The Effect of Thermal Cycling Dwell Time on Reliability and Failure Mode of 3rd Generation High-Performance Pb-free Solder Alloys

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ABSTRACT

The past decade has seen the development and introduction of commercial, third-generation, high-performance Pb-free solder alloys designed to meet the requirements of higher temperature use environments. Most of these offerings are based on the Sn-Ag-Cu (SAC) system, with major alloying additions of bismuth (Bi), antimony (Sb), or indium (In). These elements, individually or in combination, promote additional precipitate, solid solution, or dispersion strengthening that can enhance resistance to degradation at elevated temperature or during aggressive thermal cycling. Results from the literature show that an increase in thermal cycling dwell time can decrease the thermal cycling reliability of SAC solders. Because high-performance alloys are designed for extended operation at higher temperatures, it is important to understand their behavior and characterize their reliability at extended thermal cycling dwell times.

This paper presents the initial results from an experimental program designed to compare thermal cycling results for high-performance solder alloys using an extended dwell of 60 minutes to a typical short dwell time of 10 minutes. The 10-minute dwell data were generated in the initial phase of testing and published previously. The data reported here are from a thermal cycling profile of -55/125 °C (TC7 in IPC-9701B) and the test vehicle is a 192-pin chip array ball grid array (192CABGA). Contrary to the results for SAC solders, the 60 minute dwell time did not reduce the reliability consistently for all the high-performance alloys in the test matrix. Based on evaluation criteria of characteristic lifetime and 1% cumulative failure rate from a 2-parameter Weibull plot, the high-performance alloys had comparable reliability performance with 60-minute and 10-minute dwell times. Although all the alloys exhibited fatigue failures in the bulk solder, many of the alloys also exhibited interfacial and mixed mode failures, which complicates interpretation of the data. Multiple failure modes for these solder alloys also were reported for the 10-minute dwell testing.

Key words: Pb-free solder, high-performance solder alloys, thermal fatigue, thermal cycling, dwell time, solder microstructure, failure mode.

INTRODUCTION

Significant advancements have been made in Pb-free solder alloy development since the implementation of the RoHS Directive in 2006 [1]. Alloy advancement continues to be driven primarily by experience gathered through volume manufacturing and increased deployment of a variety of Pb-free products of increasing complexity. Consequently, Pb-free solder alloy offerings have increased in number and metallurgical complexity, well beyond the various commercial near-eutectic Sn-Ag-Cu (SAC) alloys that replaced eutectic SnPb solder [2]. This trend includes the emergence of a family of third generation, high-performance alloys designed to address reliability requirements for increasingly more aggressive use environments [3]. These alloys are based on the SAC system but substitute major alloying additions of bismuth (Bi), antimony (Sb), or indium (In) for tin (Sn).

Resistance to thermal fatigue damage is required for the products of many high reliability end users [4]. Solder joints age and degrade during service and eventually fail by the common wear out mechanism of thermally activated solder creep-fatigue or simply thermal solder fatigue [5]. Solder fatigue is the major wear-out failure mode and major source of failure for surface mount (SMT) components in electronic assemblies [6].

From 2008 to 2015, the Pb-Free Alloy Alternatives Project, sponsored by the International Electronics Manufacturing Initiative (iNEMI) planned and executed test programs to close knowledge gaps related to thermal fatigue performance of Sn-based, Pb free solder alloys [2, 4, 7-21]. Most of the alloys studied in the Alloy Alternatives Project had near-eutectic SAC compositions. In 2016, a new phase of the project was launched to characterize and understand the thermal fatigue performance of the emerging high-performance Pb-free solder alloys. The new project phase uses the thermal cycling practices and test vehicles developed for the original iNEMI Alloy study to generate data for high-performance solder alloys [22].

The Alloy Alternatives project team was created by a formal collaboration between iNEMI and another major industrial consortium, the HDP User Group, and includes participation from two other consortia, the CALCE (Center for Advanced Life Cycle Engineering), and AREA (Universal Advanced Research in Electronic Assembly). These consortia collectively are supported by members from high reliability telecom, automotive, avionics, and military/defense end users, solder suppliers, and electronic contract manufacturers.

The temperature cycling profiles for evaluating high-performance alloys were selected to address the requirements of three specific industries or market segments. Telecom is represented by TC1 (0/100 °C), consumer/handheld and automotive qualification by TC4 (-40/125 °C) and aerospace/defense by TC7 (-55/125 °C). These are defined in Table 4-1 from IPC-9701B [23], which specifies nominal low and elevated temperature dwell times. This paper presents results developed with the TC7 (-55/125 °C) thermal cycling profile. High-performance alloy test results for these thermal cycling profiles with the 10-minute well times were presented in six related papers between 2017 to 2022 [24-29].

The dwell time variable of the temperature profile was previously studied in the Alloy Alternatives Project since it was recognized as having a significant role in the solder alloy metallurgy evolution impacting the overall solder alloy reliability. This previous investigation demonstrated clearly that the longer thermal cycling dwell time reduced the characteristic lifetime over a range of 12-50% without altering the basic thermal fatigue failure mode in the bulk solder. Those detailed results and statistical analysis can be found in one of the previous project publications [12].

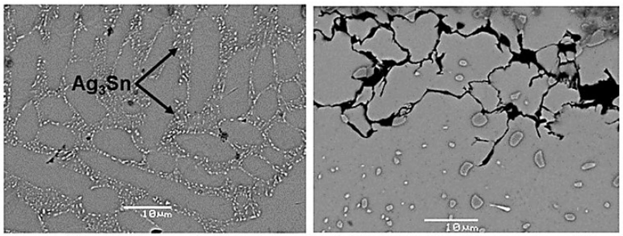
The dwell time effect has been reported and confirmed for different SAC solders alloys and a variety of area array, discrete, and quad flat no-lead (QFN) components [30-45]. The decrease in reliability under extended dwells is attributed to the longer stress relaxation duration of Pb-free solders compared to the former electronics industry de facto standard, eutectic SnPb solder. Extending the dwell time allows more creep deformation and increases the strain range [30, 40, 45], manifesting as a reduction in the number of cycles to failure.

Since the compositions of high-performance solder alloys are based on the SAC system, an extended dwell time is expected to have some bearing on board level attachment reliability [3, 22]. Any further dwell time effect related to the additional alloying elements, their strengthening mechanisms, and influence on microstructural evolution remains to be determined. This paper describes the planning and progress of the experimental program designed to assess the effect of a 60-minute temperature cycling dwell time on the thermal fatigue performance and microstructure of third generation, high-performance Pb-free solder alloys.

HIGH-PERFORMANCE Pb-FREE SOLDER ALLOYS

Background: Alloy Development and Requirements

The Sn-based, SAC alloys are more resistant to thermal fatigue than the eutectic SnPb alloy, but they have reliability limitations at higher operating temperatures [21]. During solidification of SAC solders, the Ag and Sn react to form networks of Ag_3Sn precipitates at the primary Sn dendrite boundaries. These intermetallic precipitates are recognized as the primary strengthening mechanism in SAC solders [23, 24, 32, 33]. During thermal or power cycling and extended elevated temperature exposure, the Ag_3Sn precipitates coarsen and become less effective in inhibiting dislocation movement and slowing damage accumulation. This pattern of microstructural evolution is characteristic of the thermal fatigue failure process in these Sn-based Pb-free alloys and was described originally in detail by Dunford et al in 2004 [46]. Figure 1 shows scanning electron micrographs illustrating coarsening of the Ag_3Sn precipitates in SAC305 solder caused by thermal cycling.



SAC305 as solidified SAC305 after thermal cycling

Figure 1. Backscattered scanning electron micrographs illustrating Ag_3Sn intermetallic precipitate coarsening that precedes recrystallization and crack propagation during thermal cycling of SAC305.

The commercial motivation for development of third generation Pb-free high-performance is the dramatic increase in electronic content in automobiles [47]. Automotive electronic assemblies must perform in environments characterized by long dwell times at increasing temperatures, thermal and power cycling, vibration, and thermal and mechanical shock [22]. There is a concern that SAC alloys cannot satisfy the reliability requirements for these use environments. Automotive electronics no longer can be characterized simply as "under the hood" [48, 49]. Software and electronics design are now considered core competencies of automotive manufacturing, and this is driving innovation and an increase in electronic content for automotive applications.

Circa 2003, a task group was formed of forward-looking solder suppliers, end users, and academic researchers with the objective to develop a commercial Pb-free alloy to meet the performance challenges of higher temperature automotive applications. The output of that working group was the initial third generation, commercial Pb-free solder alloy identified as Innolot or 90iSC [50-55]. The Innolot alloy is based on the ternary SAC387 formulation but contains major alloying additions of bismuth (Bi) and antimony (Sb), along with a microalloy addition of nickel (Ni).

As the electronics industry considered the adoption of high-performance Pb-free solder alloys, the question of dwell time effect surfaced as it did with the adoption of SAC solder alloys. The addition of three major alloy additions, bismuth (Bi), antimony (Sb) and indium (In), are expected to make the dwell time and long-term metallurgical effects more complex, critical, and difficult to understand in terms of thermal solder fatigue and overall alloy performance.

The nominal compositions and melting ranges for the high-performance alloys reported here are shown in Table 1. The test matrix contains the SAC305 alloy as the performance baseline. These alloys were down selected from the original, larger test matrix [22] based on prior alloy performance and resource considerations. Bismuth is the most common alloying element, which is confirmed by the attention given to Bi in the Pb-free alloy literature [21, 56-63]. Several SAC-based alloys contain a combination of Bi and Sb, and those alloys performed well in thermal cycling when tested with conventional, shorter dwell times [24-26].

Table 1. The high-performance Pb-free solder alloys used to evaluate the effect of temperature cycling dwell time on thermal fatigue life and failure mode.

Alloy	Nominal Composition (wt. %)							Melting Range, °C
	Sn	Ag	Cu	Bi	Sb	In	other	
SAC305	96.5	3.0	0.5					217-221
Innolot	91.3	3.5	0.7	3.0	1.5		0.12 Ni	206-218
M794	89.7	3.4	0.7	3.2	3.0		Ni	210-221
SB6NX	89.2	3.5	0.8	0.5		6.0		202-206
Violet	91.25	2.25	0.5	6.0				205-215
Indalloy 272	90.0	3.8	1.2	1.5	3.5			216-226
Indalloy 279	89.3	3.8	0.9		5.5	0.5		221-228

EXPERIMENTAL

Test Vehicle

Component and Test Board Description

This study utilizes the components and printed circuit board (PCB) developed as the test vehicle for the iNEMI Alloy Alternatives study [2]. The two daisy-chained ball grid arrays (BGA), a 192 I/O chip array BGA (192CABGA) and an 84 I/O thin core chip array (84CTBGA) are shown in Figure 2 [64]. The parts were purchased as land-grid arrays (LGA) to enable subsequent attachment of the various Pb-free-alloy spheres included in the scope of the program (Table 1).

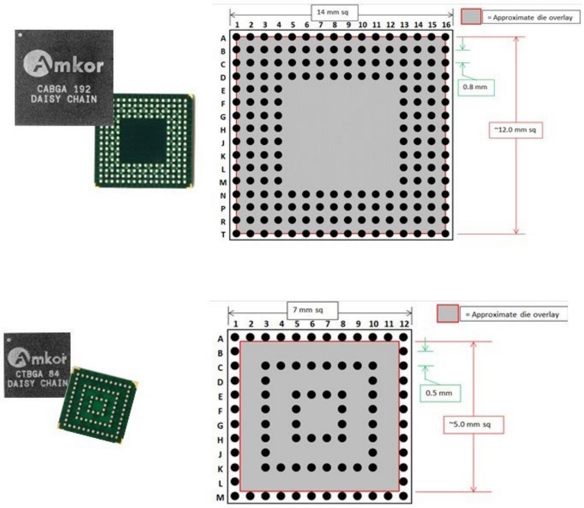


Figure 2. The 192CABGA and 84CTBGA daisy chained components and pin diagrams with die size and location [64].

The printed circuit board (PCB) test vehicle is 2.36 mm (93 mils) thick, with a 6-layer construction with 16 sites for the larger 192CABGA, and another 16 sites for the 84CTBGA (Figure 3). The boards were fabricated with the Panasonic R-1755V high temperature laminate material and the final finish is a high temperature organic solderability preservative (OSP). The complete attributes of the components and PCB are contained in Table 2.

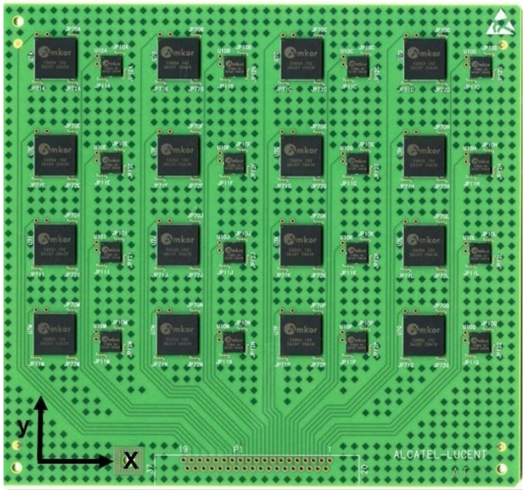


Figure 3. The fully populated, daisy chained Alloy Alternatives test vehicle.

Table 2. Ball grid array (BGA) and printed circuit board (PCB) test vehicle attributes.

BGA Package Attributes		
Designation	192CABGA	84CTBGA
Die Size	12x12 mm	5x5 mm
Package Size	14x14 mm	7x7 mm
Ball Array	16x16	12x12
Ball Pitch	0.8 mm	0.5 mm
Ball Diameter	0.46 mm	0.3 mm
Pad Diameter	0.381 mm	0.3 mm
Pad Finish	Electrolytic Ni/Au	Electrolytic Ni/Au
Au thickness	0.6 µm	0.6 µm
PCB Attributes		
Dimensions	165 x 178 x 2.36 mm	
Laminate	Panasonic R-1755V	
Surface Finish	Entek HT OSP	
No. Cu Layers	6	
Pad Diameter	0.356 mm	0.254 mm
Solder Mask Diameter	0.483 mm	0.381 mm
Glass Transition Temperature, T_g	165 °C	
Decomposition Temperature, T_d	350 °C	
Room Temperature Storage Modulus	11.6 Gpa	

Solder joint attachment reliability is dependent strongly on the coefficient of thermal expansion (CTE) mismatch (difference) between the package and the PCB as well as the distance from neutral point (DNP) [65]. Although the small chip array package sizes used in this study minimize the DNP effect, their large die to package ratios (DPR) result in substantial CTE mismatch [65]. The modulus or stiffness of the PCB also can affect solder joint reliability.

The CTE of the PCB was measured using a thermomechanical analyzer (TMA) and the composite coefficients of thermal expansion of the BGA packages were measured using microscopic Moiré interferometry. The data in Table 3a show a lower composite CTE for the 192CABGA package. The lower CTE of the 192CABGA results in a larger CTE mismatch with the PCB, hence the thermal cycling lifetime of the 192CABGA is shorter than that of the 84CTBGA [25-28]. The CTE data for the PCB laminate material are shown in Table 3b. This paper presents results only for the lower reliability, 192CABGA component tested with the -55/125 profile, which is the most aggressive test shown in Table 4 (TC7).

Table 3a. CTE of the BGA component test vehicles measured by microscopic Moiré interferometry.

BGA Package	Effective CTE α (ppm/°C) T °C:24~130	
	x-direction	y-direction
192CABGA	8.6	10.1
84CTBGA	10.9	11.0

Table 3b. CTE of the Panasonic R-1755R laminate material measured with a thermomechanical analyzer (TMA).

Panasonic R-1755V	
Effective CTE α (ppm/°C) T °C:20~140	
x-direction	y-direction
13.5	16.1

Component Ball Attachment Process

The parts were purchased as land-grid arrays (LGA) to allow subsequent attachment of each of the different high-performance Pb-free-alloy balls included in the scope of the program (Table 1). The ball attachment was performed at SemiPack (https://www.semipack.com) using the same process developed for the iNEMI Alternative Alloys project [2].

Test Vehicle Surface Mount Assembly

The solder assembly of the test vehicles was performed at Collins Aerospace, Cedar Rapids, IA. A pilot build using SAC305 components and paste was conducted to establish the stencil printing and reflow process parameters. A 5-mil (125 µm) thick stencil was used with 14 mil (0.35 mm) diameter round apertures for the larger 192CABGA and 12 mil x 12 mil (0.3 mm x 0.3 mm) square apertures for the smaller 84CTBGA. The test vehicles were reflowed in a 14-temperature zone convection oven in a nitrogen atmosphere. Type 4 no-clean solder paste was used for all the final assemblies. The nominal peak temperature measured on the board adjacent to the solder joints was 245 °C.

Accelerated Temperature Cycling (Thermal Cycling)

Accelerated temperature cycling (ATC) is the recognized technique for evaluating the thermal fatigue performance of solder attachments. The daisy-chained components and the test circuit boards enabled electrical continuity testing after surface mount assembly and in situ, continuous monitoring during thermal cycling. Thermal cycling is done in accordance with the IPC-9701B guideline [23]. The solder joint resistance is monitored using either an event detector or a data logger set at a resistance limit of 1000 ohm, also described previously [2]. The failure data will be reported as characteristic life η (the number of cycles to achieve 63.2% failure), slope β, and cumulative 1% failure from a two-parameter Weibull analysis.

The temperature cycling profiles for this investigation are shown in Table 4. These profiles are selected to address the requirements of three specific industries or market segments as defined in IPC-9701B with telecom represented by TC1, consumer/handheld by TC4, and military/defense by TC7. The 60-minute dwell times return only ten cycles per day, which results in exceedingly long test durations.

Each alloy test cell contains two fully populated replicate test boards to provide a sample size of 32 BGA components of each type for thermal cycling and an additional populated test board for baseline quality and microstructural characterization.

Table 4. Temperature cycling profiles.

Thermal Cycle	Minimum Temp. (°C)	Maximum Temp. (°C)	Temp. Range ΔT (°C)	Dwell Time (min.)
TC1	0	100	100	60
TC4	-40	125	165	60
TC7	-55	125	180	60

RESULTS

Thermal Cycling Summaries

Longer thermal cycling dwell times are known to reduce the characteristic lifetimes of SAC solders. Since the high-performance solder alloys in this project are based on the SAC system, the extended, 60-minute dwell time is expected to cause a reduction in the board level attachment reliability. However, these solders are designed to outperform high-Ag alloys like SAC305 and SAC405 by introducing elemental additions that provide supplemental strengthening mechanisms to resist damage during thermal cycling and higher sustained operating temperatures.

Table 5, Figure 4, and Figure 5 summarize the alloy performance in -55/125 °C thermal cycling with 10 and 60 minute dwell times. Table 5 includes the Weibull characteristic lifetimes, 1% Cumulative Failures, and slopes (shape parameters). Figure 5 and Figure 6 show bar charts comparing the characteristic lifetimes (N63) and 1% cumulative failures of the alloys in -55/125 °C thermal cycling with 10 or 60 minute dwell times. Weibull plots comparing performance with 10 and 60 minute dwell times for the individual alloys are provided with the results for each alloy. There is a broad range of values for the characteristic lifetime and 1% cumulative failure parameters which in part, can be attributed to the variations in Weibull slope across the datasets shown in Table 5. These variations in Weibull slope across data sets must be taken into consideration because they limit the ability to quantify differences in characteristic lifetime and 1% failure among data sets.

As a result of its low composite CTE, the 192CABGA fails much sooner than the 84CTBGA. Because none of the boards or components were removed before the test concluded, the 192CABGA components incurred a substantial amount of damage by the time the test ended. These test circumstances make it impossible to identify true first failures and make it challenging to identify representative failure modes.

Table 5. Summary of the Weibull statistics for the alloys tested using the CABGA192 test vehicle and the -55/125 °C thermal cycling profile with 10 or 60 minute dwell times.

192CABGA Thermal Cycling Data, -55/125 °C						
Solder Alloy	Characteristic Lifetime η (cycles)		1% Failure (cycles)		Slope β	
	10-min dwell	60-min dwell	10-min dwell	60-min dwell	10-min dwell	60-min dwell
SAC305	1123	886	526	380	6.1	5.4
Innolot	1690	2217	686	285	2.6	3.9
M794	1611	1632	593	1053	4.6	10.5
SB6NX	1290	2334	266	763	2.9	4.1
Violet	834	989	163	584	2.8	8.7
Indalloy 272	663	1639	62	937	1.9	8.2
Indalloy 279	1765	1906	932	962	7.2	6.7

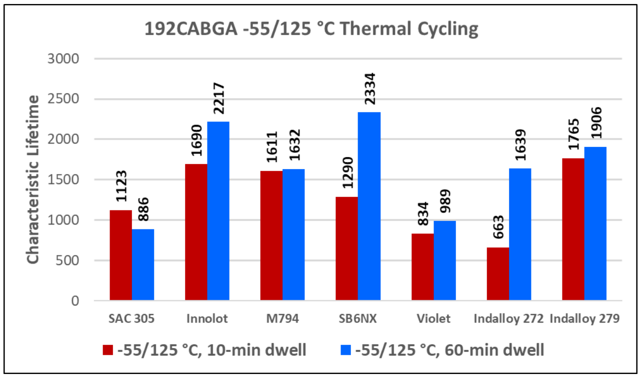


Figure 4. Bar charts showing the effect of 10-minute and 60-minute dwell time on the characteristic lifetimes of the CABGA192 with a -55/125 °C thermal cycling profile.

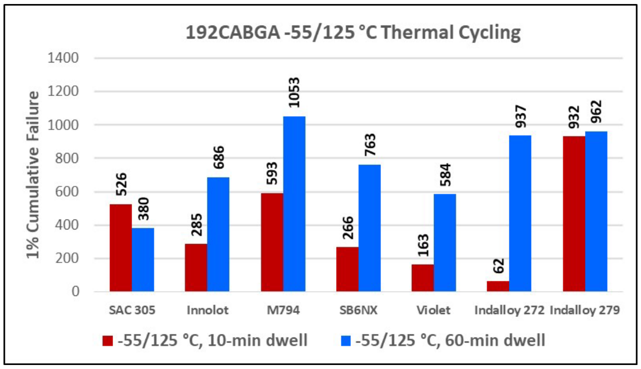


Figure 5. Bar charts showing the effect of 10-minute and 60-minute dwell time on 1% Cumulative Failures lifetimes of the CABGA192 with a -55/125 °C thermal cycling profile.

SAC305 Results

The results for SAC305 show a 20% decrease in characteristic lifetime with the 60-minute dwell time, This dwell time effect is shown clearly in the Weibull plot in Figure 6. This result is consistent with SAC305 results from an earlier dwell time test using with same test vehicle [12]. A SAC305 sample that failed by thermal fatigue in the bulk solder is shown in Figure 7. This is the same failure mode reported for the 10-minute dwell testing [27, 28].

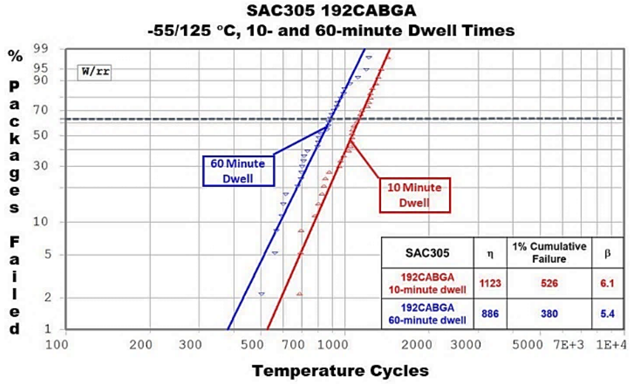


Figure 6. Weibull plot for the 192CABGA with SAC305 solder, comparing performance of 10-minute and 60-minute dwell times with a -55/125 °C thermal cycling profile.

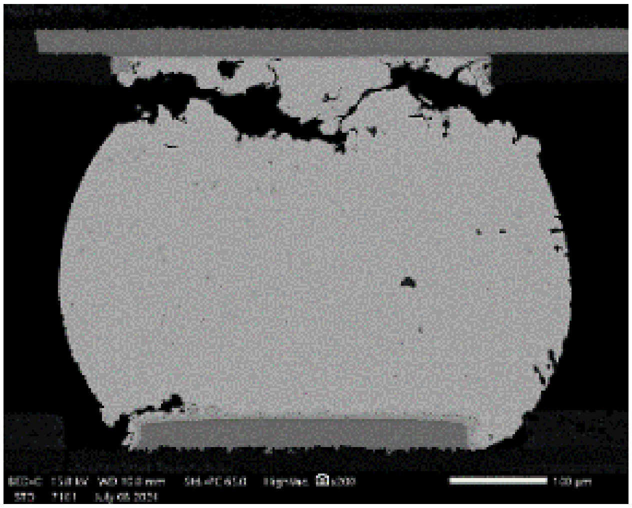


Figure 7. Thermal fatigue failure in a SAC305 192CABGA tested with a -55/125 °C thermal cycling profile and 60-minute dwell times. Thermal fatigue is the only failure mode with the 192CABGA and SAC305.

Innolot Results

The Weibull plots for Innolot shows better performance with the 60-minute dwell time, contrary to expectations. Figure 8a indicates an improvement in both characteristic lifetime and 1% cumulative failure with the 60-minute dwell time. However, the differences between the data for 10 and 60 minute dwell times are not so obvious when 90% confidence intervals are overlaid (Figure 8b). Innolot also is susceptible to non-fatigue failure modes with 60-minute dwell testing as shown in Figure 9, which also was reported for 10-minute dwell testing [25, 26]. It is reasonable to speculate that the earliest failures in both the 10 and 60 minute Innolot plots could be a manifestation of the failure modes. Innolot also is prone to solder process voiding as shown in Figure 10. Voiding typically does not affect thermal cycling performance [68-70], but the relationship between voiding in Innolot and its effect on reliability has been a concern and topic of ongoing discussion [71].

Innolot failures occur by three types of failure modes, there are a few suspicious earlier failures with both dwell times, and there may be an effect due to voiding. Together, these factors could account for the minimal statistical difference between the results for 10- and 60-minute dwell times. Thus, a more conservative conclusion is that the results for the 192CABGA with Innolot are not affected substantially by an increase in thermal cycling dwell time from 10 to 60 minutes. Regardless of the complications from multiple failure modes and voiding, Innolot continues to be one of the best performers in these thermal cycling tests [25, 26].

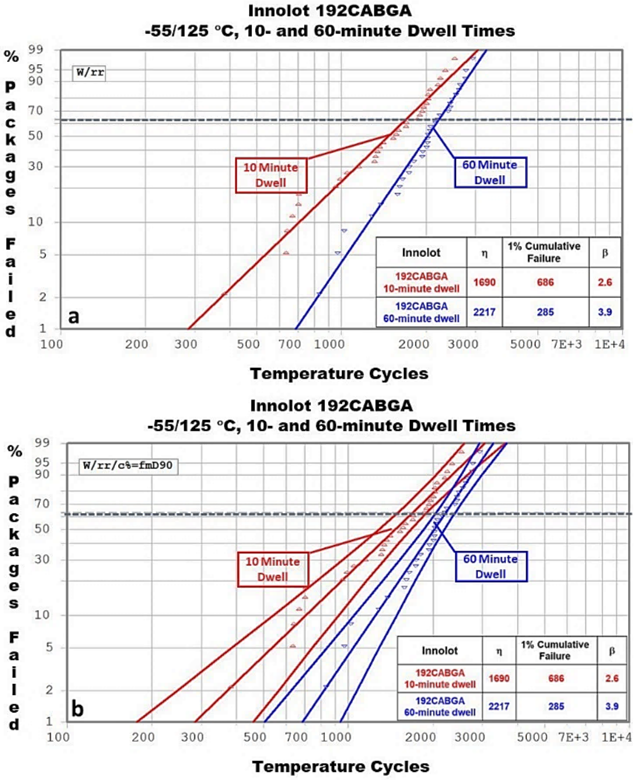


Figure 8. a) Weibull plot for the 192CABGA with Innolot solder and 10-minute and 60-minute dwell times with -55/125 °C thermal cycling, b) the same Weibull plot with 90% Confidence Intervals.

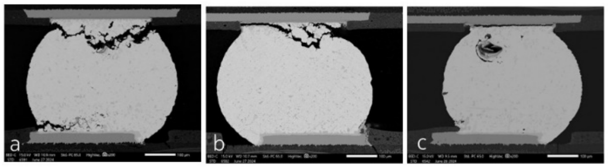


Figure 9. Examples of a) fatigue, b) mixed mode (combined fatigue and interfacial), and c) interfacial failures with the 192CABGA and Innolot solder.

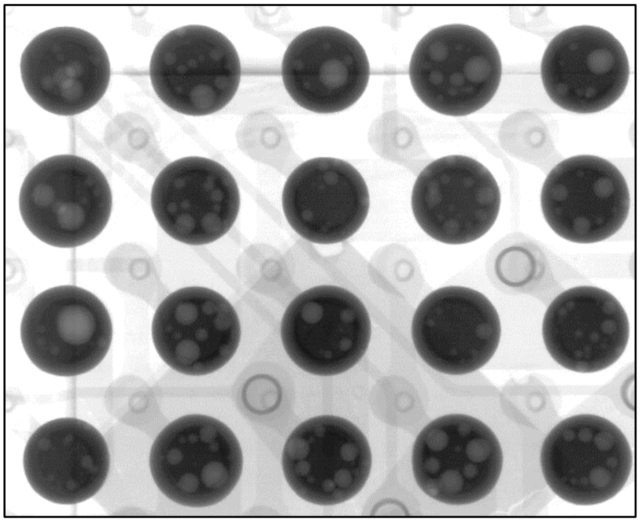


Figure 10. Solder process voiding in the near-corner region of an Innolot 192CABGA.

M794 Results

Figure 11 is the Weibull plot comparing the performance of M794 with 10-minute and 60-minute dwell times. The characteristic lifetimes are the same for both dwell times, but the Weibull slope is much higher for the 60-minute dwell, resulting in a much higher 1% cumulative failure (see Figure 4). The 90% Confidence Intervals show there is a minimal performance difference between the 10- and 60-minute dwell times. M794 also is susceptible to non-fatigue failure modes with 60-minute dwell testing as shown in Figure 12, which also was reported for 10-minute dwell testing [25, 26]. Alloys such as M794 and Innolot that contain major combined additions of Bi and Sb have been the best overall performers in this high-performance alloy investigation. These preliminary findings with the 192CABGA test vehicle and the aggressive -55/125 °C thermal cycling profile indicate that the M794 alloy does not exhibit the same dwell time dependency and degradation as SAC305.

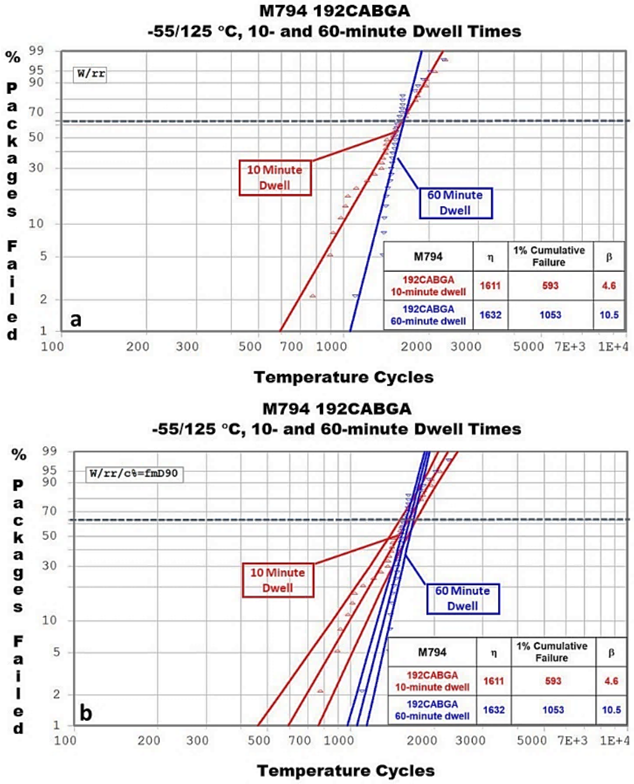


Figure 11. a) Weibull plot for the 192CABGA with M794 solder and 10-minute and 60-minute dwell times with -55/125 °C thermal cycling, b) the same Weibull plot with 90% Confidence Intervals.

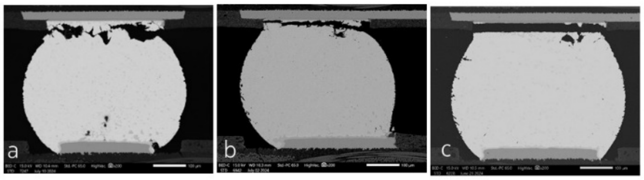


Figure 12. Examples of a) fatigue, b) mixed mode, and c) interfacial failures with the 192CABGA and the M794 solder alloy.

SB6NX Results

Figure 13 is the Weibull plot comparing the performance of SB6NX with 10-minute and 60-minute dwell times. This plot and the bar charts in Figure 4 and Figure 5 show a substantial increase in reliability with the 60-minute dwell, measured by either characteristic lifetime or 1% cumulative failure. SB6NX, not only had better performance with the 60-minute dwell, but also had performance comparable to Innolot and M794 with the 60-minute dwell, which was not the case in the 10-minute dwell test. Alloys such as M794 and Innolot that contain major combined additions of Bi and Sb were the best overall performers with the 10-minute dwell testing. In addition to the expected strengthening from Ag_3Sn precipitates, SB6NX derives strength from solid solution strengthening of indium in tin. SB6NX failed exclusively by solder fatigue as shown in Figure 14. The better performance of SB6NX with the 60-minute dwell time and its comparable performance to M794 and Innolot would seem anomalous. However, SB6NX performed extremely well with a 1206 chip resistor [24]. In depth microstructural studies may help to understand these observations. Also, the results that are pending for the 84CTBGA component and two additional thermal cycles could provide further insight.

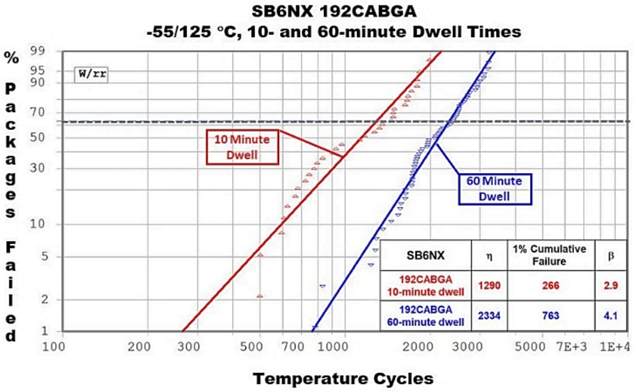


Figure 13. Weibull plot for the 192CABGA with SB6NX solder, comparing performance of 10-minute and 60-minute dwell times with a -55/125 °C thermal cycling profile.

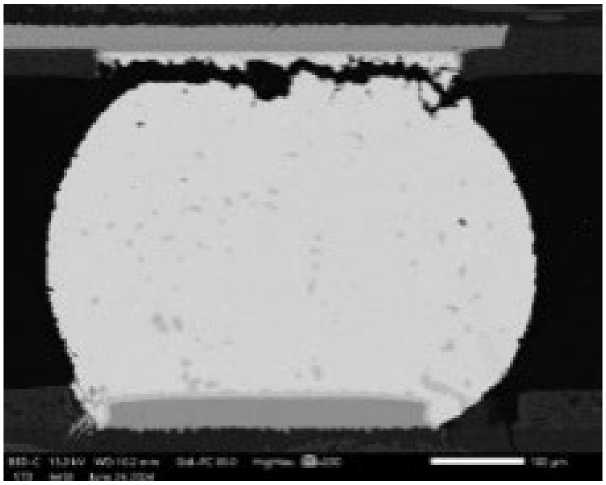


Figure 14. Thermal fatigue in the bulk solder is the only failure mode observed with the 192CABGA and the SB6NX solder alloy.

Violet Results

Figure 15 is the Weibull plot comparing the performance of Violet with 10-minute and 60-minute dwell times. Based on the data in Table 5, SAC305 outperformed Violet in the 10-minute dwell test, and Violet was only marginally better than SAC305 in the 60 minute dwell test. Violet is another alloy susceptible to non-fatigue failure modes in the 192CABGA with 60-minute dwell testing as shown in Figure 16, and these failure modes also were reported for 10-minute dwell testing. The Violet solder alloy contains only Bi as its constituent element additive and the 6 wt. % level is the highest Bi content of all the solder alloys tested. The industry low temperature solder alloys based on the eutectic 58Bi42Sn system have shown tendencies for the interfacial failure mode as seen in the 192CABGA 10-minute and 60-minute dwell solder joints [72, 73].

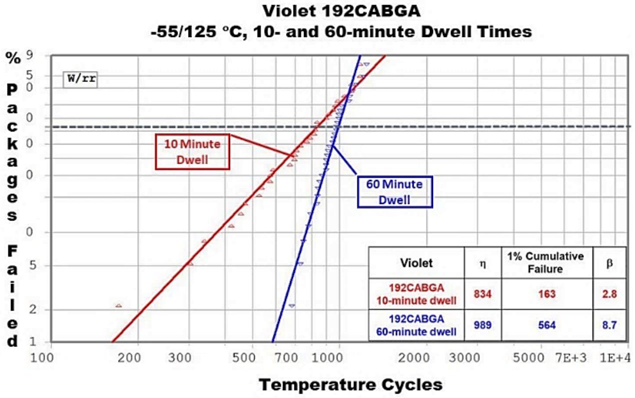


Figure 15. Weibull plot for the 192CABGA with the Violet solder alloy and 10-minute and 60-minute dwell times with -55/125 °C thermal cycling. There is a substantial increase in reliability with the 60-minute dwell, measured by either characteristic lifetime or 1% cumulative failure.

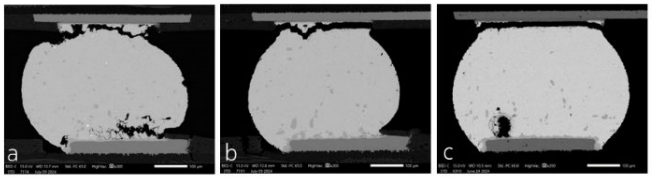


Figure 16. Examples of a) fatigue, b) mixed mode, and c) interfacial failures with the 192CABGA and the Violet alloy.

Indalloy 272 Results

Figure 17 is the Weibull plot comparing the performance of Indalloy 272 with 10-minute and 60-minute dwell times. Despite the significant difference in Weibull slopes, Indalloy 272 performs significantly better in the 60-minute dwell test, compared to the 10-minute dwell test. The characteristic lifetime with the 60-minute dwell time is greater by more than a factor of two times, and the 1% cumulative failure is greater by more than a factor of 15 times. Indalloy 272 is susceptible to non-fatigue failure modes in the 192CABGA with 60-minute testing as shown in Figure 18, and these failure modes also were reported for 10-minute dwell testing of Indalloy 272.

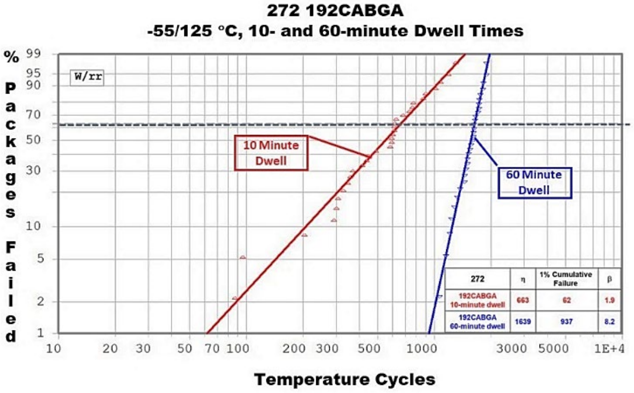


Figure 17. Weibull plot for the 192CABGA with the Indalloy 272 solder alloy, comparing performance of 10-minute and 60-minute dwell times with -55/125 °C thermal cycling.

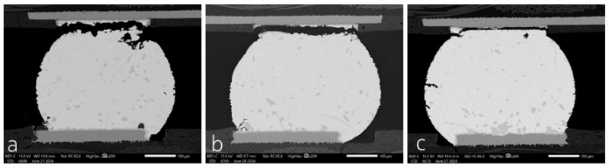
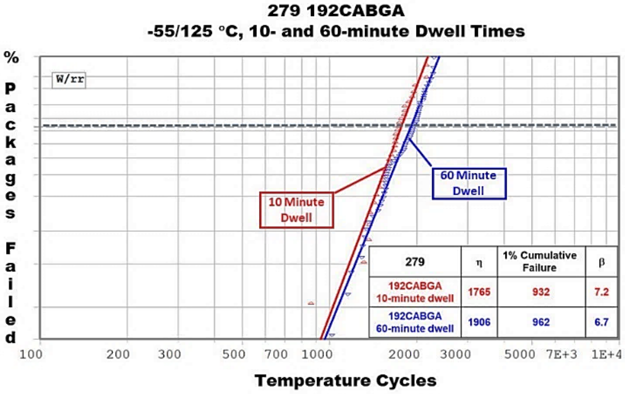


Figure 18. Examples of a) fatigue, b) mixed mode, and c) interfacial failures with the 192CABGA and the Indalloy 272 solder alloy.

Indalloy 279 Results

Figure 19 is the Weibull plot comparing the performance of Indalloy 279 with 10-minute and 60-minute dwell times. The characteristic lifetimes, 1% cumulative failures, and Weibull slopes, are practically the same for both dwell times. Indalloy 279 samples that failed by thermal fatigue in the bulk solder and mixed mode failure are shown in Figure 20. Solder fatigue and mixed mode failures also were reported for the 10-minute dwell testing.



279	η	1% Cumulative Failure	β
192CABGA 10-minute dwell	1765	932	7.2
192CABGA 60-minute dwell	1906	962	6.7

Figure 19. Weibull plot for the 192CABGA with Indalloy 279 solder and 10-minute and 60-minute dwell times with -55/125 °C thermal cycling.

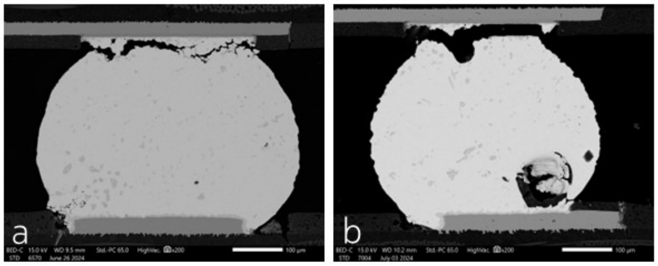


Figure 20. Examples of a) fatigue, and b) mixed mode failures with the 192CABGA and the Indalloy 279 solder alloy with the 60-minute dwell time testing.

DISCUSSION

Compared to testing with the typical 10-minute dwell time, testing with the 60 minute dwell time did not result in an appreciable reduction in the reliability of any high-performance alloy in the test matrix. Based on evaluation criteria of characteristic lifetime and 1% cumulative failure rate from a 2-parameter Weibull plot, the high-performance alloys had comparable reliability performance with 60-minute and 10-minute dwell times. For alloys SB6NX, Violet, and 272, it can be argued that performance is much better with the 60-minute dwell. These are preliminary findings, but they are encouraging, since these alloys are designed to resist damage from aggressive thermal exposures. The high-performance alloys also outperform SAC305, mostly by substantial margins. The results for SAC305 showed the expected dwell time effect with a 20% decrease in characteristic lifetime with the 60-minute dwell time. The current SAC305 results are consistent with the well-established dwell time effect in SAC solders, which provides some assurance the testing was performed correctly.

There is no doubt that the failure mode during thermal cycling influences the evaluation of these high-performance alloys. Although thermal cycling is used to evaluate thermal fatigue of the solder attachments [23], SAC305 and SB6NX were the only alloys that failed exclusively by fatigue in the bulk solder with both 10-minute and 60-minute dwell times. The remainder of the high-performance alloys exhibited various levels of interfacial and mixed mode failures. Multiple failure modes affect the Weibull statistics and complicate interpretation of the data. Although multiple failure modes also were reported for the 10-minute dwell testing, there were some differences in the results between the two sets of dwell time data. The best performers with the 60-minute dwell, M794, Innolot, and 279, also performed well with the 10-minute dwell. There is a wide range of Weibull slopes across these datasets, which appears to have more of an effect on Innolot, perhaps due to a combined influence of failure mode and solder voiding. The lower characteristic lifetimes and 1% cumulative failures in the 10-minute dwell for Violet and 272 most likely result from a significant amount of interfacial and mixed mode failures. The only obvious performance anomaly in the 60-minute dwell test is with SB6NX. This alloy has markedly better reliability with the 60-minute dwell compared to the 10-minute dwell based on both characteristic lifetime and 1% cumulative failure (Figure 12).

The Weibull slopes for the 60-minute dwell test consistently are higher than those for the 10-minute dwell test, except for SAC305 and 279, the only alloys that did not have interfacial failures. The current findings contrast with those from an earlier phase of the iNEMI Alternative Alloys project that investigated the dwell time effect on a series of SAC alloys. The results from that earlier study showed no appreciable difference in the Weibull slopes for a series of metallurgically simpler SAC alloys tested with dwell times of 10 and 60 minutes. Thus, the higher Weibull slopes for the high-performance alloys would seem to be related to the strengthening mechanisms provided by the additional alloying elements.

Multiple failure modes can lead to lower Weibull slopes, and these high-performance alloys have exhibited failures by fatigue in the bulk solder, complete interfacial cracking, and mixed mode cracking in -55/125 °C cycling with dwell times of 10 and 60 minutes. Interfacial cracking is hypothesized to occur if the solder strength in the strain localized region is high enough to limit crack initiation in the bulk solder but promote it at the soldered interface. In the simplest terms, crack initiation occurs at the weakest location. The results from 10-minute dwell time investigation showed that the 192CABGA is susceptible to interfacial cracking due to its large ratio of die size to package size.

The higher Weibull slopes with the 60-minute dwell time suggest there could be less variation in failure mode with the extended dwell time compared to the 10-minute dwell. For example, even when all three failure modes are detected for a given high-performance alloy, there may be more failures by the expected solder fatigue mechanism. This is plausible but speculative due to limitations in the number of samples analyzed and the failure analysis process. From a metallurgical perspective, sustaining satisfactory performance with less interfacial cracking would require a subtle balance between strength and ductility of the solder. As the solder undergoes in situ aging during thermal cycling, the alloy additions must strengthen sufficiently to extend the attachment lifetime with 60 minute dwells while maintaining ductility to minimize the transfer of shear strain to the soldered interface.

STATUS AND NEXT STEPS

The observations from this study are based on the thermal cycling data for the 192CABGA tested with the -55/125 °C thermal cycling profile. The data for the 84CTBGA with the -55/125 °C thermal cycling profile will be presented later. The 192CABGA package is characterized by high-strain and low CTE (Table 3a). In the previous testing with the 10-minute dwell time, less interfacial cracking was observed in the 84CTBGA. Furthermore, the smaller volume of the 84CTBGA solder balls could result in more Sn undercooling, which can influence solidification and microstructure [74]. Thus, the thermal cycling behavior and rank order of alloy performance of the two packages may not be the same. The thermal cycling tests with the -40/125 °C and 0/100 °C profiles remain under test at the time of this writing, and results from those tests also will be presented later.

Extensive solder joint microstructural analysis needs to be conducted to understand how the major alloying additions of bismuth (Bi), antimony (Sb), and indium (In) influence the precipitation hardening, solid solution, or dispersion strengthening mechanisms. How these three solder alloy constituents, either individually or in combination, are promoting improved alloy resistance to degradation is a critical parameter in understanding how the solder alloys will perform in various product environment applications. Detailed microstructural analysis may also provide insight regarding the behavior of these alloys when tested with longer dwell times in thermal cycling.

SUMMARY

This paper presented the initial findings from an experimental program designed to compare thermal cycling results for high-performance solder alloys using an extended dwell of 60 minutes to a typical short dwell time of 10 minutes. Results are reported for a daisy chained, 192-pin chip array ball grid array (192CABGA) component test vehicle tested with an accelerated thermal cycling profile of -55/125 °C. The alloy reliability test matrix consisted of six Pb-free, high performance solder alloys that were developed for use in aggressive service environments. These alloys are based on the Sn-Ag-Cu (SAC) system, but modified with combinations of major alloy additions of Bi, Sb, and In. The SAC305 hypoeutectic alloy was used as the performance baseline.

In contrast to the published results for SAC solders and the current results for the SAC305 baseline, the 60-minute dwell time did not reduce the reliability consistently for all the high-performance alloys in the test matrix. Based on evaluation criteria of characteristic lifetime and 1% cumulative failure rate from a 2-parameter Weibull plot, the high-performance alloys had comparable reliability performance with 60-minute and 10-minute dwell times. Although all the alloys exhibited fatigue failures in the bulk solder, many of the alloys also exhibited interfacial and mixed mode failures, which complicated interpretation of the data. The Weibull slopes for the 60-minute dwell test were higher than those for the 10-minute dwell test, except for SAC305 and 279, the only alloys that did not have interfacial failures. Multiple failure modes for these solder alloys had also been reported previously for the 10-minute dwell testing. Despite the complications introduced by the occurrence of multiple failure modes, the high-performance alloys outperformed SAC305 by a significant amount. These high-performance alloys perform well with the 60-minute dwell time, at least with the 192CABGA component and the -55/125 °C thermal cycling profile. Results for the 84CTBGA component and two other thermal cycling profiles will be presented later.

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