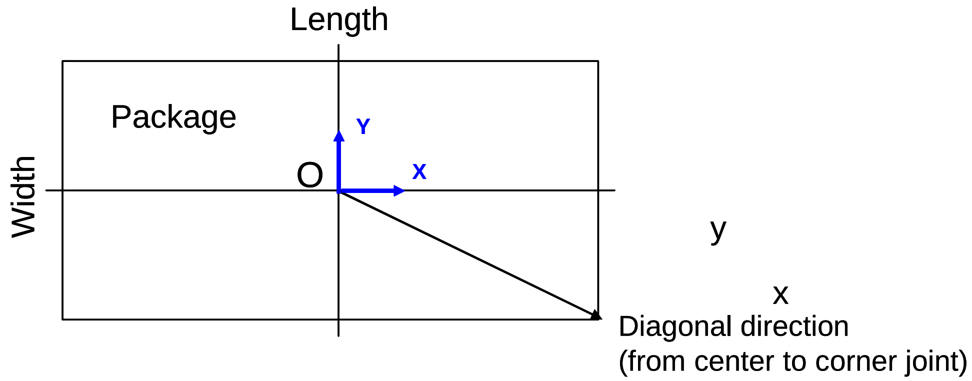

Figure 5: Component coordinate system for effective CTE calculation.

Since the maximum thermal expansion mismatch is at corner joints in the diagonal direction of the DPAM / DPAM assembly, and the components have different CTEs in the x- and y- directions (Figure 5), we need to estimate the DPAM / DPAF effective CTE in the diagonal direction of the connectors:

$$\alpha_{DIAG} = \frac{\alpha_Y + r^2 \alpha_X}{1 + r^2} = \frac{40.7 + 2.218268^2 \times 15.5}{1 + 2.218268^2} = 19.756\ ppm\ / C$$

where x- is the direction in the length direction, and α_x = 15.5 ppm/ºC and α_y = 40.7 ppm/ºC are the given (measured) CTEs of the connectors in the x- and y- directions, respectively. The “package” aspect ratio, r = “length” / “width”, is obtained based on the footprint layout in Figure 4: r = 0.935” / 0.4215” = 2.218268. Since x is the length direction of the component, the calculated effective CTE in the diagonal direction is closer to the x-CTE of the DPAM / DPAF connectors.

Board Effective CTEs and CTE Mismatches in Component Diagonal Direction

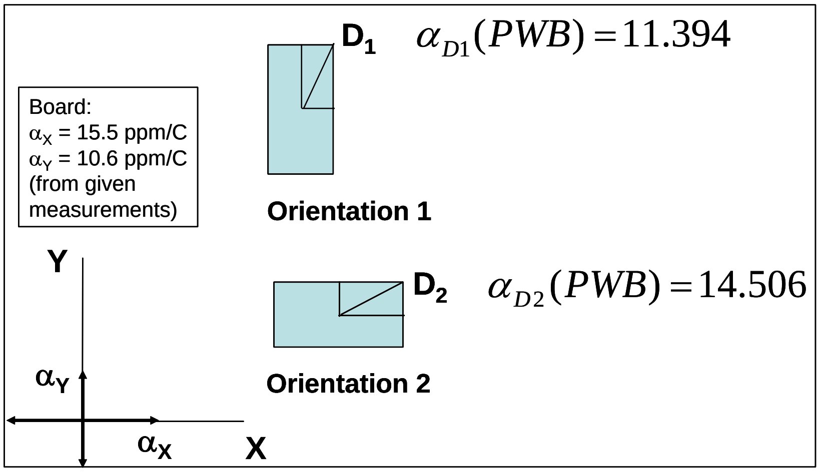

Figure 6: Board coordinate system and direction-dependent CTEs.

The board also has different in-plane CTEs in its own X- and Y-directions (see coordinate system in Figure 6): α_X = 15.5 ppm/ºC and α_Y = 10.6 ppm/ºC (given measured values). The board to connector CTE mismatch will be different in the two diagonal directions D1 and D2 on the board when connectors are mounted with the length in the Y or X direction of the board (see Figure 6).

The board effective CTEs in the D_1 and D_2 directions are calculated as:

$$\alpha_{D1} = \frac{\alpha_Y + r^2\alpha_X}{1+r^2} = \frac{15.3 + 2.218268^2 \times 10.6}{1+2.218268^2} = 11.394\, ppm/C$$

$$\alpha_{D2} = \frac{\alpha_Y + r^2\alpha_X}{1+r^2} = \frac{10.6 + 2.218268^2 \times 15.3}{1+2.218268^2} = 14.506\, ppm/C$$

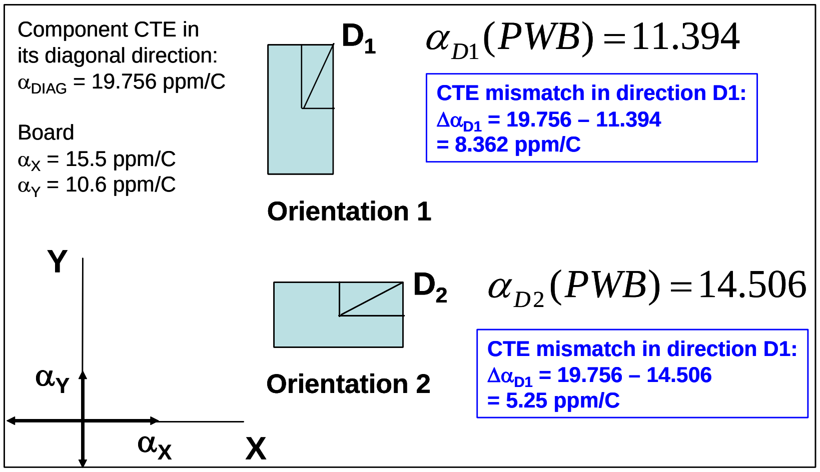

Figure 7: Maximum global CTE mismatch between board and connector in diagonal directions D_1 & D_2.

Since the corner joints of the DPAM / DPAF assemblies are more prone to failure, we are interested in board-to-connector CTE mismatches in the diagonal directions D1 and D2 (Figure 6). From the above calculated effective CTE of the connectors in their diagonal direction, and the effective CTEs of the board in the diagonal directions D_1 and D_2, CTE mismatches are obtained as shown in Figure 7. The largest CTE mismatch is in direction D1.

In subsequent analysis, acceleration factors are computed for connectors mounted in Orientation 1 in Figure 7 (connector length parallel to board direction Y with a board CTE: α_Y = 10.6 ppm/ºC), i.e., the worst case orientation with the largest CTE mismatch between the board and connectors.

Other Board Parameters

Board thickness is 92 mil.

For Young's modulus of FR-4 type boards, we use a standard value E = 2.50e6 psi.

Solder Joint / Assembly Parameters

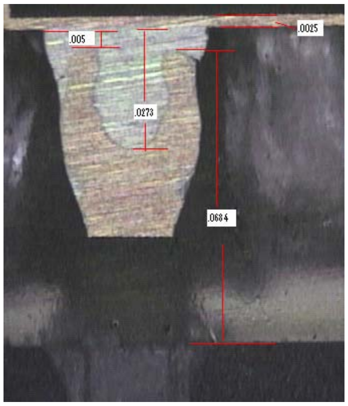

Figure 8: Solder joint cross-section

Based on the solder joint cross-section in Figure 8, the minimum solder joint thickness that is used in the analysis is $h_S = 5$ mil.

Another critical solder joint parameter is the solder joint crack area or minimum solder joint load bearing area in shear, A_S. Based on a footprint pad diameter of 30 mil, A_S is estimated as:

$$A_S = \pi * (30e\text{-}3 / 2)^2 = 7.0686E\text{-}04 \text{ in}^2$$

Other Connector Parameters

Connector parameters used in the connector / board assembly stiffness model are:

- Young's modulus of plastic insulator material (Polyplastics): E = 15,000 MPa = 2.175E6 psi
- Parts floor thickness = 60 mil for bottom of both DPAF & DPAM

In addition, the board / connector assembly model includes a constraint for no bending of the assembly once the parts are mated together. For the definition of and details on assembly stiffness, see our SMI'96 paper (http://jpclech.com/clech_SRS_Model_smi96.pdf).

STRESS / STRAIN HYSTERESIS LOOPS

Methodology

All the input parameters that were given above are used to determine stiffness and effective CTE parameters that are then used to determine the solder joint stress/strain response under thermal cycling conditions, with separate analysis for stresses driven by global and local CTE mismatch. The previous parameters and analysis types are defined in our SMI'96 paper (http://jpclech.com/clech_SRS_Model_smi96.pdf). The basic algorithm that is used to generate stress/strain hysteresis loops with ramp rate effects is explained in an online report under NIST's Metallurgy Division web site, "Review and Analysis of Lead-Free Solder Material Properties" at: http://www.metallurgy.nist.gov/solder/clech/ . The application and validation of the strain energy approach to derive acceleration factors for SAC387/396 assemblies is discussed in details in our SMTAI'05 paper: http://jpclech.com/CLECH_SMTAI2005_PAPER.pdf, with further validation data to be presented at SMTAI'06 (September '06, Chicago).

Hysteresis loops for the DPAM/DPAF assemblies are presented next, followed by the derivation of acceleration factors that are obtained as the ratio of loop areas under test and field conditions.

Hysteresis Loops

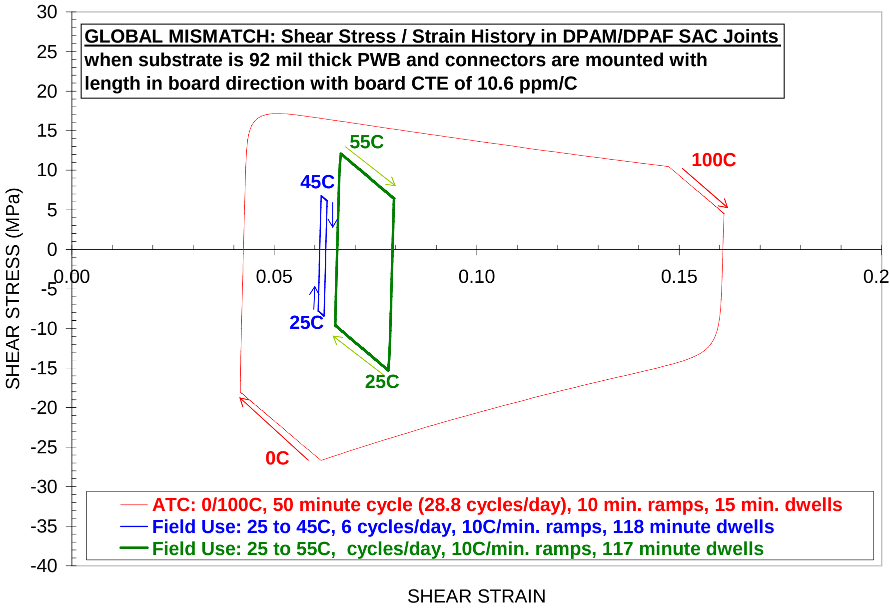

Figure 9a: SAC DPAM/DPAF Assemblies: Global Mismatch Shear Stress/Strain Loops.

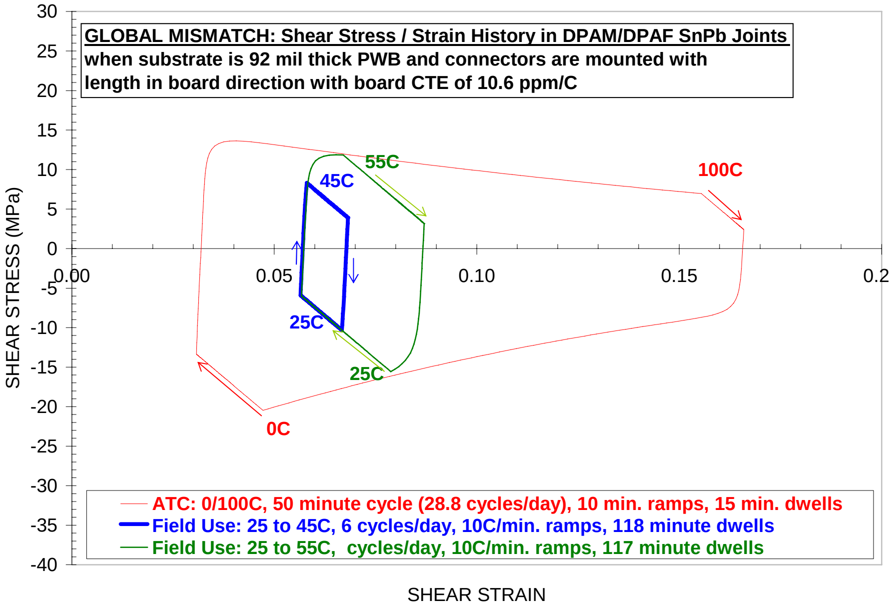

Figure 9b: SnPb DPAM/DPAF Assemblies: Global Mismatch Shear Stress/Strain Loops.

The shear stress / shear strain hysteresis loops for SAC and SnPb corner joints under ATC and use conditions # 1 and 2 are shown in Figures 9a and 9b. These loops give the cyclic history of average shear stresses and shear strains in the solder joints due to global thermal expansion mismatch between the boards and connectors. Loops associated with stresses and strains arising from local CTE mismatches between solder and the boards or connectors are not shown since, as shown in tables of strain energy in the next subsection, the contribution from local CTE mismatches to the total cyclic strain energy is negligible.

Strain Energy Results And Acceleration Factors

JPC Compact Strain Energy	**STRAIN ENERGY ΔW (MPa)**		**ACCELERATION FACTOR**
Model for SAC3807/3906	ATC	**USE = 25C to 45C, 6 CYCLES/DAY**	AF= ΔW (ATC) / ΔW (USE)
GLOBAL MISMATCH	**3.916E+00**	**2.198E-02**	**178.160**
LOCAL MISMATCH	3.056E-05	7.562E-08	na
TOTAL (LOCAL + GLOBAL)	**3.916E+00**	**2.198E-02**	**178.161**
% Local Strain Energy Over Total Strain Energy	0.001%	0.000%	

Table 1a: SAC results, 25/45C use conditions

JPC Compact Strain Energy	**STRAIN ENERGY ΔW (MPa)**		**ACCELERATION FACTOR**
Model for SAC3807/3906	ATC	**USE = 25C to 55C, 6 CYCLES/DAY**	AF= ΔW (ATC) / ΔW (USE)
GLOBAL MISMATCH	**3.916E+00**	**2.976E-01**	**13.156**
LOCAL MISMATCH	3.056E-05	5.357E-07	na
TOTAL (LOCAL + GLOBAL)	**3.916E+00**	**2.976E-01**	**13.157**
% Local Strain Energy Over Total Strain Energy	0.001%	0.000%	

Table 1b: SAC results, 25/55C use conditions.

JPC Compact Strain Energy	**STRAIN ENERGY ΔW (MPa)**		**ACCELERATION FACTOR**
Model for Sn37Pb	ATC	**USE = 25C to 45C, 6 CYCLES/DAY**	AF= ΔW (ATC) / ΔW (USE)
GLOBAL MISMATCH	**3.168E+00**	**1.533E-01**	**20.666**
LOCAL MISMATCH	4.353E-05	6.150E-07	na
TOTAL (LOCAL + GLOBAL)	**3.168E+00**	**1.533E-01**	**20.667**
% Local Strain Energy Over Total Strain Energy	0.001%	0.000%	

Table 2a: SnPb results, 25/45C use conditions

JPC Compact Strain Energy	**STRAIN ENERGY ΔW (MPa)**		**ACCELERATION FACTOR**
Model for Sn37Pb	ATC	**USE = 25C to 55C, 6 CYCLES/DAY**	AF= ΔW (ATC) / ΔW (USE)
GLOBAL MISMATCH	**3.168E+00**	**5.893E-01**	**5.375**
LOCAL MISMATCH	4.353E-05	3.983E-06	na
TOTAL (LOCAL + GLOBAL)	**3.168E+00**	**5.893E-01**	**5.375**
% Local Strain Energy Over Total Strain Energy	0.001%	0.001%	

Table 2b: SnPb results, 25/55C use conditions.

Cyclic strain energy results obtained from the area of hysteresis loops and acceleration factors for SAC and SnPb DPAM / DPAF assemblies are given in Tables 1a&b and 2a&b, respectively. Acceleration factors, defined as the ratio of cyclic lives under use and test conditions are obtained as ratios of cyclic strain energies because of the inverse relationship between cyclic lives and strain energies, as shown empirically and as discussed in our SMTAI'05 paper (http://jpclech.com/CLECH_SMTAI2005_PAPER.pdf).

The strain energy results in Tables 1 and 2 show that global CTE mismatch is the dominant cyclic stress / strain driver since the contribution of local CTE mismatches to the total strain energy (local + global) is negligible).

Acceleration factors for the 25/55ºC use conditions are also much smaller than those for the 25/45ºC use condition. This is attributed to two factors: 1) in the former condition (25/55ºC), the temperature swing ΔT = 30ºC is 50% larger than a ΔT of 20ºC in the latter use condition; 2) at 55ºC, creep rates are much larger than at 45ºC. Thus, hysteresis loops under 25C/45ºC conditions are much smaller than under 25C/55ºC conditions.

EXTRAPOLATION OF TEST RESULTS

SnPb DPAM / DPAF ASSEMBLIES			
ANALYSIS FOR USE CONDITIONS: 25 to 45C, 6 Cycles/Day			**Notes**
Characteristic life in 0/100C test:	**α_{test} (cycles) =**	**11270**	**based on Weibul distribution for 5 fails (5 of 32) at 7546 cycles. Weibull shape parameter is β = 4.736**
Acceleration factor from ATC to 25/45C Use Conditions:	AF=	20.667	from stress/strain hysteresis loops
Characteristic life under 25/45C Use Conditions:	α_{field} (cycles) =	2.329E+05	$\alpha_{field} = AF * \alpha_{test}$
Target design life (Years):	**N_{Years} =**	**20**	
Number of Use Cycles at N_{Years}:	$N_{UseCycles}$ =	43830	$N_{UseCycles} = N_{Years}$ * 365.25 Days/Year * 6 Cycles/Day
Cumulative Fraction Failed at N_{Years}:	**F =**	**3.6671E-04**	based on two-parameter Weibull distribution:
	F in ppm =	**366.7082**	$F = 1 - \exp[-(N_{UseCycles} / \alpha_{field})^{\beta}]$
Years to 0.01% Cumulative Fraction Failed	**Years =**	**15.20**	
(i.e. F = 0.01% = 100 ppm)	**F =**	**0.0100%**	
	F(ppm) =	**100.000**	
Years to 0.1% Cumulative Fraction Failed	**Years =**	**24.72**	
(i.e. F = 0.1% = 1000 ppm)	**F =**	**0.1000%**	
	F(ppm) =	**1000.000**	
ANALYSIS FOR USE CONDITIONS: 25 to 55C, 6 Cycles/Day			**Notes**
Characteristic life in 0/100C test:	**α_{test} (cycles) =**	**11270**	**based on Weibul distribution for 5 fails (5 of 32) at 7546 cycles. Weibull shape parameter is β = 4.736**
Acceleration factor from ATC to 25/45C Use Conditions:	AF=	5.375	from stress/strain hysteresis loops
Characteristic life under 25/45C Use Conditions:	α_{field} (cycles) =	6.058E+04	$\alpha_{field} = AF * \alpha_{test}$
Target design life (Years):	**N_{Years} =**	**20**	
Number of Use Cycles at N_{Years}:	$N_{UseCycles}$ =	43830	$N_{UseCycles} = N_{Years}$ * 365.25 Days/Year * 6 Cycles/Day
Cumulative Fraction Failed at N_{Years}:	**F =**	**1.9422E-01**	based on two-parameter Weibull distribution:
	F in ppm =	**194218.2939**	$F = 1 - \exp[-(N_{UseCycles} / \alpha_{field})^{\beta}]$
	F in % =	**19.4218%**	
Years to 0.01% Cumulative Fraction Failed	**Years =**	**3.95**	
(i.e. F = 0.01% = 100 ppm)	**F =**	**0.0100%**	
	F(ppm) =	**100.000**	
Years to 0.1% Cumulative Fraction Failed	**Years =**	**6.43**	
(i.e. F = 0.1% = 1000 ppm)	**F =**	**0.1000%**	
	F(ppm) =	**1000.000**	

Table 3a: Extrapolation of **SnPb** test results to field conditions: 25/45ºC and 25/55ºC (6 cycles/day).

SAC DPAM / DPAF ASSEMBLIES

ANALYSIS FOR USE CONDITIONS: 25 to 45C, 6 Cycles/Day			**Notes**
Characteristic life in 0/100C test:	**α_{test} (cycles) =**	**14331**	**based on 1st failure (1 of 32) at 6917 cycles, assuming Weibull shape parameter β = 4.736**
Acceleration factor from ATC to 25/45C Use Conditions:	AF=	178.161	from stress/strain hysteresis loops
Characteristic life under 25/45C Use Conditions:	α_{field} (cycles) =	2.553E+06	$\alpha_{field} = AF * \alpha_{test}$
Target design life (Years):	**N_{Years} =**	**20**	
Number of Use Cycles at N_{Years}:	$N_{UseCycles}$ =	43830	$N_{UseCycles} = N_{Years}$ * 365.25 Days/Year * 6 Cycles/Day
Cumulative Fraction Failed at N_{Years}:	**F =** **F in ppm =**	**4.3597E-09** **0.0044**	based on two-parameter Weibull distribution: $F = 1 - \exp[-(N_{UseCycles} / \alpha_{field})^{\beta}]$
Years to 0.01% Cumulative Fraction Failed (i.e. F = 0.01% = 100 ppm)	**Years =** **F =** **F(ppm) =**	**166.63** **0.0100%** **100.000**	
Years to 0.1% Cumulative Fraction Failed (i.e. F = 0.1% = 1000 ppm)	**Years =** **F =** **F(ppm) =**	**270.99** **0.1000%** **1000.000**	
ANALYSIS FOR USE CONDITIONS: 25 to 55C, 6 Cycles/Day			**Notes**
Characteristic life in 0/100C test:	**α_{test} (cycles) =**	**14331**	**based on 1st failure (1 of 32) at 6917 cycles, assuming Weibull shape parameter β = 4.736**
Acceleration factor from ATC to 25/45C Use Conditions:	AF=	13.157	from stress/strain hysteresis loops
Characteristic life under 25/45C Use Conditions:	α_{field} (cycles) =	1.886E+05	$\alpha_{field} = AF * \alpha_{test}$
Target design life (Years):	**NYears =**	**20**	
Number of Use Cycles at N_{Years}:	$N_{UseCycles}$ =	43830	$N_{UseCycles} = N_{Years}$ * 365.25 Days/Year * 6 Cycles/Day
Cumulative Fraction Failed at N_{Years}:	**F =** **F in ppm =** **F in % =**	**9.9715E-04** **997.1503** **0.0997%**	based on two-parameter Weibull distribution: $F = 1 - \exp[-(N_{UseCycles} / \alpha_{field})^{\beta}]$
Years to 0.01% Cumulative Fraction Failed (i.e. F = 0.01% = 100 ppm)	**Years =** **F =** **F(ppm) =**	**12.31** **0.0100%** **100.000**	
Years to 0.1% Cumulative Fraction Failed (i.e. F = 0.1% = 1000 ppm)	**Years =** **F =** **F(ppm) =**	**20.01** **0.1000%** **1000.000**	

Table 3b: Extrapolation of **SAC** test results to field conditions: 25/45ºC and 25/55ºC (6 cycles/day).

Details of the extrapolation of test results for DPAF / DFAM assemblies to the two sets of field conditions are as shown in Tables 3a (SnPb) and 3b (SAC). The main input of each sub-table is acceleration factors and test characteristic lives and shape parameters. Using two-parameter Weibull statistics, we then compute the cumulative fraction failed F at 20 years. The two-parameter Weibull equation is also back-solved for years in the field to a specified fraction failed (F = 0.1% or 0.01%). Results are summarized in Table 4.

	Condition: 25 to 45C, 6 cycles/day		**Condition: 25 to 55C, 6 cycles/day**	
	SAC	**SnPb**	**SAC**	**SnPb**
Cumulative Fraction Failed at 20 years	**0.044 ppm**	**367 ppm**	**997 ppm**	**1.95e5 ppm**
Years to 0.01% Failed	**166 years**	**15.2 years**	**12.31 years**	**3.95 years**
Years to 0.1% Failed	**270 years**	**24.72 years**	**20.01 years**	**6.43 years**

Table 4: Summary of DPAM/DPAF SAC and SnPb reliability projections under field conditions: 25/45ºC and 25/55ºC at a use frequency of 6 cycles/day.

CONCLUSIONS

- For field conditions: 25/45ºC, 6 cycles/day, the extrapolation of ATC (0/100ºC, 10C/min ramps, 15 minute dwells) test results gives cumulative fraction failed, F, at 20 years of use:

  - For SAC, F = 0.0044 ppm or less than 1 ppm
  - For SnPb, F = 367 ppm

- For field conditions: 25/55ºC, 6 cycles/day, the extrapolation of ATC (0/100ºC, 10C/min ramps, 15 minute dwells) test results gives cumulative fraction failed, F, at 20 years of use:

  - For SAC, F = 997 ppm or about 0.1%
  - For SnPb, F = 19.5%

- The above results are for DPAM / DPAF product boards with similar properties as the test board under ATC testing, with a board to connector CTE mismatch of 8.4 ppm/ºC in the diagonal direction of the connectors.

- Under test and field conditions considered in this study, the SAC DPAM/DPAF assemblies have a longer life than SnPb assemblies and SAC fraction failed at 20 years in the field are significantly lower than in the case of SnPb assemblies.

- The above reliability projections are application-dependent and will change for other board materials and use conditions.

- All needed geometric details and material properties that were used in this study are given in the first part of the report.

ACKNOWLEDGMENTS

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