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The Impact of Solderability on Reliability and Yield of Surface Mount Assembly

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ABSTRACT

This report contains the results of an NPL programme to develop test methods for assessing joint reliability by thermo-mechanical fatigue. The impact of solderability degradation on solder joint fatigue is discussed and illustrative data on ceramic chip resistors are given. Components were exposed, prior to assembly, to six ageing regimes to modify the solderability of the surface finish. Following the accelerated ageing for various times at 155°C, components were soldered using a no-clean reflow process. The solder fillets on these components ranged from unacceptable non-wetting to excellent wetting. The process yield was correlated with the solderability. Assemblies were then thermally cycled between -20 and 120°C. The results revealed that the thermal fatigue failure rate, as measured by electrical continuity of the resistors, is also correlated with solderability. The relationship between solderability and solder fillet shape, and hence process yield, has been demonstrated, and in turn solderability and yield have also been correlated with thermal fatigue properties.

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1. INTRODUCTION

Predictions of product lifetimes are often required and are clearly more important for safety critical and military applications, than in most domestic scenarios. For the majority of surface mount (SM) products the most common cause of mechanical stress is mismatch in coefficients of thermal expansion (CTE) of the various PCB assembly constituents. As assemblies are cycled between the power on and off state, in different ambient temperatures, all the components experience varying degrees of physical stress depending on their size and relative CTE mismatch. The strain energy created in this stress cycling is absorbed by the component, the component lead, the solder fillet and the substrate. In most instances this energy is principally absorbed in the component lead and the solder fillet, but when there is no component lead, such as for LCCCs, chip capacitors and resistors, the energy is dissipated in the solder joint. A compliant lead effectively isolates the component from the board whereas with leadless components it is the solder joint that deforms to relieve the stress. The relative CTE values for a resistor assembly are shown in Figure 1. As can be seen the largest difference in CTE is between the ceramic resistor body and the solder, but the biggest strain will result from the difference between ceramic and the substrate since this is operating over a larger distance.

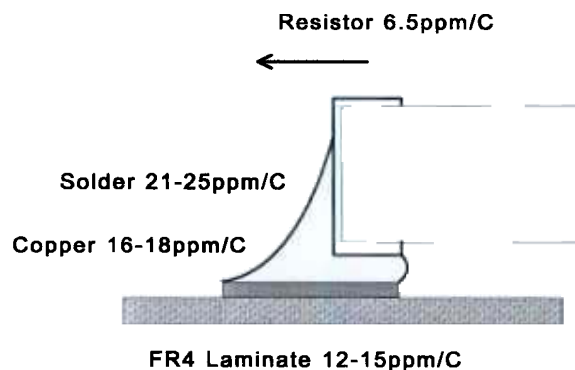


Figure 1. CTE (x-axis) mismatches in SM assemblies

To screen products from failing by stresses resulting from temperature excursions, complete PCBs are thermally cycled in chambers to test their reliability, and the results from the test used to qualify the design and production process. This however assumes a future product is the same or better than the original test pieces. Clearly if the solderability is poor, the wetting will be poor, and solder will not rise as far up the component lead and a different fillet shape will be formed. We would clearly expect the poorer joint to fail earlier, but the relation between fillet shape and time to failure, or median life-time and hence reliability, is not known and this is the issue addressed here.

2. MANUFACTURE OF TEST ASSEMBLIES

For this experiment sixty PCB assemblies were manufactured by a contract manufacturer with SM capability. Each assembly incorporated **fifty 0805 chip resistors with a nominal value of 1000 Ω** . The resistors were arranged in independent circuits on the PCB and could be

electrically monitored individually using a multiple pole switching system and a digital volt meter via a 50-way connector on each board. During thermal cycling, this circuit design enabled the resistors on each assembly to be monitored periodically at room temperature, and a selection of resistors to be monitored during thermal cycling at both the hot and cold dwells in the cycle. The values of all resistors soldered were checked electrically after assembly using this method. The layout of the assembly is shown in Figure 2. The design also incorporates three SOIC14s (1.27 mm pitch) and one QFP120 (0.6 mm pitch). These devices could not be monitored electrically. The PCB was a double-sided FR4 substrate, 1 mm thick, with a photo-imaginable wet solder resist. All PCBs were from the same batch from a single manufacturer.

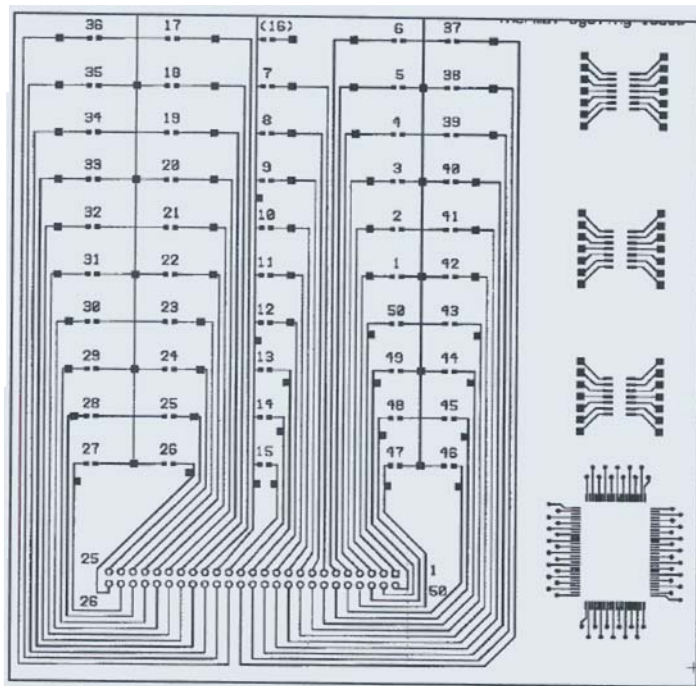


Table 1. Artificial ageing regime for resistors

Heat treatment Designation	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6
Hours at 155 °C	0	50	150	300	700	1000

The resistors used were all from a single reel of components from a major European manufacturer. The termination was a nickel barrier type with a plating of 90Sn10Pb to an average thickness of 9.4 μm . To investigate the effect of varying solderability, the components were split into six batches artificially aged in an air-circulation oven at 155 °C. The ageing regimes are given in Table 1. The assembly process and constituent parts were identical for all six sets of assemblies, with the exception of the solderability of the SM resistors.

The solderability of the resistor termination after ageing was determined using a Multicore MUST System II solderability tester using the globule test method carried out to IEC 68-2-69.

The solder temperature was 235 °C and the solder used was 60/40 SnPb. The flux was as specified in IEC 68-2-20 with 0.5% chloride and was supplied by Multicore Solders as Actiec 5. The components were dipped at 1 mm s⁻¹ to a depth of 0.1 mm. The force at two seconds was recorded for all the measurements.

The assembly method was a simple single-sided reflow process of stencil printed solder paste, using manual placement equipment and mixed IR/convection reflow. A single pot of paste(60/40 Sn/Pb with no-clean flux) was used. Only one operator was used for each operation. The stencil used was manufactured from 0.15 mm thick stainless steel. Apertures were chemically etched with a 10% linear reduction on corresponding component land size. The components were placed manually as they had to be removed from tape to be artificially aged. All assemblies were reflow soldered using the same profile in a mixed convection/IR machine. The peak reflow temperature was 220°C and the maximum molten solder time was 45 s. No touch-up was performed at any part of the process. The assemblies were left uncleaned.

2.1 THERMAL CYCLING

The assembled PCBs were inserted into a cycling oven for thermal cycling. The cycle was selected on the basis of being representative of what is currently in use, and the damage to the substrate if the T_g were exceeded. The two hold temperatures were -20 °C and 120 °C with 10 minute dwells and 1 hour cycling period. A typical thermal profile is shown in Figure 3.

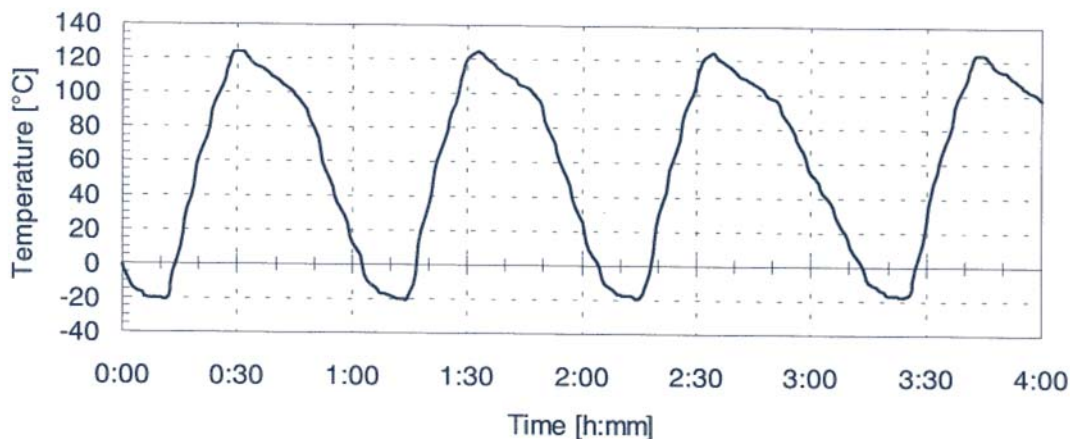


Figure 3. Temperature profile in the thermal cycling chamber

3. EXPERIMENTAL

3.1 VISUAL INSPECTION

After manufacture every joint on each assembly was visually inspected using a stereo zoom microscope with 10-30x magnification by a single operator. Hence 6000 joints were inspected and scored. Each solder joint was given a score out of five for the height of fillet rise and a similar score for wetting angle. A diagrammatic representation of the scoring system is given in Figure 4. A wetting angle value of 2 corresponds to an approximate wetting angle of 90°

and a score of 1 is greater than 90° . A fillet rise value of 2 corresponds to a fillet rise of a quarter the component height. Both these criteria are recognised in many national standards as being the minimum acceptable solder joint criteria. An unacceptable joint is considered to have a wetting angle of less than or equal to 2 and a fillet height of less than or equal to 2. Thus an ideal joint with a low wetting angle and a high fillet rise to the top of the component would be given a score of 10 (5+5). An unsoldered joint with no fillet rise would score 2 (1+1).

Despite generating more than 1500 visually defective joints, the post-assembly electrical test could only locate one component with a resistance of greater than $1050\ \Omega$. This was a tombstoned resistor which was an open circuit. All other components exhibited an electrical resistance which was within the tolerance of the resistor ($1000\ \Omega \pm 5\%$). This important result confirms the widely held belief that electrical testing is not a reliable method of finding substandard solder joints.

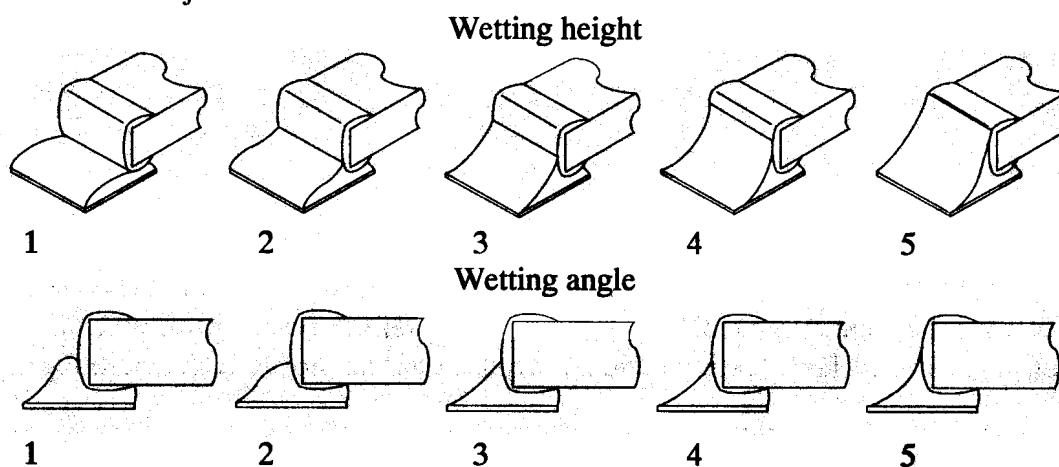


Figure 4. Fillet rise and wetting angle criteria

3.2 SOLDERABILITY MEASUREMENTS

The solderability of the lead termination for each component age is plotted in Figure 5. The solderability degradation follows typical ageing behaviour. Initially there is only a small change in solderability in the first 100 hours due to oxide action of the fusible coating. Thereafter the solderability deteriorates more quickly as the effect of the intermetallic becomes apparent. When the intermetallic oxide has formed over a large part of the surface, the latter is rendered completely unsolderable to electronics grade fluxes. At 1000 hours the solderability has fallen to the minimum value as measured on the wetting balance for this component type.

The process yield was calculated by analysing the visual inspection scores and is also plotted in Figure 5 with the solderability data. The yield data were calculated as a percentage based on a total possible visual inspection score, using the criteria discussed above. Hence an average score of 9 corresponds to a 90 % yield.

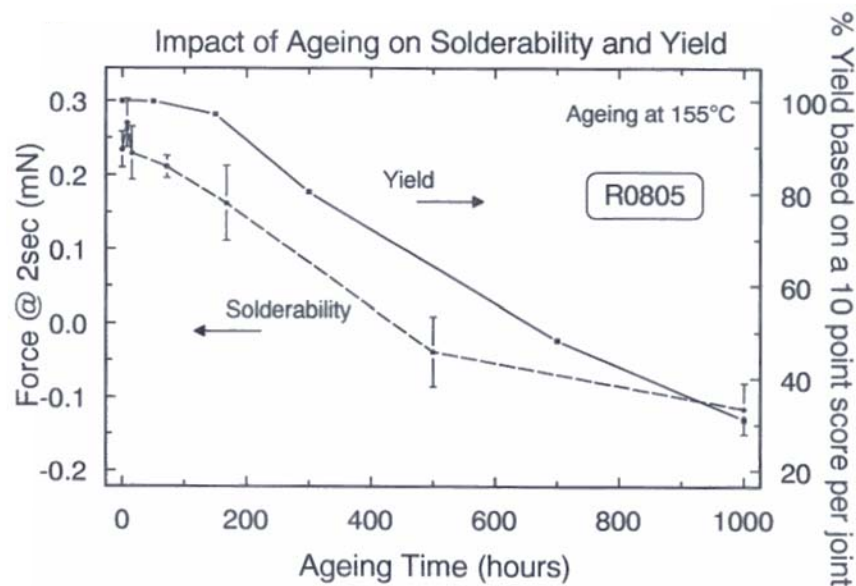


Figure 5. Comparison of solderability & process yield

It is immediately apparent from Figure 5 that there is an excellent correlation between solderability and process yield. This result clearly demonstrates that the solderability, as measured with the wetting balance, can be correlated with process yield. Each PCB assembly also contained three SOICs and one QFP. A very similar correlation between solderability results and visual inspection were obtained for the SOICs and QFPs. Hence, it is established here that solderability measurements are very effective in predicting yields.

4. MEASUREMENT OF RESISTANCE

The resistance of each resistor was measured by the Voltage Method, where a constant voltage across a resistor of 1 ± 0.0001 V was applied, and the current through the resistor was measured.

There were two modes of resistance measurement:

- 1) Continual measurement of 80 selected resistors - at every hot and cold dwell in the thermal cycle
- 2) Periodically measurement of all resistors - every 2 weeks at room temperature. Each board was connected through an 80 way switch bridge to the measuring equipment, which was controlled using a LabVIEW® program and a IEEE-488.2 interface.

4.1 ERRORS OF MEASUREMENT AND MANUFACTURING

The errors of measuring resistance are considered below.

V-source:

In the range of ± 1.1000 V resolution step..... $\Delta V = 100 \mu\text{V}$,

Operation point..... $V_0 = 1.0000$ V

$$\text{Relative error} \quad \delta V = \frac{\Delta V}{V_0} = \frac{100 \times 10^{-6}}{1.0000} = 0.01 \% \quad (1)$$

A-meter:In the range of ± 10.000 mA resolution step $\Delta I = 1 \mu\text{A}$,Operation point $I_0 = 1 \text{ mA}$

$$\text{Relative error} \quad \delta I = \frac{\Delta I}{I_0} = \frac{1 \times 10^{-6}}{1 \times 10^{-3}} = 0.1 \%$$

Resistance:Nominal value..... $R_0 = 1000 \Omega$ Relative measurement error: $\delta R = \delta V + \delta I = 0.01 \% + 0.1 \% = 0.11 \%$ Manufactured resistor tolerance:..... $\delta R' = 5 \%$

Absolute Error of Resistance:

$$\Delta R = (\delta R + \delta R') \times R_0 = 0.0511 \times 1000 = 51.1 \Omega$$

5. VISUAL INSPECTION SCORE

As mentioned previously each joint was measured for wetting height and angle, and the possible correlation of these measurements and the distribution of the scores, were investigated.

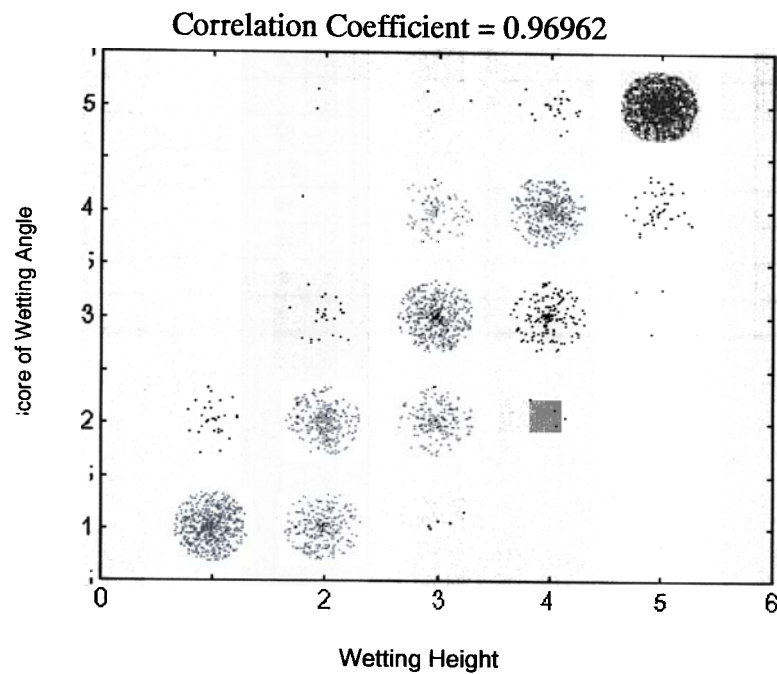
First, the correlation between wetting height and angle for each score was considered. In Figure 6. each joint score is plotted, height against angle. The occurrence of a specific score is plotted randomly within a circle at each score location. Hence the darker the area, the more prevalent is the score. These results show that a correlation between height and angle exists, with a correlation of 0.96962. It is also clear that 5_5 is the most frequent score. The relative distribution of scores is tabulated in Table 2. Since the height and angle scores correlated very well a reduction of the scores was carried out.

5.1 HEIGHT AND ANGLE SCORE OF SOLDER FILLET

Nineteen combinations of height and angle scores were identified and their frequency of occurrence is given in Table 2. It is clear from this table, Figure 6. and the correlation coefficient of 0.96962 that there is a good correlation between height and angle, and these scores can be merged. Thus each joint score was modified from height and angle to a single score which was the lowest of either score. Continuing on this theme a new combined score was created, the **resistor score**, which was defined as the minimum from the height and angle of wetting for both the left and right side of the resistor. An example of this process is shown in Figure 7., in which the score for a resistor was reduced from 4 to 2 parameters and was written as 3_1, where 3 was the left hand angle score and 1 right hand height score.

Table 2. Frequency of Height and Angle Scores

No.	Height(H)-Angle(θ)	Frequency of Joints
1	2-4	1
2	2-5	2
3	5-3	3
4	3-5	4
5	4-2	4
6	3-1	5
7	4-5	22
8	2-3	25
9	1-2	29
10	5-4	39
11	3-4	89
12	4-3	151
13	3-2	196
14	2-1	307
15	2-2	325
16	4-4	348
17	3-3	491
18	1-1	678
19	5-5	3261

**Figure 6. Correlation between height and angle of wetting from visual inspection**

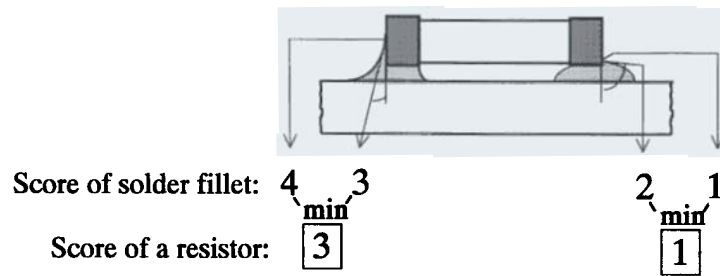


Figure 7 Example of resistor's score generation

5.1.1 Resistor Score

In Table 3. all the scores for the resistors are shown, except for 39 resistors in Age 1, and 20 resistors in Age 2 to Age 6 which were not measured. They were omitted, because of errors in the initial experimental set up, and for example include a grounded wire on a connector, and missing resistors. Table 3 is plotted in Figure 8 as a 3D graph and it is clear that the resistors with the longest ageing treatments, have the poorest scores.

Table 3. Distribution of resistor's scores in Ages

Score	Age 1	Age 2	Age 3	Age 4	Age 5	Age 6	Sum of Ages	Fraction
1_1				1	89	276	366	12.8%
2_1				5	67	89	161	5.6%
3_1				3	37	22	62	2.2%
4_1			1	4	2	1	8	0.3%
5_1				9	2		11	0.4%
2_2				9	52	37	98	3.4%
3_2			3	20	74	26	123	4.3%
4_2				13	9	6	28	1.0%
5_2			11	10			21	0.7%
3_3			2	52	87	17	158	5.5%
4_3			5	98	27	5	135	4.7%
5_3			23	42	10		75	2.6%
4_4			5	38	13	1	57	2.0%
5_4		10	40	56	8		114	4.0%
5_5	461	470	390	120	3		1444	50.5%

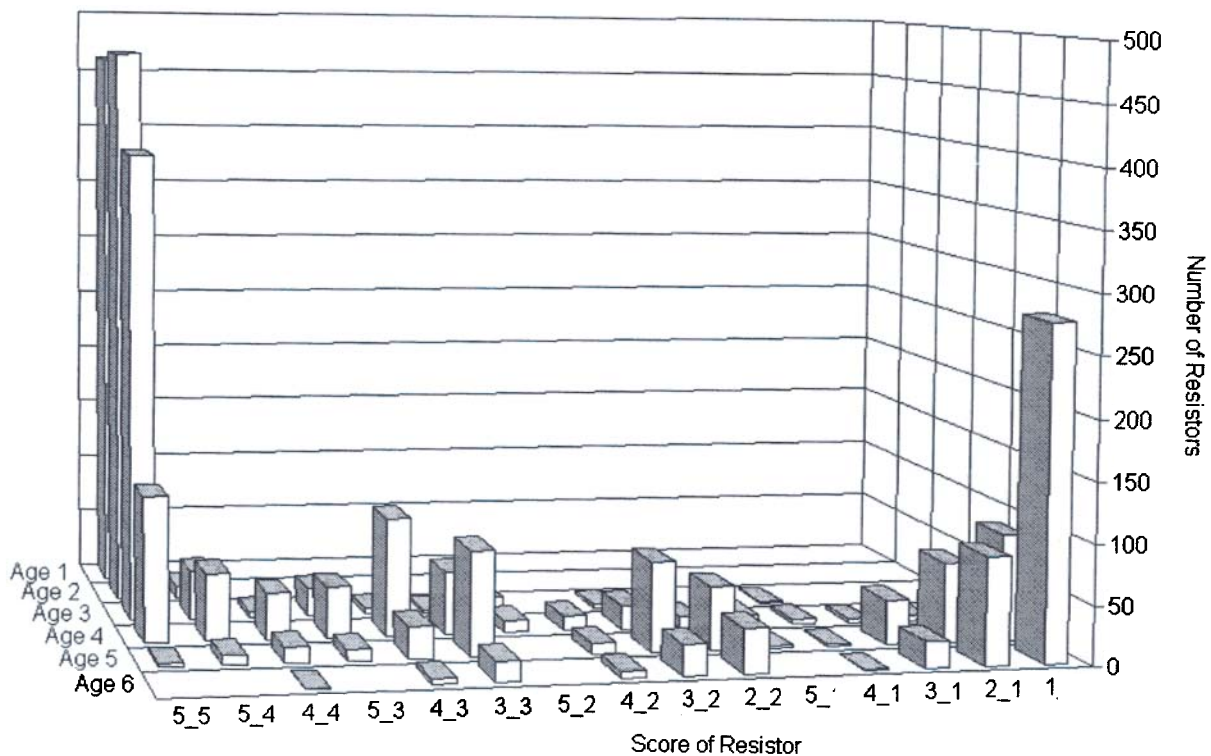


Figure 8. Amount of resistors with the certain resistor score in the age groups

The distribution of scores in Figure 8 is very interesting since it is clear, that the resistor score does not progress smoothly from the top score to the bottom score with the resistor Age sets. From figure 5 a clear diminution in resistor score with the Age set would be expected, but Figure 8 shows that the resistor score is mainly distributed at the high and the low score, with a trough in the number of intermediate resistor scores. This is significant, since it clearly illustrates that as the solderability deteriorates, the range of wettability within a batch increases. Hence, for quite small reductions in the average wettability a critical number of solderability failures will occur in the important sub 100 ppm range.

In this work this large range of solderabilities is apparent for Ages 3, 4 & 5, whereas for Ages 1, 2 & 6 the resistor scores are distributed over a much narrower range. For example, the wettability of Age 3 is 10 % less than Age1, and there is a resistor score of 4_1 & three 3_1; these low scores will undoubtedly lead to early failures (see below).

6. RESULTS OF THERMAL CYCLING

The sixty boards for the six Age sets were cycled as described earlier. Although in-situ monitoring was implemented initially, this proved to be problematic, with observed failures being confused with connector problems. Hence the only reliable electrical data were taken with the boards outside the cycling chamber. Furthermore it is important to note that all the data were checked, and any correlated errors removed. Correlated errors did occur, for example connection problems still occurred with the measurement equipment. A failure was counted as the first excursion above the failure limit.

6.1 PASS / FAIL CRITERIA

From Equation 4, for resistance deviation, we estimate a limit, which represents an open circuit for a particular resistor of 1100 Ω . The counting of failures from the measured data file was conveniently visualised in sets of tables, where each cell represented a resistor, and was colour coded to indicate its status. The colour of a cell has a memory function which was used to distinguish the resistor's states. Furthermore, the current status in a measured cycle was provided by a fill pattern. The rules for assigning colours and fill pattern were the following:

Colours

White colour - resistor's resistance has never crossed the failure limit of 1100 Ω .

Green colour - resistor's resistance has been above the failure limit only once.

Yellow colour - resistor's resistance has been above the failure limit more than once

Dark Blue colour - resistor's resistance is not defined; there is no resistor at this coordinate.

Light Blue colour (marking of board) - the marked board was not measured or removed for cross-sectioning and optical analysing of the cracked joints.

Patterns

Without pattern - in the current number of cycles the resistor's resistances is below the failure limit of 1100 Ω .

Cross pattern - in the current number of cycles the resistor's resistance is above the failure limit of 1100 Ω .

This procedure proved invaluable in identifying rogue failures and deficiencies in the measurements.

6.2 ACCURACY OF ESTIMATING FAILURE RATES

The failure data can be analysed using the discontinuous Binomial distribution. This approach is valid even when there are large numbers of resistors in a specific resistor score category, and furthermore there are different numbers in each category. The distribution is often used in SPC of electronics' assembly [8]. Equation 5 is the probability relation, based on the Bernoulli trial sequences (selection with return), i.e. independent events.

$$P(k) = \left(\frac{N!}{(N-k)! \cdot k!} \right) \times p^k \times (1-p)^{N-k} \quad (5)$$

Where:

N - number of trials

k - number of successes in N trials (integer and $0 \leq k \leq N$)

p - Bernoulli probability parameter (probability of a success at a single trial)

$(1-p)$ - survival probability of success (probability of a no success at a single trial)

$P(k)$ - probability of k successes in N trials

In Figure 9 the Binomial probability function is plotted for the resistors with a 2_2 score. In this experiment, the number of trials N , is the number of resistors with the same score. The number of

counted failures (successes) is k . Since we have a limited data set, the estimate of the probability of failure will have a distribution, as shown in Figure 9. The value of k/N is the most likely frequency of a failure. It is apparent that the maximum of the function is at $p = k/N = 0.540$. The area below the curve is equal to 1 or 100% respectively.

If we would like to find the range in which a certain fraction of failures lie, we solve the inversion task for Equation 5, and it can be shown to be equal to Equations 6a, 6b. We calculate a numerical integral of density function (Equations 6a, 6b) for each resistor group and set the probability range of failure at 0.95 (note right side of Equations 6a, 6b: 0.975 - 0.025).

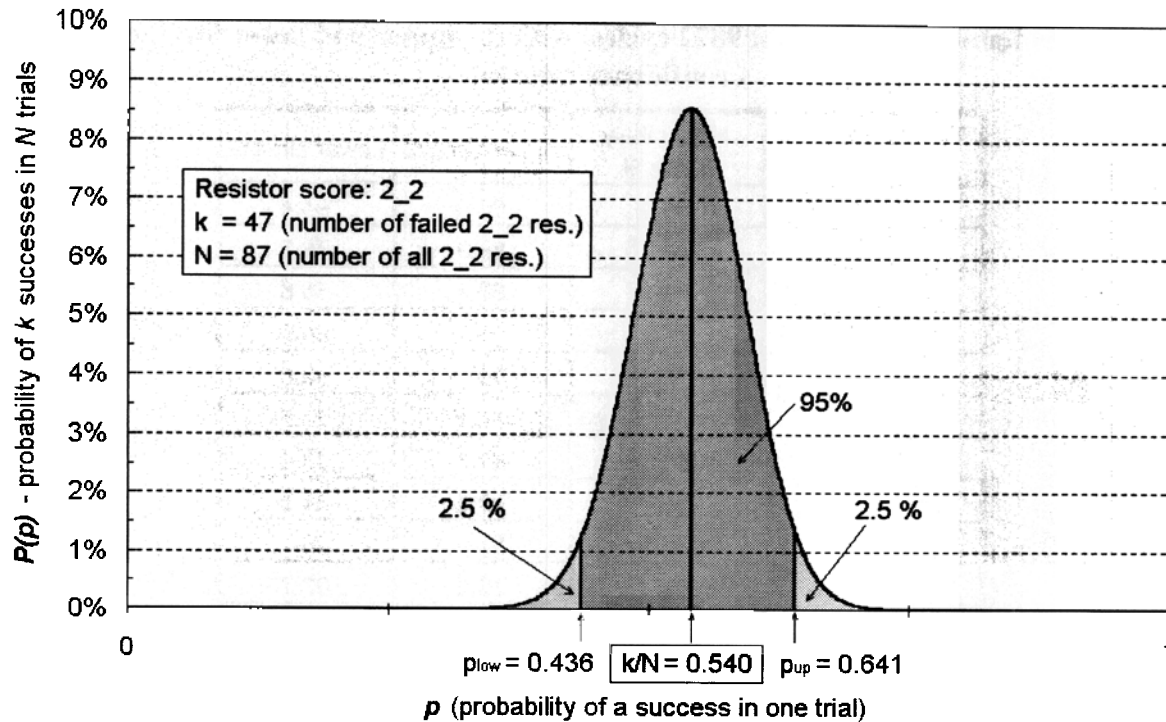


Figure 9. Binomial probability functions with lower and upper probability limits for resistor score 2_2

Limits p_{low} and p_{up} (Bernoulli probability parameters) are the results of this calculation providing k and N are constants and p is a variable.

$$(N + 1) \int_0^{p_{low}} P_{k,N}(p) dp = 0.025$$

$$(N + 1) \int_0^{p_{up}} P_{k,N}(p) dp = 0.975$$

Where:

- N - number of resistors with the same score
- k - number of failed resistors (integer and $0 \leq k \leq N$)
- p - failure rate variable
- p_{low} - lower limit of the failure rate range
- p_{up} - upper limit of the failure rate range
- $P_{k,N}$ - probability of k -failed resistors among N possible cases

Equations 6a, 6b were derived for comparing different size data sets, but with a constant 95 % confidence level. For example in the case of the 3_1 resistors the failure rate is in the range of <56.6; 88.3>% and there are 62 resistors with this score. If a resistor score set contains more resistors such as resistor score of 1_1 (there were 366 with this score, see Table 3) the failure rate can be predicted more precisely <94.4; 98.5>% i.e. the resulting range is smaller. So a constant confidence interval can be defined accommodating different data set sizes, and hence better accuracy with larger data sets. This approach has the advantage of using true confidence ranges which is better than the alternative of using just the “most likely value”. In an industrial context this will prove very useful in comparing ppm-defect rates from different sources or processes, or even different inspection frequencies.

Table 4. Probability of failure at 9872 cycles, with the upper and lower limit with 95 % confidence interval

Type of Resistor Score	Most Likely Value %	Upper Limit %	Lower Limit %
1_1	96.9	98.5	94.4
2_1	83.2	88.3	76.5
3_1	69.6	80.1	56.6
4_1	71.4	91.5	34.9
5_1	72.7	90.1	42.8
2_2	54.0	64.1	43.6
3_2	52.3	61.5	43.0
4_2	54.5	73.2	34.5
5_2	35.0	57.0	18.1
3_3	40.3	48.3	32.7
4_3	29.0	37.6	21.8
5_3	22.1	33.3	13.9
4_4	16.7	28.8	9.1
5_4	17.6	26.2	11.5
5_5	25.4	26.1	24.9

Solutions of Equations 6 are shown in Table 4 for all resistor scores after 9872 cycles. Figure 10 shows the calculated failure rate (the most likely value = k/N) for selected resistor scores for a range of cycles up to 9872.

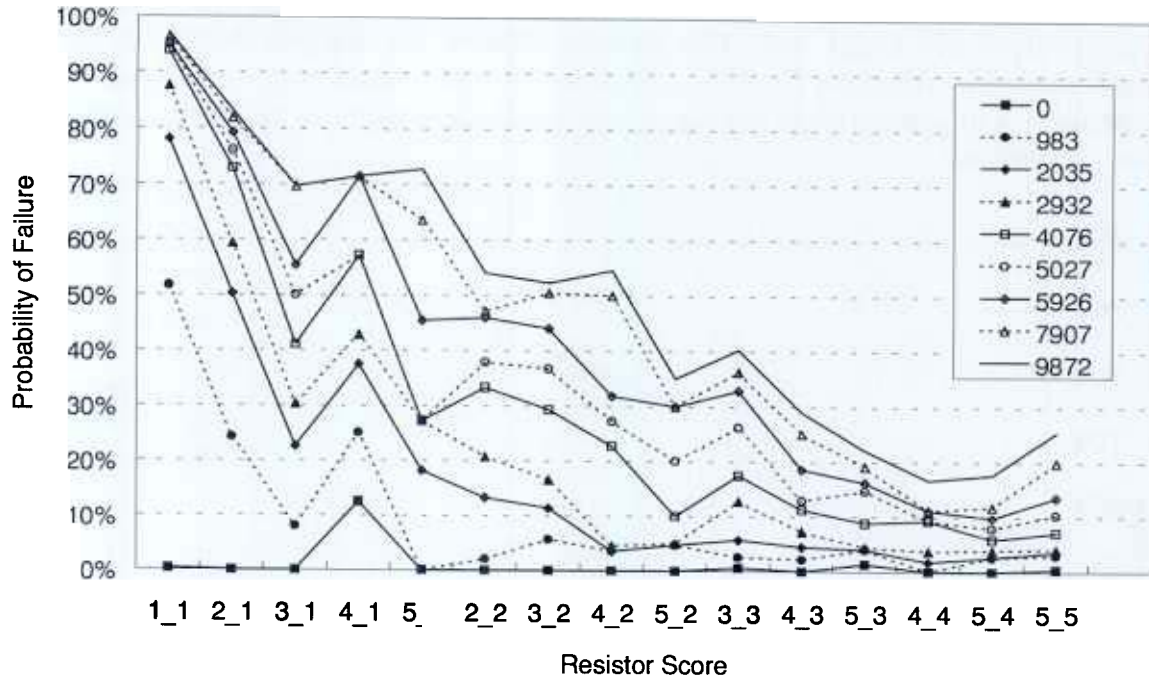


Figure 10. Probability of failure for various thermal cycles for resistor scores from all Age groups

6.3 FITTING OF THE WEIBULL DISTRIBUTION

This part of the analysis was carried out to allow **relative** comparisons of resistor reliability, belonging to the same Age and the same resistor score group. To maintain the statistical integrity of the results two conditions were set:

- 1) The minimum number of resistors in one group (the same resistor score and Age) is set at 25
- 2) 5 % of a group must have failed, for that group to be counted as a failure.

Only 20 resistor score combinations met both conditions. One combination Age 4, 4_4, which contained 38 resistors, had still not reached the second condition after 9872 cycles. For this group an estimate was made for a 1% failure rate. Fitting for the 20 groups has been achieved using a modified Weibull distribution Equation 7.

$$F(n) = \left[1 - 2^{-\left(\frac{n}{N_f}\right)^\beta} \right] \times (1 - B_v) + B_v \quad (7)$$

Where:

$F(n)$ - failure rate at n number of cycles

n - number of cycles

B_v - bias value is an offset to accommodate “infant mortalities” that are not included in the pure formula of Weibull distribution (0 - 1.7 %)

β - Weibull shape parameter

N_f - Median life to failure when $F(N_f)=0.5$

The value B_v is set by inspection of the data. From β and N_f the number of cycles can be calculated, to reach 1 % failure rate ($N_{1\%}$) which corresponds with the first failed resistor on an average electronic board with 100 resistors R0805. An analysis based on the Binomial distribution was carried out for 95 % confidence level of a result range for $N_{1\%}$, see Table 5. The combinations of resistor score and Age group which are missing in the Table 5 did not meet the above conditions.

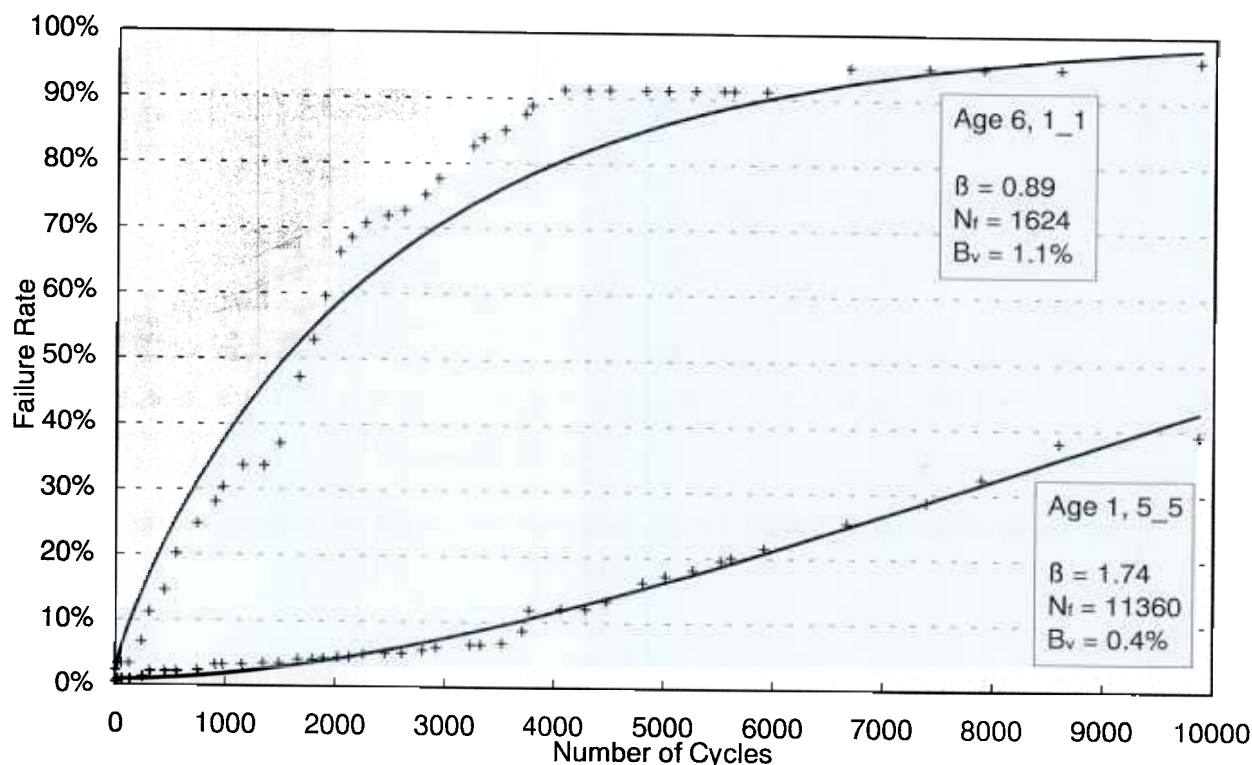


Figure 11. Observed failure rate and fitted Weibull distribution for Age 6, 1_1 & Age 1, 5_5

7. CROSS-SECTIONED SAMPLES

Throughout the thermal cycling experiment samples were removed for cross-sectioning and polishing. The micrographs in Figure 12 show crack development in the solder fillets. The position of the section through the fillet is not known precisely, hence it maybe at an edge or in the centre of the fillet. Each micrograph contains information when the sample was removed from the thermocycling oven and the joint visual inspection score (bold characters). The stand-off height of a resistor is about $30\ \mu\text{m}$ and does not vary with artificial ageing time. It is clear that extensive fatigue cracks are present in some of the joints. Where cracks are present the surrounding microstructure has significantly coarsened. But for Age 6 (Figure12., b), and where there is no evidence of cracking, the microstructure is much finer.

Table 5 Result from Weibull function fitting and Binomial distribution error analysing and $N_{1\%}$ with 95% confidence band

Age	Resistor Score	β	N_f	$N_{1\%}$ Most likely value	$N_{1\%}$ Upper Limit	$N_{1\%}$ Lower Limit
6	1_1	0.89	1624	8	28	3
6	2_1	0.87	1615	13	102	3
6	2_2	1.10	4833	101	1187	68
6	3_2	1.17	6801	183	2461	169
5	1_1	1.24	1661	55	239	19
5	2_1	1.13	3067	71	464	29
5	3_1	1.22	5573	171	1572	119
5	2_2	1.22	9914	307	2128	162
5	3_2	1.28	8677	318	1528	132
5	3_3	1.46	8789	484	1716	200
5	4_3	0.86	8216	58	1956	50
4	3_3	1.59	23918	1675	7370	1027
4	4_3	2.21	14593	2153	4705	1139
4	5_3	1.15	48440	1214	11383	741
4	4_4	4.54	15191	5974	10760	5388
4	5_4	2.03	25077	3130	9627	2059
4	5_5	2.70	15380	3202	5643	1764
3	5_4	1.20	22176	645	5753	418
3	5_5	1.36	23693	1049	2132	549
2	5_5	2.49	16290	2969	4277	2187
1	5_5	1.74	11360	1012	1746	654

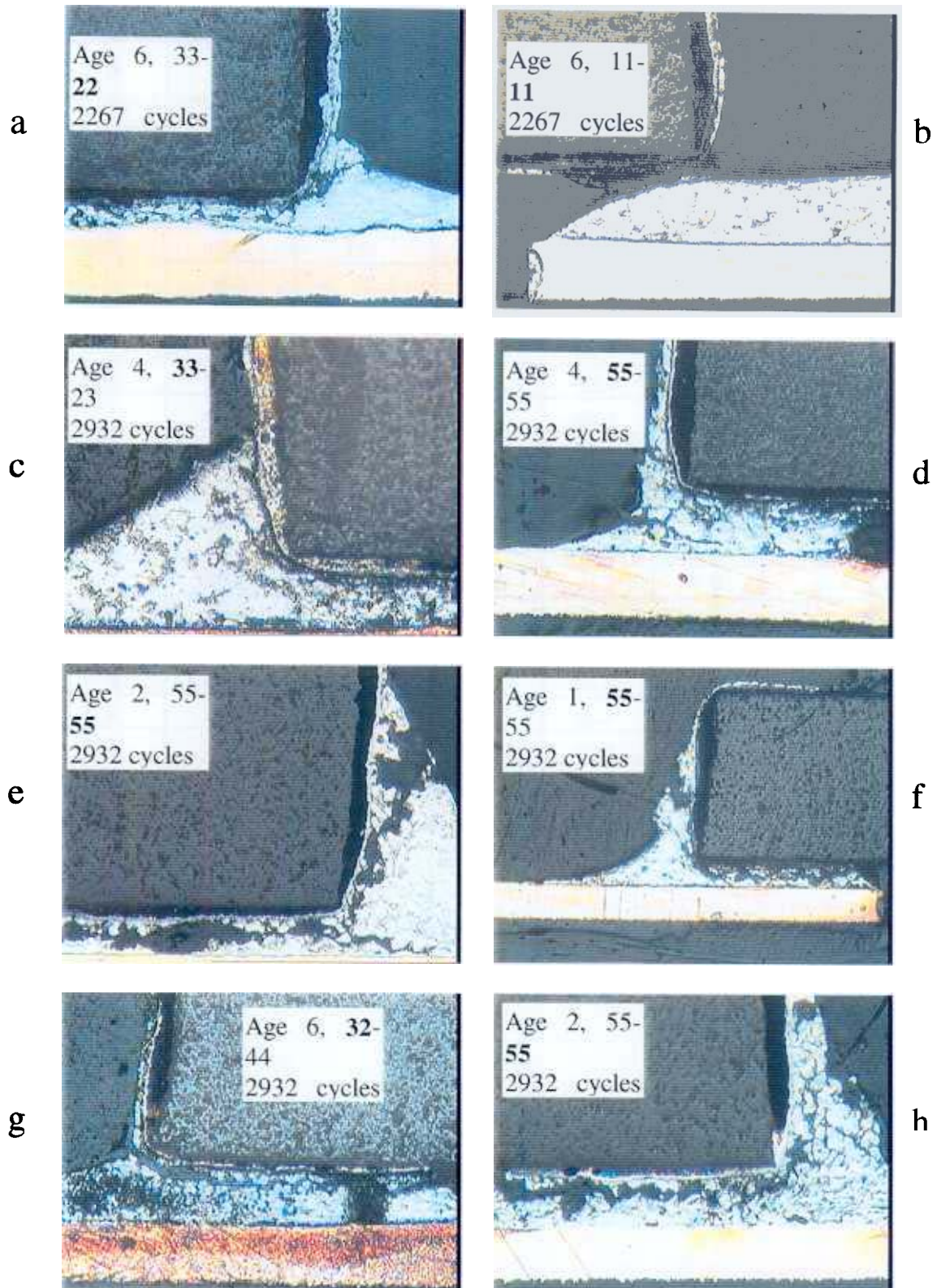


Figure 12. Cross-sectioned samples of cycled resistors from different Age groups and evaluated by a joint score (L Height L Angle - R Height R Angle)

8. RESULTS

The results can be analysed using three approaches:

8.1 CUMULATIVE FAILURES FOR DIFFERENT AGE GROUPS

The time development of cumulative failures (expressed as a function of the thermal cycles) for the six age groups is shown in Figure 13. It is clear that with Ages 5 & 6 failures occur far earlier than the other Ages. What is also significant is that after 4000 cycles the failure rate for Age 1 exceeds that of Ages 2, 3 and 4. This is a somewhat surprising result, especially since the solderability of Age 1 and Age 2 are very similar, see Figure 5. Furthermore, the visual inspection scores for Ages 1 and 2 are very similar, see Figure 8. The assembly processes were also identical. The only difference was the ageing treatment at 155 °C. It is possible that the ageing treatment refines out defects and impurities from the component coating. These anomalies are envisaged as being on the atomic scale. In the subsequent soldering process of these aged coatings these defects are flushed away and are no longer incorporated in the solder joint fillet. For Age 1 components (the as-received set) these defects are still intrinsic to the coating and are retained in the solder joint and hence are latent defects facilitating crack initiation and propagation.

The relative failure rates for Ages 1, 2, 3 and 4 are explored further. The failure rates of the joints with a 5_5 resistor score from each Age are analysed and these are plotted in Figure 14. Long artificial ageing causes a wider distribution of solder fillet shapes as shown in Figure 8. This wide variation means that it is not possible to make accurate reliability prediction based solely on the data for resistors with high scores (e.g. 5_5, 5_4 etc.). If we look at the resistor score 5_5 from different Age groups, in Figure 14, we can see again anomalous effect of accelerated ageing.

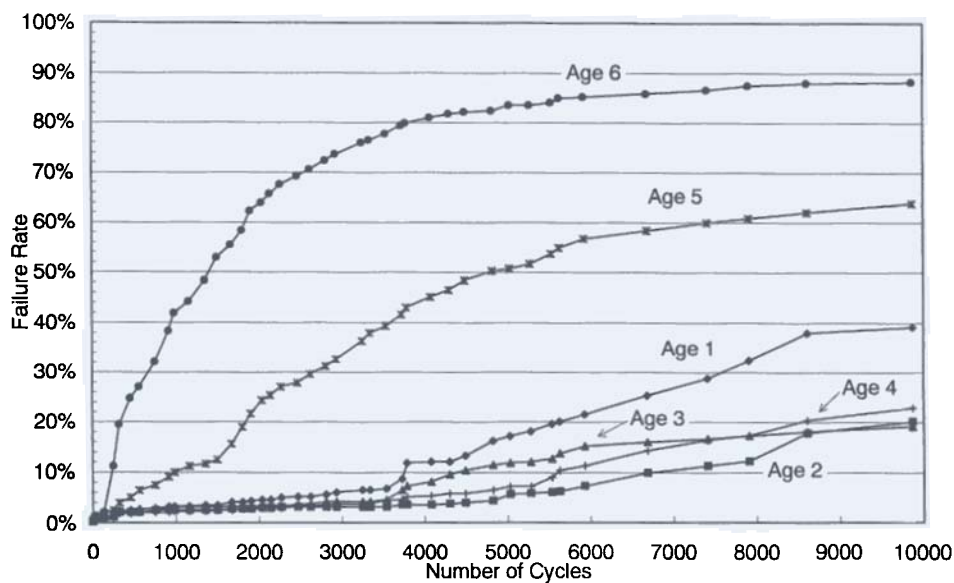


Figure 13. Development of cumulative failures rate for different age group

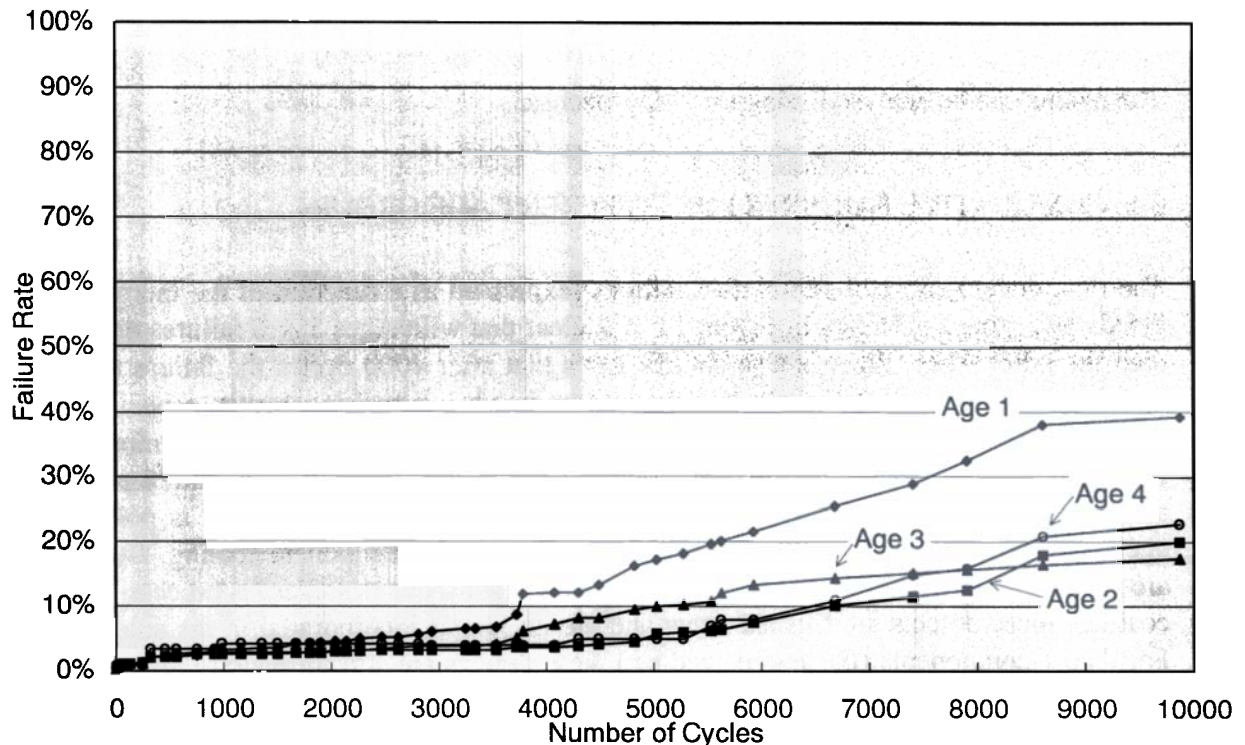


Figure 14. Differences between resistors with a score 5_5 from different ages

8.2 CUMULATIVE FAILURES FOR DIFFERENT RESISTOR SCORES

We now consider how failures develop based on the resistor score, rather than ageing treatment. We will deal with this in two parts: first, where both joints on the resistor are the same i.e. symmetric joints, and second where they are asymmetric. Failure rates for symmetric resistor scores are shown in Figure 15.

It is apparent that in spite of these joints all having the same visual appearance there is a marked difference in behaviour, with two populations. Age 1 failure rates are twice that of the other group of Ages 2, 3 and 4 above 4000 cycles. This again reinforces the conclusion from the more general set of results, that there is something different about the Age 1 set. As identified above the only difference is the lack of an ageing treatment at 155 °C. In Figure 13 the failure rates as function of the ageing treatment are shown. However from Figure 8, it is clear that there is a range of resistor scores within any Age set.

There is a general trend for the reliability to improve for symmetrical resistor scores as the resistor score increases. This simple trend is broken for the cases of 4_4 and 5_5, where accelerated ageing increased the 5_5 failure rate as discussed previously.

Pure asymmetrical attachment is less likely to occur in an optimised industry process. However, if one termination of resistor scores more highly than the other, the life-time of the resistor appears to be better than a symmetrical joint score for the lower score. This can be seen more clearly if we look at the last cycle, 9872, in Figure 10. For example the difference in reliability of the 2_2 and 5_2 resistors is approximately 20 %.

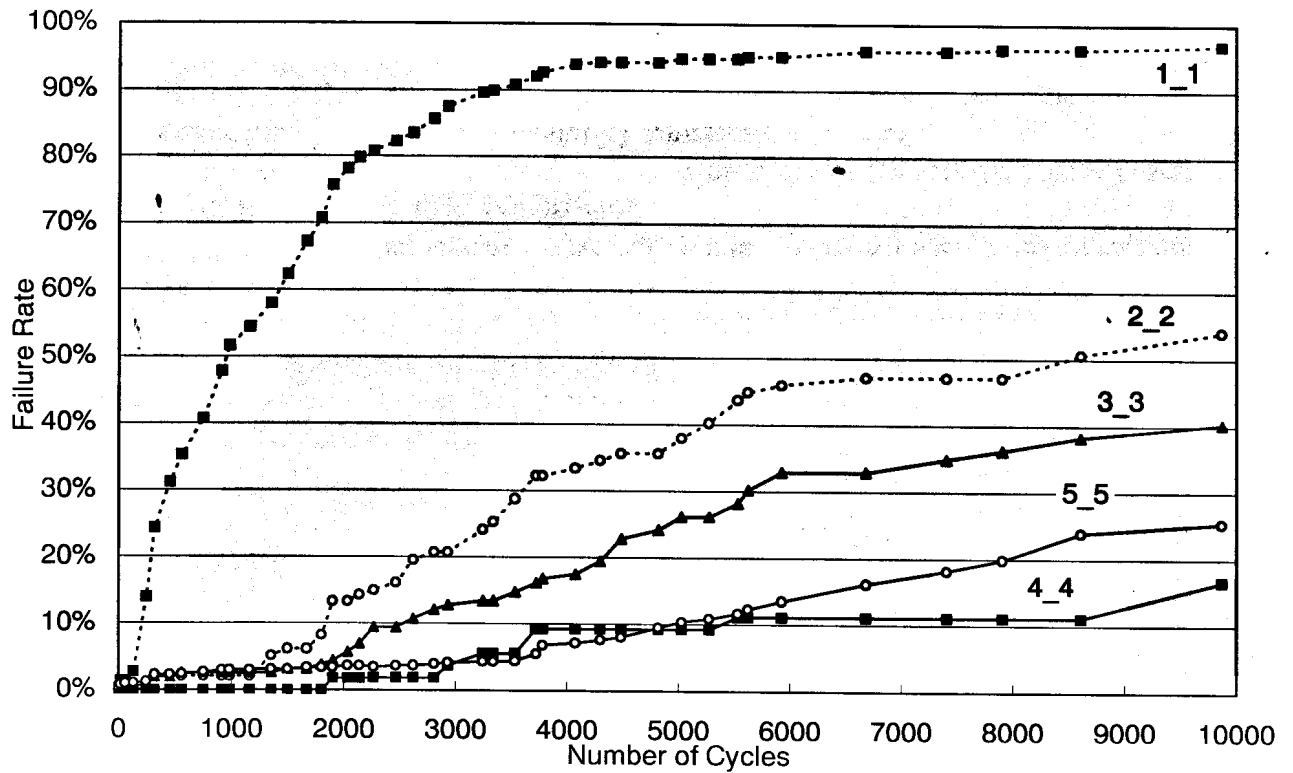


Figure 15. Development of cumulative failure rate for different symmetrical resistor scores

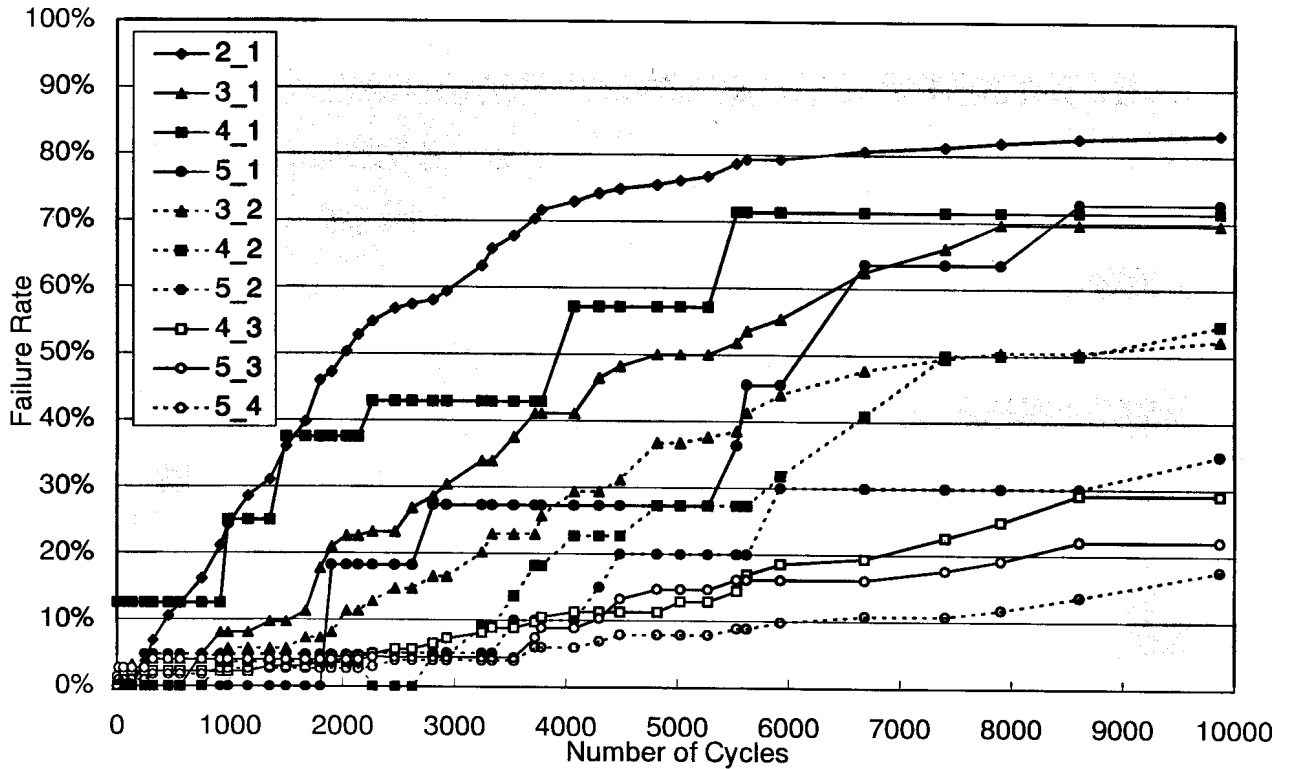


Figure 16. Development of cumulative failure rate for different asymmetrical resistor scores

8.3 PREDICTING FAILURE RATES

We now take the predictive analysis developed in Section 6 and use the failure rate data to predict the number of cycles to 1% failure (1 failure in 100 resistors on a PCB). These failure rates are calculated for each resistor score and each Age in this study, and are shown in Figure 17 and tabulated in Table 5. Figure 17 clearly shows that the number of cycles to failure significantly decreases for Ages 5 and 6. The Age 4 results have a surprisingly low failure rate. But the resistor scores for Age 4 are widely distributed over the lower scores, as shown in Figure 8, although the frequency of these scores is low. Hence only the more common scores, which are coincidentally the higher scores, appear in Figure 17. Similar comments apply to the Age 3 results. Figure 17 again illustrates the dip in reliability of the 5_5 scores of Age 1.

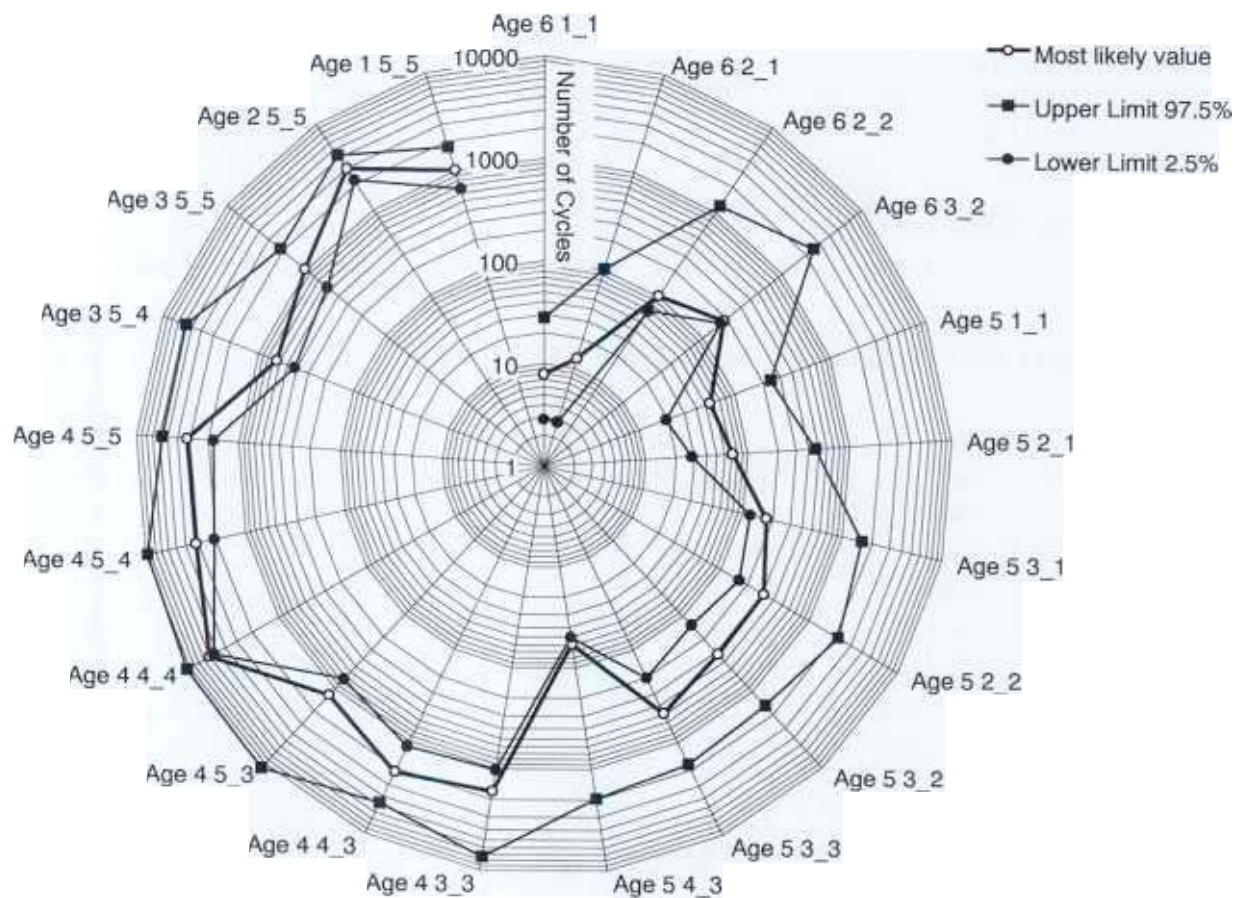


Figure 17. Hodograph of number of cycles to 1 % failure rate with upper and lower deviation limits

9. CONCLUSIONS

- Process yield as determined by visual inspection, has been shown to be related to the solderability of components, and that to obtain a zero defect process, **it is necessary to have components with solderabilities that are close to the optimum values.**

Hence solderability testing is an efficient way of estimating yield prior to production

providing experienced inspector is used. The qualitative nature of visual inspection is to a large extent offset here by the large number of joints inspected.

Although the solderability test conditions of temperature and flux are different to those used in the manufacture of the assemblies, the results demonstrate a good correlation between solderability measurements and visual inspection of the joints.

- Measuring joint resistance is a poor method finding visually unacceptable joints.
- Fatigue properties of solder joints in thermal cycling have been shown to be closely related to the fillet shape for resistors. The study has concentrated on chip resistors which have proved far more susceptible to fatigue cracking than the leaded components in the study, SOICs and QFPs. As such the resistors can be considered to constitute the weakest part of the assembly in terms of reliability. Poor fillet rise on chip resistors reduces the amount of material the crack has to penetrate to cause an open circuit. With improved wetting and greater fillet rise there is the possibility that the remaining fillet, during cracking, acting like a lead and conferring some compliance to the remaining solder joint.

The solder joint characteristics demonstrate an intimate relationship. Therefore, the wetting balance measurements can be used to predict reliability of soldered chip resistors, within any given set of process parameters.

A statistical approach was developed, based on the Binomial distribution (Eq. 6a, 6b), which allowed the comparison of different size data sets with constant 95 % confidence level. This is useful in comparing ppm-defect rates from different processes.

Recommendation for electronics manufacturers, using 0805 chip resistors:

- If the wetting force of 0805 resistors on the wetting balance is good (0.08 mN at 2 s or higher) and the reflow process is properly tuned, we would not expect poor joints. If the wetting force is lower than this value, the variations in solder fillet geometry will result in variations in reliability.

The visual inspection results have shown that it does not matter whether height or wetting angle is evaluated. There is a strong correlation between them, as shown in Figure 6.

Artificial ageing of components (~ 50 hours) can improve the wetting forces and hence solder fillet formation, which will improve reliability of the assembly.

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