Via (Plated Through Hole) Integrity with Lead Free Soldering

Joe Smetana, Alcatel
Ken Ogle, Sanmina-SCI
Bob Sullivan, HDPUG

Abstract
Bare printed wiring board materials require changes from today's typical standard dicy cured FR4 materials in order to support lead-free assembly. The High Density Packaging User's Group has completed a study of via reliability through air-to-air thermal cycling after various SnPb and lead-free reflow profiles. Six different materials, with different numbers of reflow profiles were studied in this test through 6000 accelerated thermal cycles. Data from this testing will be presented that clearly shows that all materials claimed to be lead-free compatible are not created equal. A review of relevant material properties vs. the results will also be attempted.

Introduction and Background

Previous testing and publications have detailed some of the impacts of Pb-free soldering on bare printed circuit board materials and plated through hole reliability [1,2,3,6]. The High Density Packaging User's Group (HDPUG) consortium has run a series of projects to better determine the effects of Pb-free soldering on the plated through hole integrity and long term reliability. This second phase of testing looks at long term reliability based on accelerated testing using air-to-air thermal cycling after typical SnPb and SnAgCu reflow profiles. (Additional testing using liquid-to-liquid testing was also completed, but will not be addressed here.)

This work was done by a number of different companies. The test boards were designed by Alcatel with inputs from Sanmina-SCI. The test plan documentation was completed by Alcatel, with various team member inputs. Bare board fabrication was done by Sanmina-SCI at their San Jose facility. Test board preconditioning reflow and wiring was completed by Flextronics. Air to air thermal cycling and monitoring was done by the Sanmina-SCI Reliability Engineering Lab. Finally, failure analysis was completed by the Sanmina-SCI PART Lab. Materials used in the board fabrication were provided by Isola, Nelco, and Polyclad.

This work was started in mid-2003. At that time, there were a limited number of bare board materials specifically designated as Pb-free compatible and a number of these were new and unavailable for testing. Since this time, additional materials have been introduced specifically designed for improved performance in Pb-free soldering. All of the materials studied here remain production available materials today.

Printed Circuit Board Design

The test boards used in this testing were 4 inches by 7 inches by 0.125 inches thick. See Figure 1. They are eight layer boards and include non-functional pads on all internal layers, which was determined from previous testing [1] to be the worst case (vs. removing non-functional pads). There are 32 daisy chains of 50 vias each on the test boards. On 24 of these daisy chains the connections are made on layer 2 and 7. The remaining 8 daisy chains have the connections on layers 1 and 8. Only the daisy chains connecting on layers 2 and 7 were used in this testing. The material stack up was designed to intentionally place layers 2 and 7 near the outside layers of the board. By using this connection strategy, both barrel cracking and foil cracking or interconnect separation can be monitored on the same nets. Each net is terminated in a connector pattern. The connector pattern has larger holes which are expected to outlast the smaller, higher aspect ratio, via holes being tested during the thermal cycling. The connections to the connector pattern are made on layers 4 and 5, near the central z-axis of the board to minimize any chance of failure in the layer foil or interconnect adversely affecting the results. Microsections confirmed that none of these connections were the source of any failures. Connections were made by soldering wires to these connector pattern holes using SnPb solder. This eliminates the possibility of connector failures causing erroneous data.

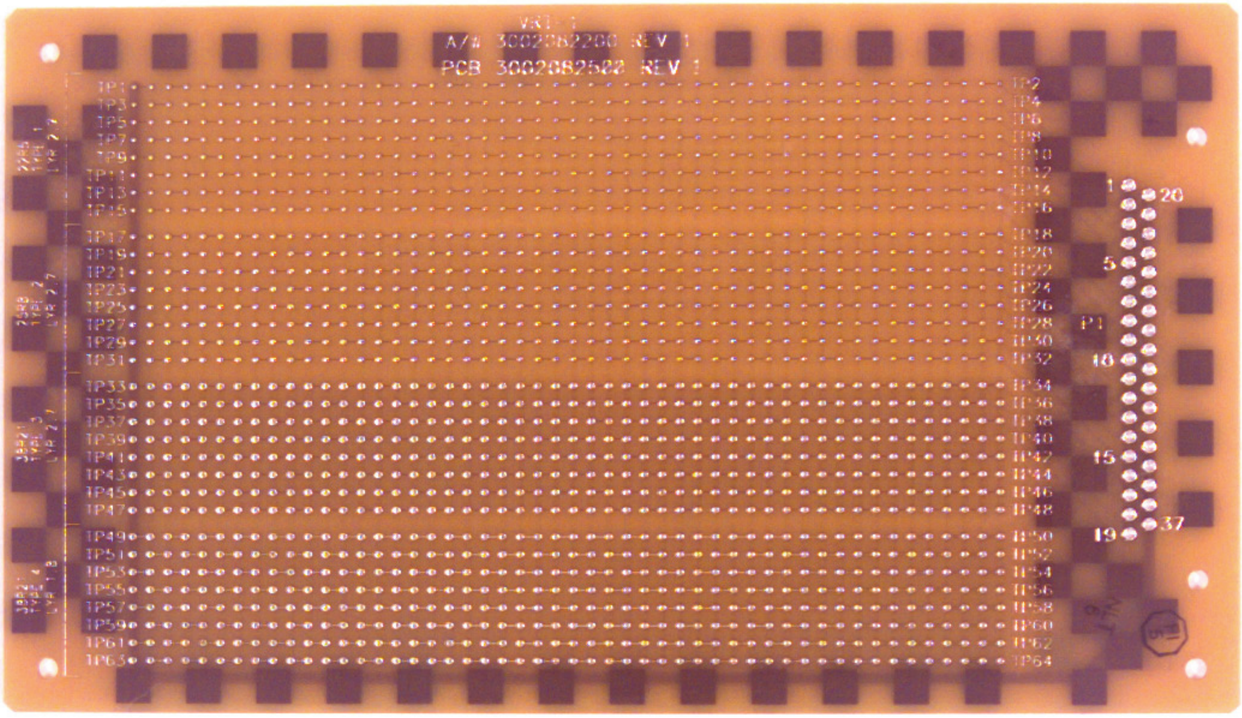


Figure 1 - Via Integrity Test Board

The test board is designed with 4 groups of 8 daisy chains of vias. The drill sizes of each group (drill size prior to plating) are as follows: .010 inches, .0135 inches, and two groups of .026 inches in drill size. The second group of .026 holes has connections on layers 1 and 8, and as mentioned above, was not used for this testing. Given the .125 inch thickness, these hole sizes result in aspect ratios of 12.5:1, 9.26:1, and 4.81:1.

Material Stack up

All the test boards, regardless of material type, had identical constructions as follows (Figure 2):

Thickness: .125 +/- .012, laminate to laminate

	Layer		
---------------------------	1	1/2 ounce	
xxxxxxxxxxxxxxxxxxx		Prepreg, 2 sheets 106 glass,	.004 REF
---------------------------	2	1/2 ounce, Signal	
////////////////////////////////		Laminate, 4 sheets 7628 glass	.0279 REF
---------------------------	3	1/2 ounce, Signal	
xxxxxxxxxxxxxxxxxxx		Prepreg, 1 sheet 2113/1sheet 7628/1 sheet 2113 glass	.0142 REF
---------------------------	4	1/2 ounce, Signal	
////////////////////////////////		Laminate, 4 sheets 7628 glass	.0279 REF
---------------------------	5	1/2 ounce, Signal	
xxxxxxxxxxxxxxxxxxx		Prepreg, 1 sheet 2113/1sheet 7628/1 sheet 2113 glass	.0142 REF
---------------------------	6	1/2 ounce, Signal	
////////////////////////////////		Laminate, 4 sheets 7628 glass	.0279 REF
---------------------------	7	1/2 ounce, Signal	
xxxxxxxxxxxxxxxxxxx		Prepreg, 2 sheets 106 glass,	.004 REF
---------------------------	8	1/2 ounce	

Figure 2 - Material Stack up Construction

It is important to understand the resin content of the materials in this stack up, as this plays a significant role in the ultimate thermal cycle reliability of the vias. The 7628 glass 28 mil cores are about 39% resin content. The 2113 standard prepreg resin content is approximately 58% and the 7628 approximately 44%. The 106 standard prepreg resin content is approximately 75%. The result is an overall board resin content of roughly 45%. This is a low number and will result in good thermal cycle results compared to higher resin content constructions. This should be factored in when evaluating the data from this test for use in high layer count boards, which typically have higher resin content.

PCB Surface Finishes

All of the test boards were finished with Immersion Silver with the exception of one test cell which used Electroless Nickel-Immersion Gold (ENIG) finish.

Materials

The materials tested were the following:

Nelco 4000-6	Dicy Cured High Tg FR4
Nelco 4000-7	Dicy Cured Mid Tg FR4, Low Z-Axis CTE
Nelco 4000-11	Non-Dicy Cured High Tg FR4
Polyclad Turbo 370	Non-Dicy Cured High Tg FR4
Isola IS410	Non-Dicy Cured High Tg FR4
Isola IS420	Non-Dicy Cured High Tg FR4, Low Z-Axis CTE

PWB Fabrication

All the PCB's were fabricated at the same time. Great care was taken to ensure that they were all plated in exactly the same lot, to minimize any plating variations.

Test Matrix

The resulting test matrix is shown in Table 1. It was set up to establish a baseline performance using 215°C reflow (SnPb) on dicy cured FR4 (Nelco 4000-6). It also was designed to establish a similar baseline for non-dicy cured FR4 (Polyclad Turbo 370) with lead-free (255°C) reflow. A mid-Tg, low z-axis expansion material (Nelco 4000-7) was also studied at a single hole size with both SnPb and lead-free reflow. The NiAu finished boards were added to follow up on a previous HDPUG project[4] that experienced exceptionally poor performance on ENIG finished boards when they were not subjected to reflow and also enable a brief look at the effect of the nickel on the via reliability. The other materials tested (IS410, IS420, and Nelco 4000-11) were non-dicy cured "Pb-free" compatible materials. Only the smallest hole size/highest aspect ratios were evaluated on these materials.

Table 1 - Test Matrix

Test Matrix

Board Designator	BD Type	Material	Finish	Drilled Hole Size	Connection Layers	# Reflows	Reflow Type	Nets/Bd	#Bds Req'd	Bds/Type	Total Nets
12HS0	12	N4000-6	Silver	10	2,7	0	n/a	8	4	24	
12HS3L	12	N4000-6	Silver	10	2,7	3	215	8	4		
12HS3H	12	N4000-6	Silver	10	2,7	3	255	8	4		
12HS5L	12	N4000-6	Silver	10	2,7	5	215	8	4		
12HS5L	12	N4000-6	Silver	13.5	2,7	5	215	8	same board		
12HS5H	12	N4000-6	Silver	10	2,7	5	255	8	4		
12HS5H	12	N4000-6	Silver	13.5	2,7	5	255	8	same board		
12HS5H	12	N4000-6	Silver	26	2,7	5	255	8	same board		
13HG0	13	N4000-6	NiAu	10	2,7	0	n/a	8	4	12	
13HG5H	13	N4000-6	NiAu	10	2,7	5	255	8	4		
14PS0	14	Polyclad Turbo 370	Silver	10	2,7	0	n/a	8	4	16	
14PS3H	14	Polyclad Turbo 370	Silver	10	2,7	3	255	8	4		
14PS3H	14	Polyclad Turbo 370	Silver	13.5	2,7	3	255	8	same board		
14PS5H	14	Polyclad Turbo 370	Silver	10	2,7	5	255	8	4		
14PS5H	14	Polyclad Turbo 370	Silver	13.5	2,7	5	255	8	same board		
14PS5H	14	Polyclad Turbo 370	Silver	26	2,7	5	255	8	same board		
15I41S5H	15	IS410	Silver	10	2,7	5	255	8	4	8	
16I42S5H	16	IS420	Silver	10	2,7	5	255	8	4	8	
17N7S0	17	N4000-7	Silver	10	2,7	0	n/a	8	4	24	
17N7S3L	17	N4000-7	Silver	10	2,7	3	215	8	4		
17N7S3H	17	N4000-7	Silver	10	2,7	3	255	8	4		
17N7S5L	17	N4000-7	Silver	10	2,7	5	215	8	4		
17N7S5H	17	N4000-7	Silver	10	2,7	5	255	8	4		
18N11S5H	18	N4000-11	Silver	10	2,7	5	255	8	4	8	
								192	72	100	768

The number of nets was cut down as much as practical to still look at the various parameters. Samples sizes of 32 nets per test cell were used. This ensures that if the test is continued to characteristic life (63% failures), that the resulting 20 failures would allow for reasonable statistical comparisons and distributions. All nets were monitored continuously (in-situation) during the testing.

Preconditioning

Test boards were preconditioned with either no preconditioning, or with 3 or 5 SnPb (215°C) (Figure 3) or SnAgCu (255°C) reflow cycles (Figure 4) in accordance with the test matrix as shown in Table 1. This provides data on both the effect of reflow temperatures and the number of reflow cycles. Zero reflow cycles is representative of the boards as received and also represents the performance of non-soldered boards such as backplanes that use only compliant pin assembly. Comparison of non-reflowed boards to reflowed boards also illustrates the effect of reflow directly. Three reflow cycles was chosen as representative of a board that sees double-sided reflow assembly followed by wave soldering without any rework. This should be typical of most complex assemblies (as rework is device specific). Five reflow cycles were used to represent a board that sees double-sided reflow assembly, wave solder and a typical SMT repair cycle which includes both a removal and a replacement thermal cycle.

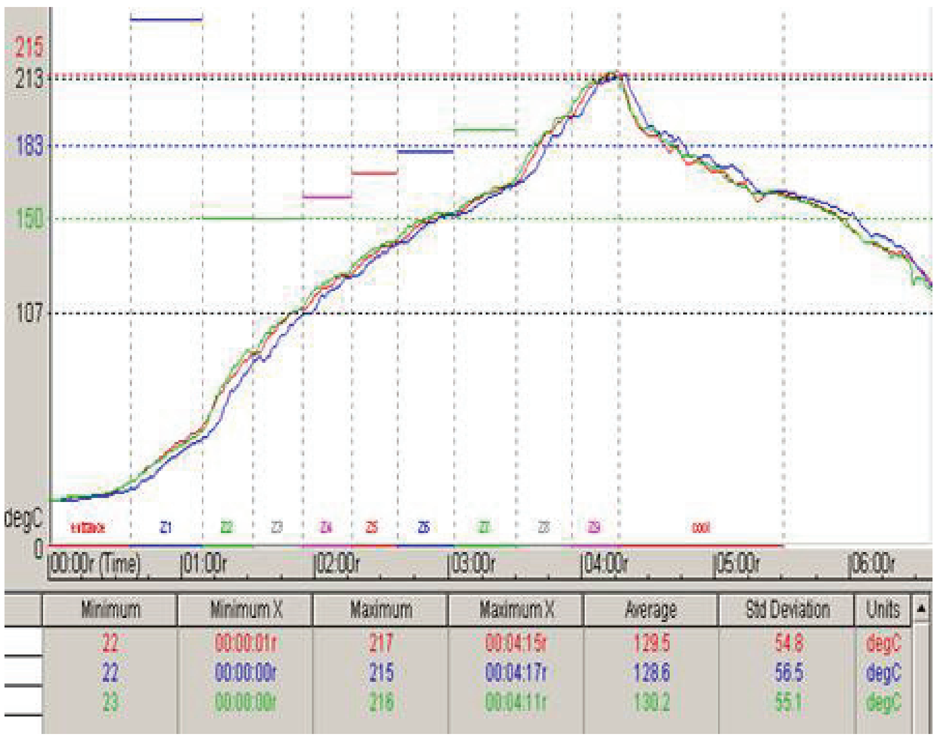
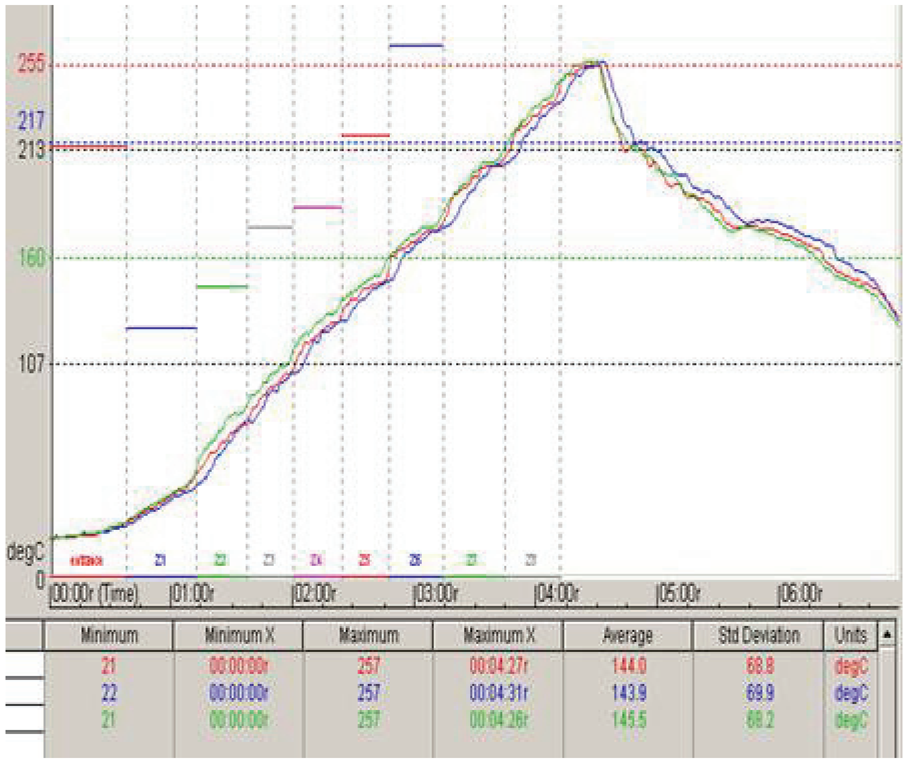


Figure 3 - SnPb Reflow Preconditioning Profile with 215°C Peak



Minimum	Minimum X	Maximum	Maximum X	Average	Std Deviation	Units
21	00:00:00r	257	00:04:27r	144.0	68.8	degC
22	00:00:00r	257	00:04:31r	143.9	69.9	degC
21	00:00:00r	257	00:04:26r	145.5	68.2	degC

Figure 4 - SnAgCu Reflow Preconditioning Profile with 255°C Peak

Thermal Cycling

After wiring, the test boards were placed in a refrigerated thermal cycle chamber (see Figure 5), a Testequity Model 1020C temperature chamber, and cycled 6009 cycles from -5°C to +100°C with a 10 minute dwell time at the temperature extremes and a ramp rate of 18 minutes. Temperatures were monitored continuously using an Agilent 20 Channel Multiplexer model 34901A. The thermal cycling averaged approximately 19 thermal cycles per day. There was some minor variation in the number of thermal cycles actually accomplished per day across the test, ranging from a low of 16 to a high of 23 as chamber maintenance issues affected the cool down ramp for a number of days until this was corrected. The resulting thermal cycle is shown in Figure 6. Based on the criteria of IPC-9701 [7] for thermal cycling dwell times at the temperature extremes, the actual thermal cycle range would be better specified as 0°C to 95°C and any reliability estimates based on this data should be based on that temperature range.

Figure 5 - Test Boards in The Thermal Cycle Chamber

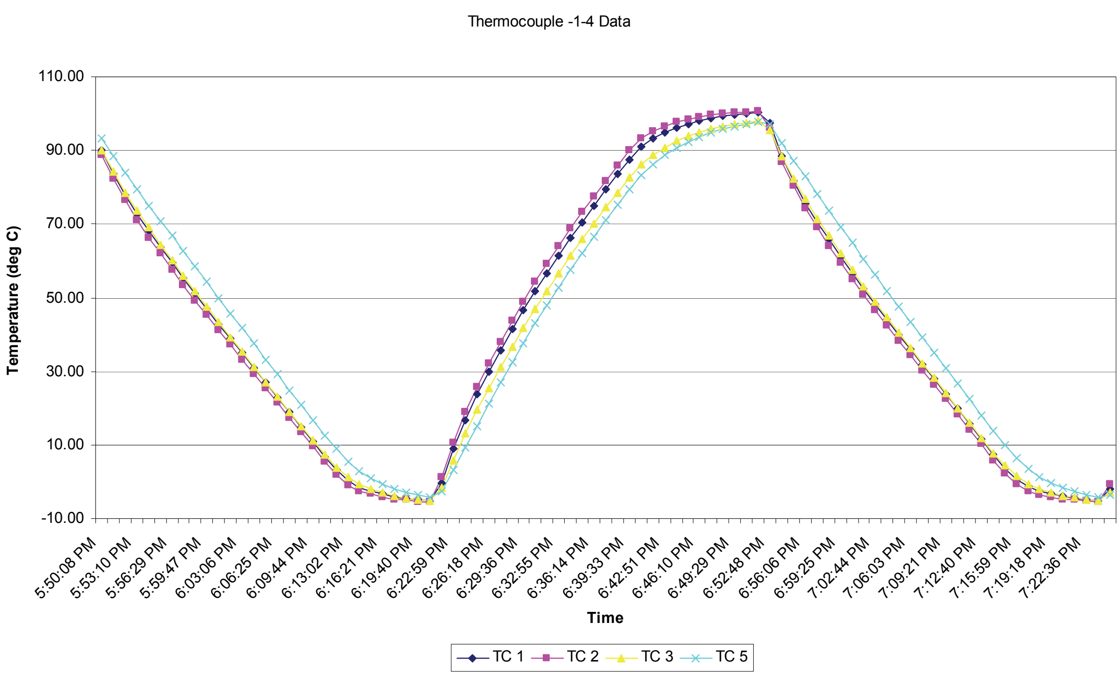


Figure 6 - Actual Thermal Cycle Profile

All the nets were continuously monitored using an Agilent Data Acquisition Unit 34970A, driven from LabView 6.1. Resistance measurements were made every minute using an Agilent 40 Channel Multiplexer Single ended model 34908A.

Values for both resistance and temperature were recorded into a file. The files were then scanned using Visual Basic programming in conjunction Excel to retrieve the event information for the specified limit. A failure was determined to be an increase in the resistance of the nets to 11 ohms. The resistance used for final evaluation was done after evaluating the results using threshold resistances of 4, 5, 7, 11, and 200 ohms. Eleven ohms typically gave the most consistent results and in many instances was indistinguishable from the 4, 5, and 7 ohm results. Figure 7 shows an example of this analysis. It was done for all materials.

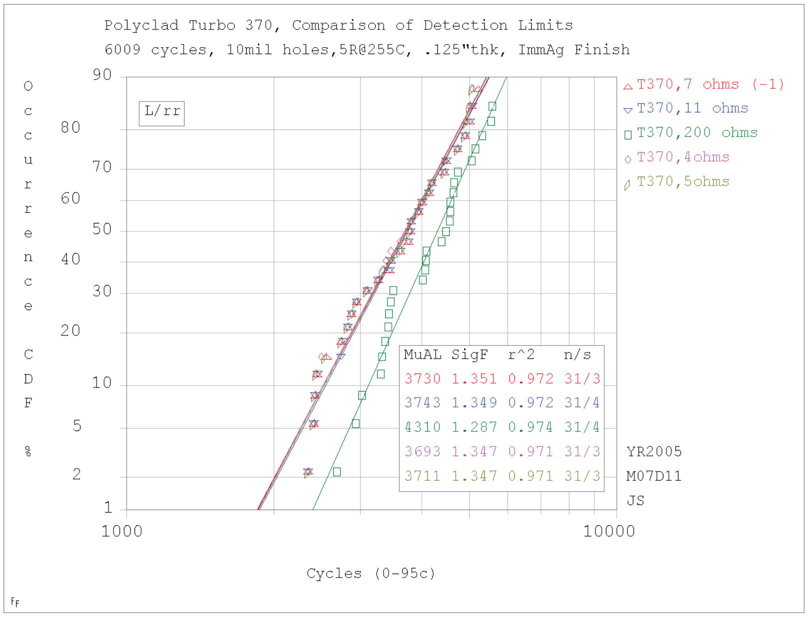


Figure 7 - Example of Analysis of Detection Limits

Weibull and Regression Analysis

Exhaustive Weibull and regression analysis was done on the test results and summarized in Table 2. For a barrel cracking failure mode, the failure distribution is expected to fit the Log Normal distribution [1]. Weibull distribution is generally a better fit when the failure mode includes foil cracking. The table highlights the best fit distributions based on either regression analysis (where data was sufficient) or is selected based on observed failure mode. Areas where the fit to the distribution is poor are also highlighted. Where the number of failures was too low for a valid statistical analysis, the best fit distribution was assumed to be Weibull since failure analysis indicated the failure to be barrel fatigue cracks. A selected number of Weibull plots of this data is shown following to highlight specific test results.

Table 2 - Summary of Weibull and LogNormal Analysis

Via Size Prior to Plating (mils)	Reflow Peak Temperature (ºC)	# Reflows	Material	Finish	Comments	Sample Size	Suspen-sions	2 Parameter Weibull			Log Normal		
								Eta	Beta	r^2	MuAl	SigF	r^2
10	NA	0	N4000-6	Imm. Ag		32	27	5849	19.18	0.987	5974	1.114	0.988
10	215	3	N4000-6	Imm. Ag		32	17	6078	6.891	0.949	5944	1.281	0.954
10	255	3	N4000-6	Imm. Ag		32	6	5209	5.181	0.974	4785	1.313	0.942
10	215	5	N4000-6	Imm. Ag		32	4	5532	5.162	0.97	5038	1.296	0.91
10	255	5	N4000-6	Imm. Ag		32	10	5162	5.185	0.878	4851	1.356	0.939
13.5	215	5	N4000-6	Imm. Ag		32	9	5377	4.45	0.974	4942	1.398	0.957
13.5	255	5	N4000-6	Imm. Ag		32	2	4542	5.385	0.94	4133	1.283	0.965
26	255	5	N4000-6	Imm. Ag		32	27	7706	4.931	0.875	8264	1.512	0.841
10	255	5	N4000-6	ENIG		32	29	635669	0.535	0.978	NA	NA	NA
10	NA	0	N4000-6	ENIG	2 Fails @ 5237 cycles	32	29	NA	NA	NA	NA	NA	NA
10	NA	0	T-370	Imm. Ag		32	0	3614	7.509	0.923	3357	1.187	0.988
10	255	3	T-370	Imm. Ag		32	2	4454	4.758	0.981	4000	1.319	0.967
13.5	255	3	T-370	Imm. Ag		32	3	4241	40213	0.941	3779	1.39	0.988
10	255	5	T-370	Imm. Ag	1 Early Fail Removed	31	4	4120	40783	0.911	3743	1.349	0.972
13.5	255	5	T-370	Imm. Ag		32	3	3865	40822	0.871	3496	1.336	0.928
26	255	5	T-370	Imm. Ag		32	27	8172	4.017	0.899	8937	1.665	0.874
10	255	5	IS410	Imm. Ag		32	0	2649	3.7	0.972	2281	1.4	0.972
10	255	5	IS420	Imm. Ag	Zero Fails	32	32	NA	NA	NA	NA	NA	NA
10	NA	0	N4000-7	Imm. Ag		32	30	8016	9.299	1	8697	1.277	1
10	215	3	N4000-7	Imm. Ag		32	26	6619	11.48	0.775	6852	1.199	0.82
10	255	3	N4000-7	Imm. Ag		32	19	7463	3.493	0.967	7228	1.641	0.944
10	215	5	N4000-7	Imm. Ag		32	26	8565	4.28	0.986	9179	1.6	0.971
10	255	5	N4000-7	Imm. Ag		32	15	6217	6.937	0.966	5973	1.276	0.989
10	255	5	N4000-11	Imm. Ag		32	17	6203	6.891	0.965	6076	1.283	0.988

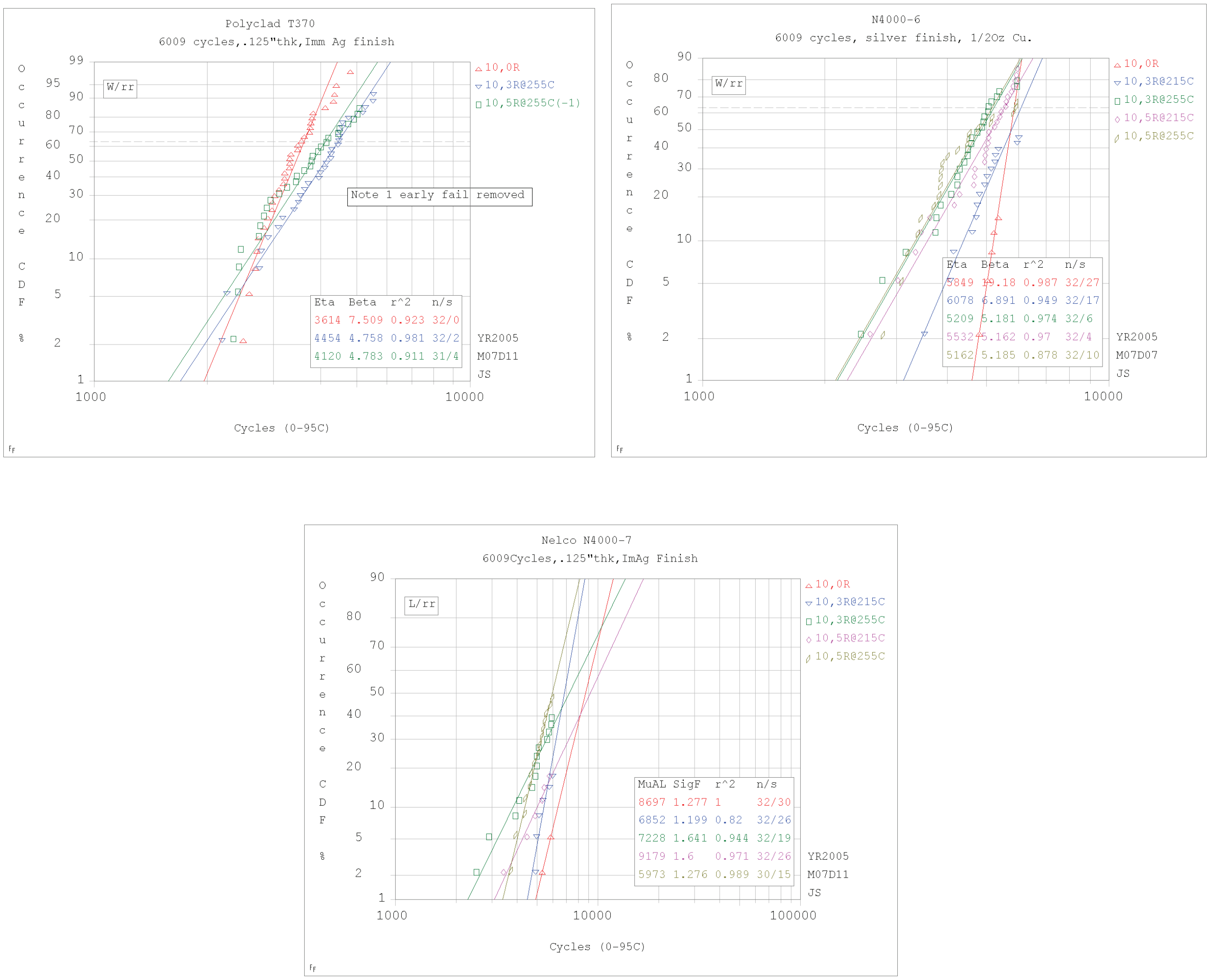
= Indicates best fit distribution either by regression analysis(or assumed by failure mode if too little data)

= Indicates distribution is a statistically poor fit by regression analysis

= Indicates acceptable fit by regression analysis (if enough data - if not, then barrel cracks assumed)

The Impact of Different Reflow Profiles

Figure 8 a, b, and c show the effect of different reflow peak temperatures and number of reflow cycles on the thermal cycle fatigue life of the 10 mil vias. As expected from previous testing [4], the Weibull shape parameter (β [MuAl for Log Normal Distribution]) is reduced after exposure to reflow temperatures. For the Polyclad Turbo 370 material (Figure 8a), increasing the number of reflow cycles from 3 to 5 at 255°C reduced the reliability of the vias. For the Nelco 4000-6, this trend held true for boards reflowed at 215°C. Three and 5 reflows at 255°C on this material performed worse than even 5 reflows at 215°C, but the differences between 3 and 5 reflows at 255°C were statistically indistinguishable. Statistically, many of the distributions for the Nelco 4000-6 were a better fit to the Weibull distribution than the Log Normal distribution. However, in most cases the fit to either distribution is acceptable. For the Nelco 4000-7, increasing the number of reflows reduced the reliability. In this case the data is less clear due to the lower number of failures in the sample populations.

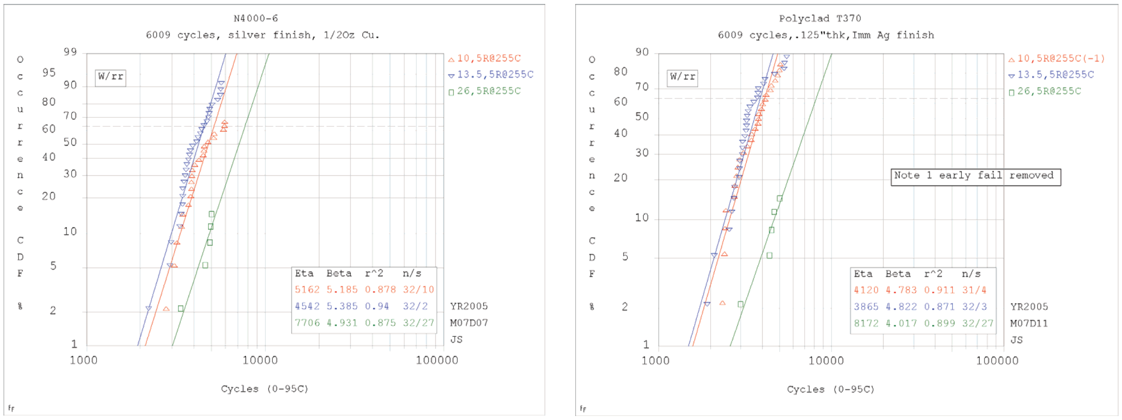


(c)

Figure 8 - The Effect of Varying # of Reflows and Peak Temperatures. (a) Polyclad Turbo 370, (b) Nelco 4000-6, (c) Nelco 4000-7

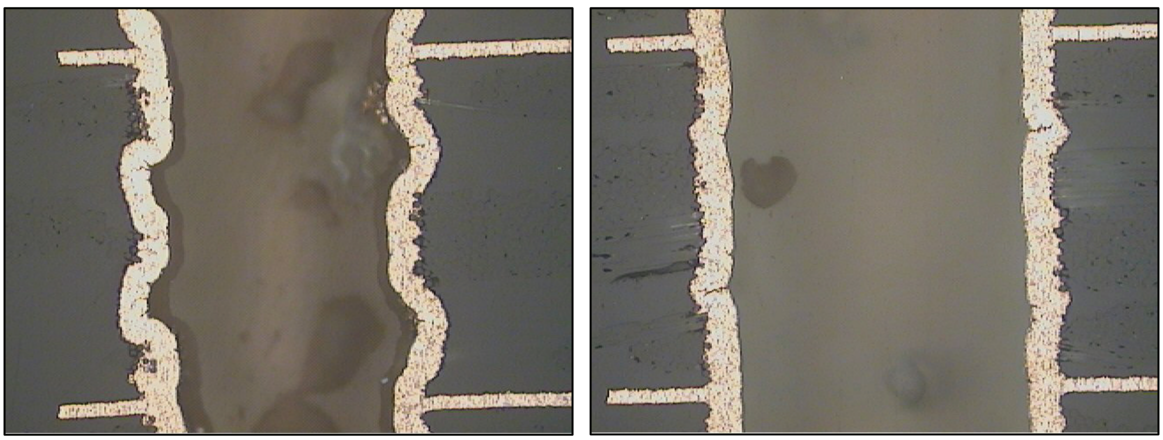
The Impact of Different Hole Sizes and Resulting Aspect Ratios

Hole size and the related aspect ratio are well known to have a significant effect on via reliability [1,4,5]. This is due to both the greater difficulties in plating smaller holes, when the aspect ratio gets larger, and the larger stresses on the plated through hole wall during thermal cycling or thermal excursions such as reflow. Similar trends are shown in this data. However, there are some rather unusual results for the smaller hole sizes. As shown in Figure 9 a and b, for both Nelco 4000-6 and Polyclad Turbo 370, the 10 mil hole size had a slightly better reliability than the 13.5 mil hole size. When statistically analyzed, these distributions are not greatly different, but even the same performance would be a surprise considering the difference in aspect ratios (12.5:1 vs. 9.26:1). Microsection comparison was completed for each material type to evaluate differences. The 10 mil holes generally had more small to mid-sized cracks spread throughout barrel in addition to the large, circumferential cracks. The 10 mil holes also sometimes had laminate voids or resin starvation that the 13.5 mil holes did not. These might have allowed the expansion of the material to relieve stress in the material or across a wider area of copper, so as not to focus the stress in one or two locations, which seems to be the case on the 13.5 mil vias. As can be seen from Figure 10, the hole walls are also smoother for the 13.5 mil vias. Smoother hole walls are expected to improve reliability[8,9], but this effect was not noted here. The overriding factor appears to be the small to mid-sized cracks spread through out the plated through hole barrel.



(a) (b)

Figure 9 - Effect of Varying Hole Size. (a) Nelco 4000-6, (b) Polyclad Turbo 370



(a) **(b)**

Figure 10 - Comparison of Hole Wall Quality between 10 mil holes (a) and 13.5 mil holes (b)

Comparison of Materials

As shown in Figure 11, which compares the via reliability of six different materials all at 10 mil drill hole size, through five reflow cycles at 255°C, there are significant differences in the via reliability associated with the various materials. Regression analysis was done comparing the 1% failure rates with various material parameters. (Note that IS420 could not be included in the regression analysis since there were zero failures.) The coefficient of thermal expansion (CTE) below Tg, CTE above Tg, and CTE % expansion from 50-260°C were evaluated vs. the failure rates. Only the CTE below Tg has any reasonable correlation to the results. Figures 12a and 12b show the regression analysis and plot of this parameter vs. the failure rate. Figure 12a shows this including all materials that had failures and Figure 12b is a replication of this data, but taking out Nelco 4000-11, which appeared to be an outlier in the data. At this time, however, a valid reason for this outlier is not clear, so both are shown. Figure 13 shows a comparison of material properties as published by the material supplier and as measured by TMA analysis on the 8 layer test vehicles after 5 reflow cycles at 255°C, but before the thermal cycling. The differences between these two are related to a combination of sample selection and preparation at the individual material suppliers, who test their laminate separately, and the fact that the test vehicles are 8 layer constructions and have also been through 5 reflow cycles at 255°C. These differences plus the poor correlations between CTE and thermal cycle performance make it very difficult to specify a specific set of material CTE parameters and relate them with any confidence to via reliability.

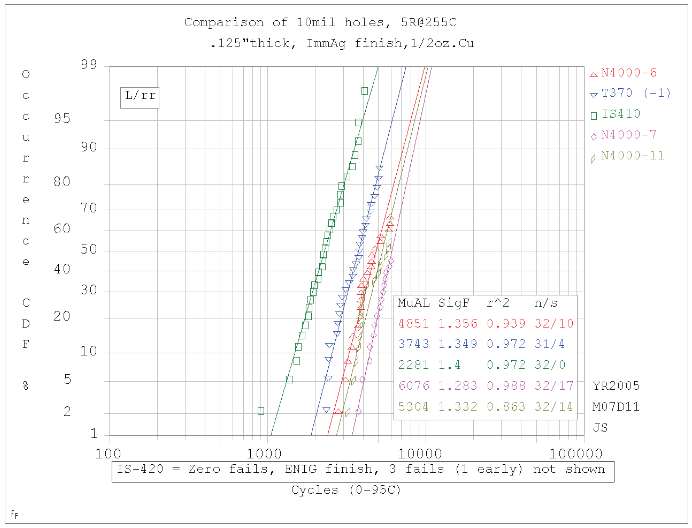
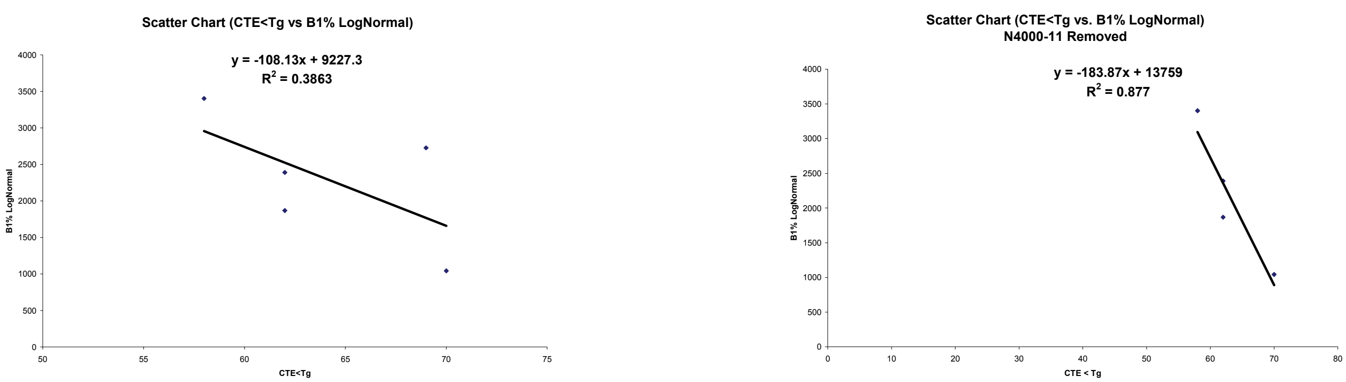


Figure 11 - Comparison via Reliability with Different Materials



(a) (b)

Figure 12 - CTE <Tg vs. B1% Log Normal (a) All Data (b) with Nelco 4000-11 Removed

Material Type	Tg (TMA)ºC		Overall CTE(%)		CTE<Tg		CTE>Tg	
	Measured	Supplier	Measured 50-250ºC	Supplier 50-260ºC	Measured	Supplier	Measured	Supplier
Nelco N4000-6	151.2	170	3.98	3.7	62	68	339	320
Nelco N4000-7	137.7	150	3.99	3.5	58	50	308	270
Nelco N4000-11	151	170	3.68	3.2	69	65	299	265
Polyclad 370 Turbo	153.6	170	3.53	3.5	62	50	300	250
Isola IS410	152.8	NA	3.82	3.5	70	60	320	NA
Isola IS420	163.2	NA	2.75	2.8	53	40	247	NA

Figure 13 - Supplier Data Sheet Material Values vs. Measured Values (by TMA) on The 8 Layer Test Vehicle after 5 Reflow Cycles

Effect of Board Finish

As mentioned above, two test cells were included to evaluate the effect of a nickel underplating (ENIG finish) on the plated through hole reliability and follow up on previous testing that had extremely poor performance from the ENIG finish when the boards were not subjected to reflow[4]. Figure 14 shows this comparison. The poor performance of ENIG with zero reflow did not repeat in this test. Zero reflow only had 2 failures, both at 5237 thermal cycles. The previous test identified nickel separation (not seen on the reflowed samples) that appeared to be the cause of the early failures in that test. In this case, the number of failures for ENIG finished plated through holes is very low. However, what becomes apparent from both the previous testing and this testing is that this finish may be susceptible to early via fatigue failures during thermal cycling.

If there is a defect in the nickel, or an area of thin nickel, the stress on the copper barrel will concentrate in a specific area of the plated through hole making it more susceptible to premature failure. Considering the sample size of the number of holes in this test compared to typical high complexity circuit boards, this becomes an area of concern. If, however, the nickel is sufficiently thick, uniform and defect free, it is expected to improve the plated through hole reliability. Nickel, as will be shown later in the failure analysis review, can stop the crack propagation in the copper plating. For an open to occur, the crack must reinitiate in the nickel and propagate through both the copper and the nickel. These results are consistent with previous studies on the effect of nickel [4, 10].

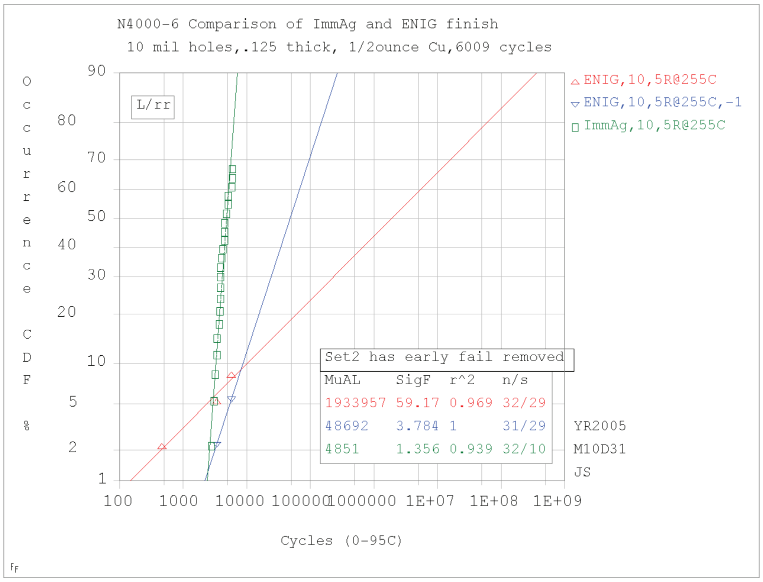


Figure 14 - Comparison of ENIG vs. Immersion Silver Finished on Nelco 4000-6

Effect of Drill and Plating Processes

Drilling and plating processes have always been a significant factor in plated through hole reliability [8,9]. In general, the hole wall quality related to the drill and plating processes of the various board materials evaluated in this study were very similar. However, the hole wall roughness on the Polyclad Turbo 370 material was notably greater than the other materials. A number of plating folds, and resulting low copper thickness, in isolated areas were noted in the holes of this material. (See Figure 15.) Due to the way the test was designed it is impossible to verify, but this is the likely cause of the one early failure that occurred on this material.

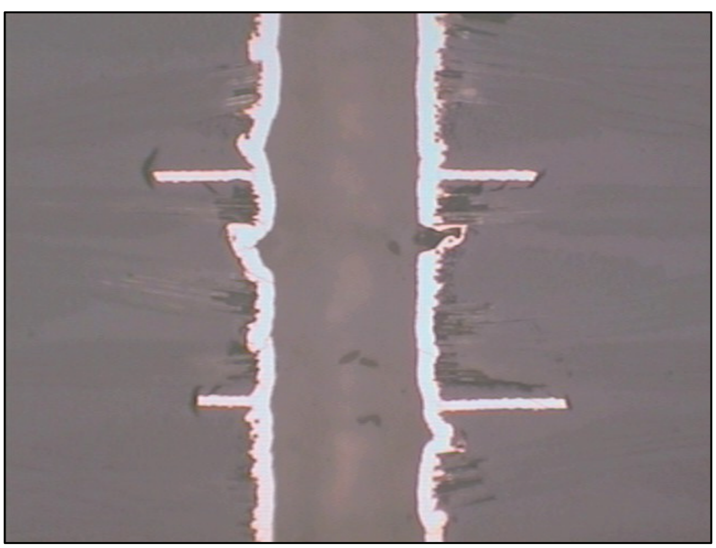


Figure 15 - Example of Plating Fold and Resulting Low Copper Thickness on Polyclad Turbo 370 Materials

Effect of Plating Characteristics

Significant differences in performance on the Nelco 4000-6 material were noted between this test and previous HDPUG testing on the 10 mil holes. As noted previously, however, on this test the 10 mil holes performed essentially the same, or maybe even slightly better than the 13.5 mil holes. One of the reasons that this material was in the test was to enable a comparison of this data to previous test data. The boards used in that testing were similar construction and resin content. Review of the microsections and plating thickness showed similar hole wall quality and plating thickness. The artwork and layers were identical. The primary difference is that the boards were thinner. They were 0.093" thick, versus 0.125" thick used in this test. Thus for a direct comparison, the 13.5 mil holes in this test (9.26:1 aspect ration), after 5 reflow cycles at 215°C can be compared to the 10 mil holes in the previous test (9.3:1) with the same 5 reflow cycles at 215°C. It should also be noted that the phase 1 data used a HASL finish, where this test was immersion silver. Because the thermal cycle conditions are different for the 2 tests (the earlier testing was from -40 to +125°C, 36 cycles per day), an acceleration factor (based on Coffin Manson) is applied to the data. For clarity the data is only shown with acceleration factors applied to the phase 1 data. As can be seen, these two Weibull plots (phase 1 x acceleration factor and phase 2) are virtually indistinguishable. Also included on this plot are the 10 mil hole results from the phase 1 testing (multiplied by the acceleration factor). This is a significant difference since the 10 mil holes performed essentially the same as the 13.5 mil holes in this test (Figure 9). Already noted previously is the difference in the way the cracks were distributed on these smaller holes. However, there is also a difference in the plating chemistry. During the roughly 1.5 years between these test samples being built, the fabricator improved the copper plating baths significantly. The phase 1 boards were plated with copper with an average tensile strength of 37,600 psi and 12% elongation. The boards for this test were plated with copper with an average tensile strength of 40,500 psi and 27.6% elongation. This is probably the difference in the crack performance on the smaller holes. Where the stresses are less on the lower aspect ratio holes, the impact of the copper plating characteristics appears to have less effect on the ultimate via reliability.

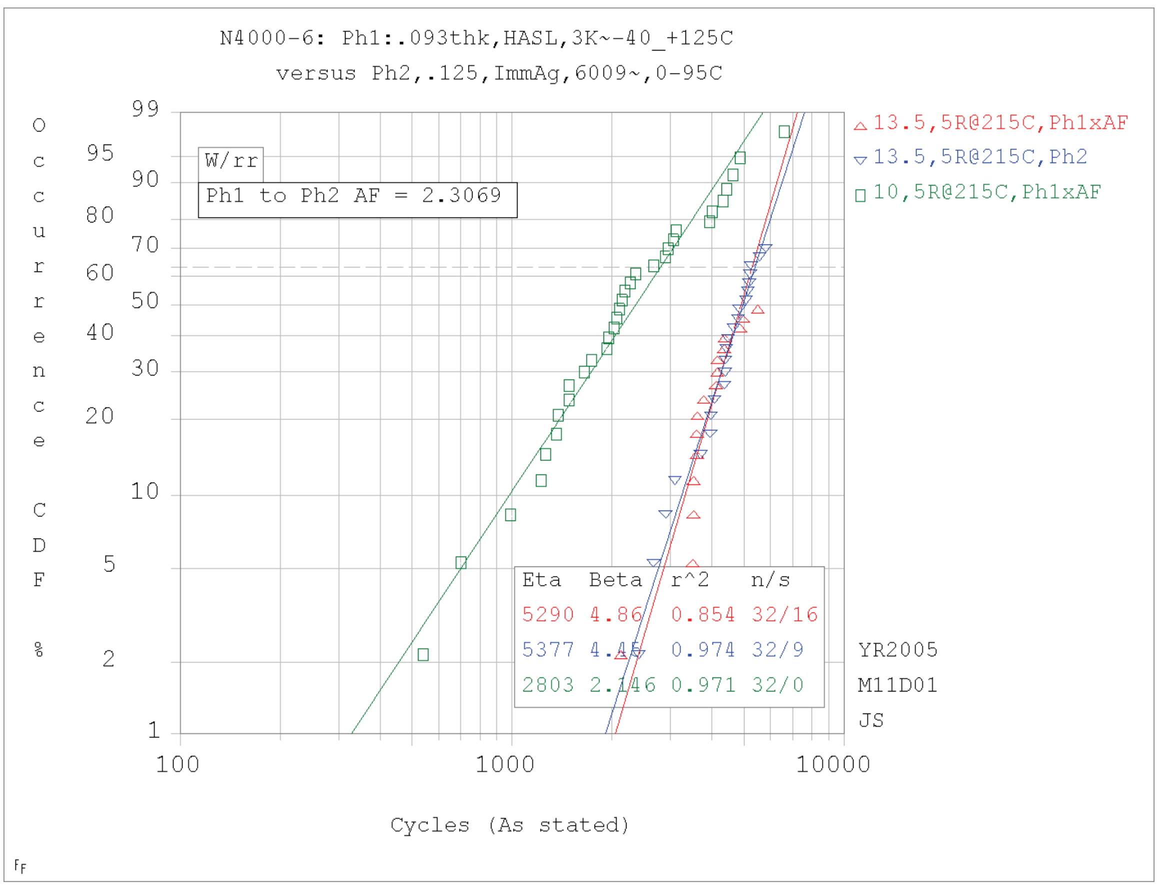


Figure 16 - Comparison of Previous Test Data (Ph1) vs. This Test for 13.5 mil holes. For clarity the Weibull plots from phase 1 testing are shown using an acceleration factor to correct for differences in thermal cycles between tests. The 10 mil holes from phase 1 testing are also shown.

Failure Analysis

Extensive cross sections for failure analysis were completed on the test boards after thermal cycling. Most of these were done after completion of 6009 thermal cycles. The IS410 microsections were taken after completing approximately 4000 thermal cycles. Some specific examples have been previously shown to help explain the Weibull analysis results. At a minimum, one section was taken of each sample as shown in Figure 17. The focus of these microsections was the 10 mil holes. As expected, the minimum copper wall thickness on the holes was consistent between board types, averaging approximately 1 mil minimum on each board type. Consistent results were expected as they were plated at the same time, with only normal variations in the minimum copper thickness expected related to different locations on the fabricator panel and inherent variability in the process. The minimum copper wall thickness in individual microsections ranged from 0.8 mils to 1.3 mils.

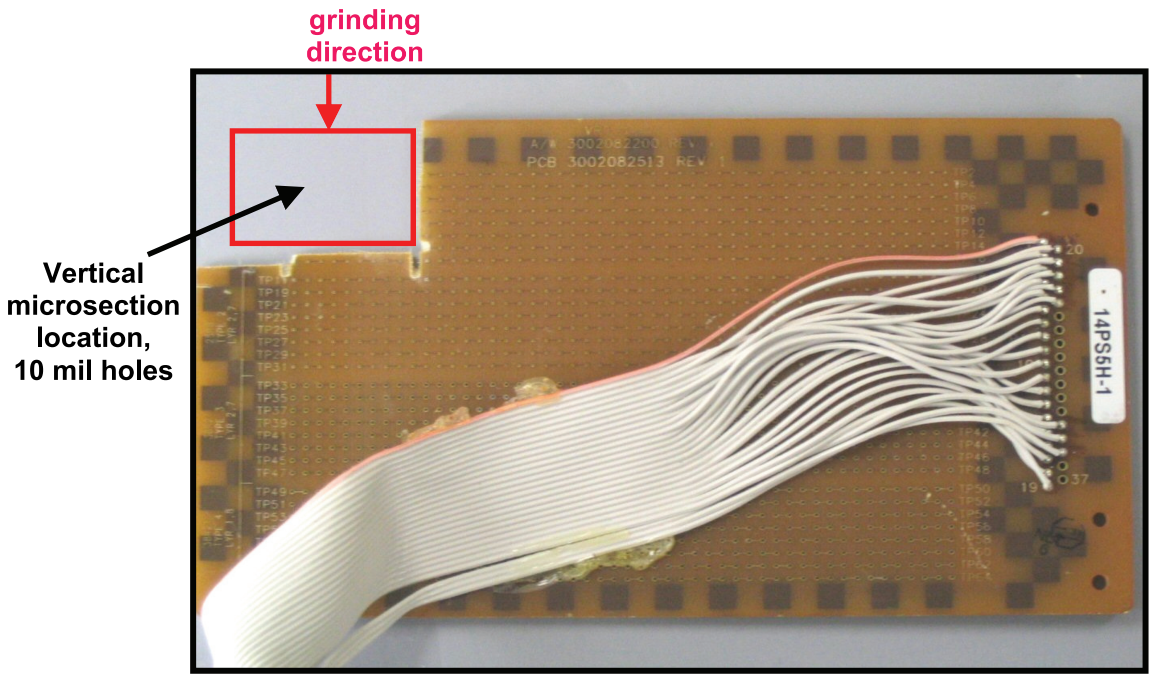


Figure 17 - Area Where Each of The Boards was Microsectioned

A summary of the results for each of the respective materials follows:

Nelco 4000-6

Twenty eight of 28 microsection samples identified barrel cracks that extended through the width of copper plating. Two of the samples also identified some small zone A laminate voids. Figure 18 shows an example microsection showing a small zone A laminate void and typical large size barrel cracks.

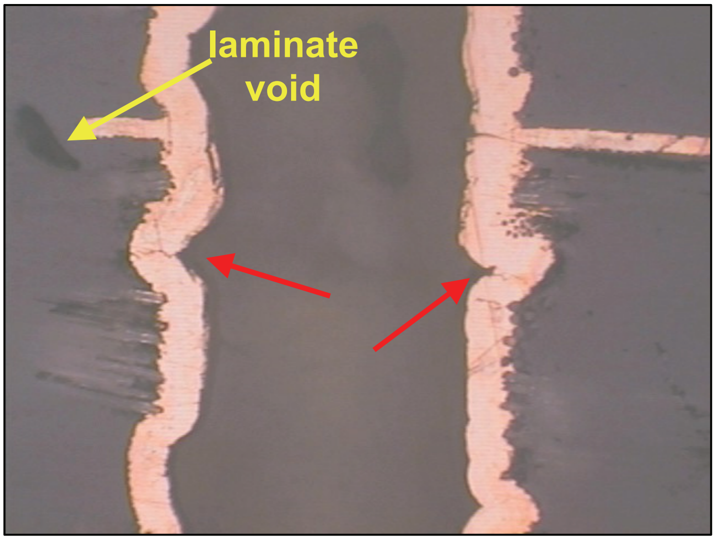


Figure 18 - Example N4000-6 Cross section Showing Zone A Laminate Voids and Large Size Barrel Cracks Sample #12HS5H-3 (5 LF Reflow Cycles, 200X)

Nelco 4000-6 with ENIG Finish

The failure analysis for these boards yielded results virtually identical to the Nelco 4000-6 boards with Immersion silver finish, with one notable exception. As can be seen in Figure 19, the cracks that go through the copper barrel stop at the nickel layer. There are cracks in the nickel also, but these are generally in different locations from the fatigue cracks in the copper barrels. Thus the cracks don't result in opens until they propagated through both plating materials.

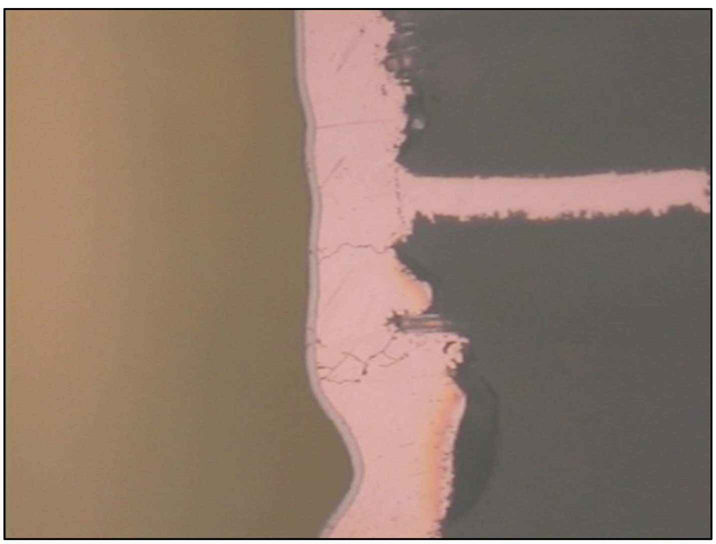
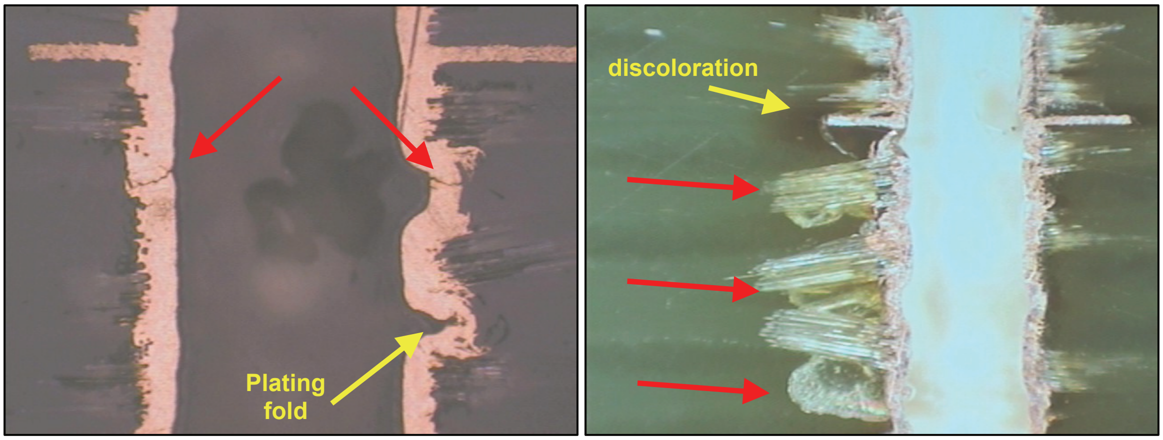


Figure 19 - Nelco 4000-6 with ENIG Finish Showing Cracks in Both The Copper and Nickel but The Cracks are in Different Locations. Thus Opens don't Occur. (5 LF reflow cycles, 400X).

Polyclad Turbo 370

Microsection evaluation of the Polyclad Turbo 370 showed 12 of 12 samples with barrel fatigue cracks that extended through the width of copper plating, 11 of 12 samples with large zone A and/or zone B laminate cracks, and 6 of 12 samples with plating voids (due to rough hole wall where plating folds). Also some slight discoloration was noted near surfaces and interconnects. Figure 20a shows examples of a plating fold causing localized low copper thickness and typical large size barrel cracks. Figure 20b shows the large laminate cracks and the dark discoloration around the interconnect areas.



(a) (b)

Figure 20 - Polyclad Turbo 370 (a) Examples of Plating Fold Causing Localized Low Copper Thickness and Large Barrel Fatigue Cracks (5 LF Reflow Cycles, 200X) and (b) Example of Large Laminate Cracks Observed Next to Hole Wall. Note also darker coloration around interconnects and small laminate crack (3 LF reflow cycles, 100X, Darkfield)

Isola IS410

The IS410 failure analysis was completed after approximately 4000 thermal cycles. These microsections showed foil cracking of the inner layer copper, close to the hole wall. This was probably the initial failure location. This failure mode is consistent with the regression analysis on the data that indicated a best fit to the Weibull distribution. All of the samples (12 of 12) also exhibited large barrel cracks that extended through the width of the copper plating. Figure 21 shows an example of the inner layer foil cracks found in these microsections.

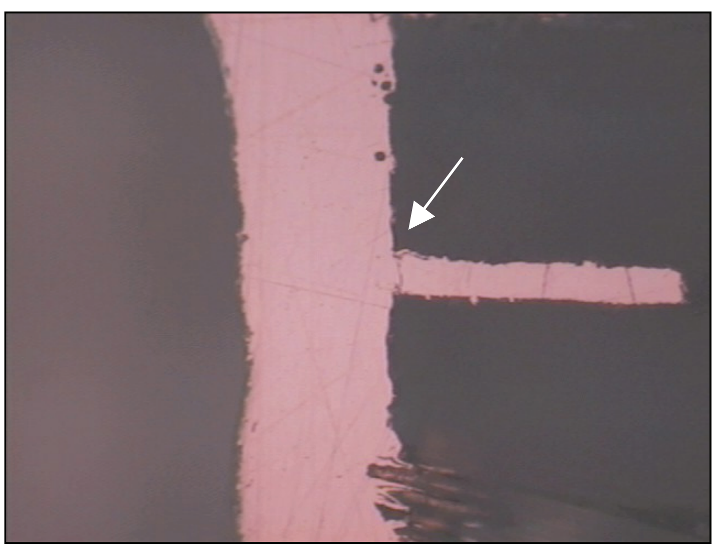


Figure 21 - Isola IS410 Example of Foil Crack Through Entire Width of Inner Layer (5 LF Reflow Cycles, 4,000 Thermal Cycles, 400X)

Isola IS420

The Isola IS-420, which had zero failures during the test, also had the best hole ranking in the study of any material. There were no barrel cracks extending through the width of the copper plating and only a few small barrel cracks propagating partially through the copper plating were noted. The samples did have some large zone A laminate voids and also exhibited resin starvation. It is clear that these did not have a significant effect on the reliability of these holes through this testing. Figure 22a shows an example of some drill smear at the interconnect and Figure 22b shows examples of the small fatigue cracks.

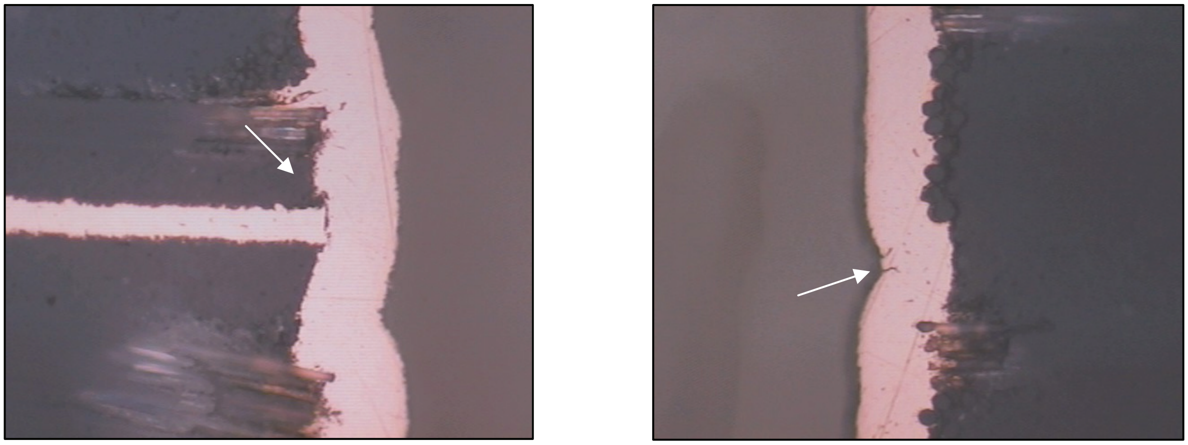
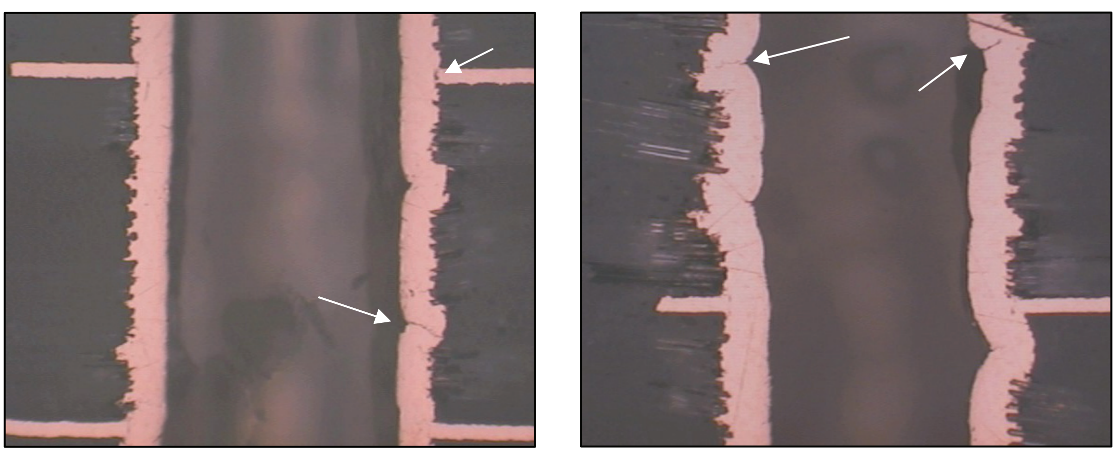


Figure 22 - Isola IS420: (a) Some Drill Smear at The Inner Layer Connection. (b) Example of Small Barrel Crack Observed (5 LF Reflow Cycles, 400X)

Nelco 4000-7

The failure analysis of the Nelco 4000-7 boards showed 20 of 20 samples with barrel cracks extended through the width of the copper plating. Seven of the samples also showed large zone A and/or B laminate cracks. Twelve of the samples were noted with slight smear/drill debris at the inner layer connections that did not cause any separation. Some slight discoloration of the laminate was noted near the surface and the internal layer connections. Figure 23 shows an example of this with Figure 23b showing that the cracks were more prevalent where the hole walls were rougher.



(a) (b)

Figure 23 - Nelco 4000-7 (a) Example of Mid- to Large-Sized Barrel Cracks Observed. Also note some drill smear at interconnect (No reflow cycles, 200X), (b) Example of barrel cracks prevalent where drilled hole wall is rough (No reflow cycles, 100X)

Nelco 4000-11

Microsection evaluation of the Nelco 4000-11 material showed 4 of 4 samples with barrel fatigue cracks that extended through the width of copper plating. (See Figure 24.) No other defects were observed.

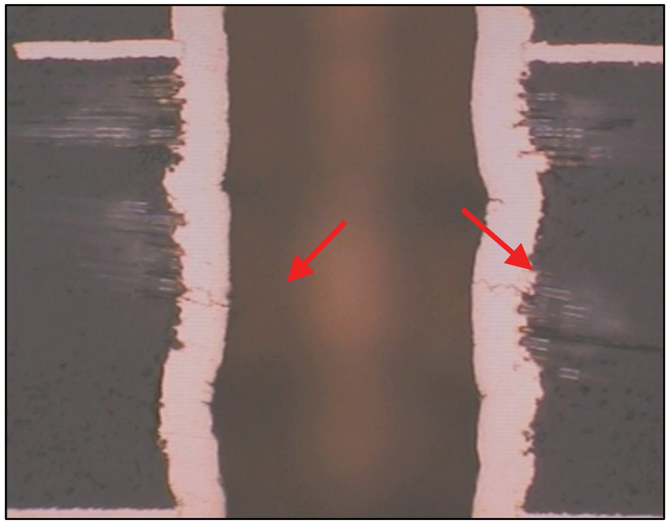


Figure 24 - Nelco 4000-11 Example of Barrel Fatigue Cracks (5 LF Reflow Cycles, 200X)

Summary

Via reliability is only one of a number of factors that need to be considered in the choice of materials for printed wiring board fabrication when assembly is to be done using high temperature Pb-free solders such as SnAgCu. Material parameters such as decomposition temperature, glass transition temperature, and T-288°C capabilities are other factors that also need to be considered. This study was limited to specifically looking at the effect of Pb-free reflow temperatures on via reliability. As expected, the higher temperature lead-free reflow cycles have an adverse affect on plated through hole reliability. This study confirmed that materials are available that provide sufficient via reliability performance even for the most demanding of applications. Every material studied in this test, even those that are not specifically designated by material suppliers for Pb-free applications might be acceptable for a given product depending on the thermal complexity of the design and the field life and environmental requirements of the product.

Design considerations and manufacturing processes also play a key role in via reliability. This study showed via reliability reducing as the via aspect ratio increased, but only to a point. The copper plating characteristics of tensile strength and elongation appears to have a major impact on this, particularly above approximately a 10:1 aspect ratio.

The z-axis CTE characteristics of the materials surprisingly did not have a strong correlation to the reliability performance. However it is clear that they play a role, particularly the CTE below the glass transition temperature. f the one outlier (Nelco 4000-11) is removed from this data, then the correlation improves dramatically. Complicating this were significant differences between supplier reported material parameters and measured parameters of the materials when used in an actual printed wiring board and subjected to five Pb-free reflow cycles. It becomes clear that improvements to the IPC tests methods for these material parameters should be made to more completely specify sample selection, resin content, and sample preparation. It would also make sense to include some type of standard multilayer construction and subject it to multiple reflow cycles to provide material parameters more accurately in line with the actual use conditions of the materials.

Given the differences in material performance related to plated through hole reliability and the difficulty in relating material properties directly to the resulting plated through hole reliability, it is highly recommended that high reliability and/or long life applications include some quantifiable fatigue life evaluation of materials prior to specifying them on this type of product. The data from this test could readily serve as a baseline for comparison whether the method used is air to air thermal cycling, liquid to liquid thermal shock, Interconnect Stress Test (IST) or some other viable fatigue life test.

The nickel plating associated with ENIG finishes can improve plated through hole reliability. However the uniformity, quality and consistency of this finish in the plated through holes is critical to reliability. A quality problem in the nickel plating can result in early life failures that would otherwise not occur with a different surface finish.

Drill hole wall roughness and plating quality continue to be key parameters in plated through hole reliability. Additionally, for higher aspect ratio plated through holes, the tensile strength and elongation properties of the copper appear to be a significant variable substantially affecting long term reliability.

Future Work

Since the start of this testing, many new materials have been introduced specifically targeted for Pb-free assembly applications. For example Isola has introduced IS-415 to provide lower Dk compared to IS420, while improving the thermal performance compared to IS410. Similarly, Polyclad introduced the 370HR material for higher reliability performance. Numerous other printed wiring board material suppliers have also introduced materials specifically targeted for Pb-free compatibility. Follow up and additional other testing to look at these and also halide free material performance is being considered by the High Density Packaging Users Group consortium.

Acknowledgements:

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References:

1) Joe Smetana, "Plated Through Hole Reliability with High Temperature Lead Free Soldering", The Board Authority, Volume 4, Number 1, April 2002, pp. 50-64

2) Michael Freda and Jason Furlong, "Application of Reliability/Survival Statistics to Analyze Interconnect Stress Test Data to Make Life Predictions on Complex, Lead-free Printed Circuit Board Assemblies", Proceedings of EPC2004, Oct. 2004, Cologne, Germany.

3) John J Davignon and Randy Reed, "Effects of NEMI Sn/Ag/Cu Alloy Assembly Reflow On Plated Through Hole Performance", Proceedings of SMTA Lead-Free Conference, June 2000

4) Previous HDPUG test data (unpublished)

5) IPC-TR-579, "Round Robin Reliability Evaluation of Small Diameter Plated Through Holes in Printed Wiring Boards"

6) iNEMI Advanced Lead-Free Assembly & Rework Development Project, April 2005

7) IPC 9701 "Performance Test Methods and Qualification Requirements for Surface Mount Solder Attachments"

8) A. Gusdupta and V. Ramappan, "Simulation of the Influence of Manufacturing Quality on the Reliability of Vias", Journal of Electronic Packaging, June 1995, Vol 117, pp 141-146

9) K, Ramakrishna, G. Subbarayan, B.G. Sammakia, "Effect of Non-uniformities and Defects in PTH Strain During Assembly and Thermal Cycling", Advances in Electronic Packaging, ASME 1992

10) K.T. Knadle and M.G. Ferrill, Failure of Thick Board Plated Through Vias with Multiple Assembly Cycles, The Hidden BGA Threat, Proceedings of Surface Mount International Conference, April 1997, pp. 109-115.