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**Statistical Analysis of the
Effect of PCB Finish and
Processing of Solder Joint
on Integrity**

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Statistical Analysis of the Effect of PCB Finish and Processing of Solder Joint on Integrity

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ABSTRACT

The reliability of electronics assemblies is crucially dependent on the quality of the solder joint. Credible data on the latter can be assessed using destructive shear testing and accelerated ageing techniques, and relating the joint shear strength to the damage induced by the thermal cycling. Previous work had successfully generated such mathematical relationships for the impact on joint reliability of joint shape and volume. That work has been extended in an attempt to generate similar relationships for other factors (PCB pad finish, substrate material, thermal processing variables, and solder alloy) possibly impacting on joint reliability.

The shear strength data were encouraging and indicated that:

- they did not exhibit any dependence on the pad finishes studied, a finding of comfort to board assemblers
- they did not exhibit any dependence on the thermal process treatments studied
- the joint strength was dependent on the solder used, and the findings confirm those in the literature
- the joint strength was dependent on the type of substrate, again confirming literature data

Statistical tests have been applied to all four sets of materials data in order to ascertain whether or not subsequent regression analysis could be undertaken. These statistical tests indicated that only in one case, the “solder factor” data, did differences exist between data sets. Moreover, the statistical tests indicated that none of the materials data sets were sufficient or adequate enough to allow meaningful multiple regression analysis or the construction of a suitable model.

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Approved on behalf of the Managing Director, NPL,
by Dr M G Cain, Knowledge Leader, Materials Processing Team
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1 INTRODUCTION

Any electronics assembly subjected to temperature changes (e.g. from equipment switched on/off, power and/or ambient changes) expands/contracts due to differences in the coefficients of thermal expansion (CTE) of the materials used. This causes localised stresses and strains which are concentrated between components and substrate. Solder, as the interconnection material, has to withstand these stresses and strains, and provide both mechanical attachment and electrical functionality. But it must also be compliant to avoid build up of extreme stresses in the components or substrate. However, after thousands of cycles the solder itself may fail due to the propagation of fatigue cracks. Hence, there is a requirement to measure the thermo-mechanical performance of solder joints and use the data to predict assembly reliability. An approach commonly used by the industry to generate these data is that of shear testing of joint strength after accelerated thermal cycling.

In previous work [1,2] the impact on joint reliability of joint shape and volume was explored using a multiple regression analysis of shear strength data after different applied thermal cycling regimes. In that work equations were generated relating shear strength to joint shape and volume. In the present study that approach has been extended to investigate the impact on joint reliability of four further factors (PCB pad finish, substrate material, thermal processing variables, and solder alloy). This work was described in detail in [3]. The experimental arrangement is described below

2 EXPERIMENTAL

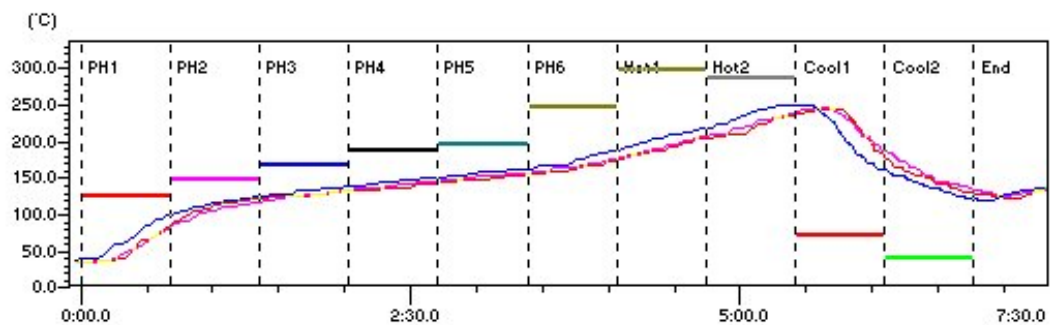
The test vehicle design contained two sizes of chip resistors, 1206 and 0603. Assemblies were fabricated from two substrate materials: a multilayer FR4 epoxy glass laminate, 1.6 mm thick with copper tracks and 35 μm thick pads (copper plating 1 oz/sq.ft); and an epoxy woven aramid with copper clad invar, 1.4 mm thick with 17 μm thick copper tracks and pads (copper plating $\frac{1}{2}$ oz/sq.ft). The pad finish was either immersion gold over electroless nickel (ENIG), or immersion silver.

Substrates were stencil printed with solder paste using a laser cut 150 μm thick stainless steel stencil. Three solder pastes were used; **95.5Sn3.8Ag0.7Cu (SAC)**, **96.5Sn3.5Ag (SnAg)** and **62Sn36Pb2Ag (SnPbAg)** with a no-clean type flux. Components were placed onto the substrates using an automatic placement system, ensuring a consistent solder joint volume.

A total of 12 sets of PCBs were manufactured - see Table 1. A typical build for set B would be 10 assemblies soldered using SnAgCu (SAC) solder alloy. Reflow of the lead-free solder paste was achieved in a convection reflow oven, and the measured peaks of reflow temperature profiles were between 245 and 260°C. The time above 220°C was between 60 and 90 seconds depending on the location on the PCB. The reflow profile for the lead-free solders is shown in Figure 1, and after reflow the B assemblies were thermally aged at 125°C for 1000 hours. The thermal ageing treatment was selected because it accelerates microstructural growth within the solder. Set J contained 10 identical assemblies soldered with SnPbAg alloy on a PCB having an immersion silver surface finish. These boards were subjected to the reflow process followed by one run through a wave soldering process. The units from set L were the only assemblies manufactured with a substrate, the CTE of which matched that of ceramic components, i.e. the epoxy woven aramid with copper clad invar.

Table 1. Process conditions applied to test samples

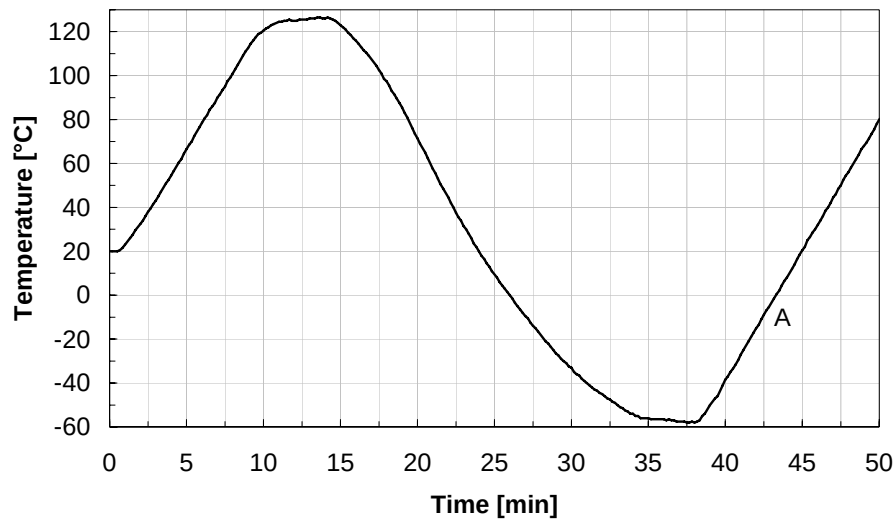
Set	Alloy	Process	Conditioning	PCB
A	SAC	Reflow 1x	None	ENIG
B	SAC	Reflow 1x	1000 h @ 125 °C	ENIG
C	SAC	Reflow 1x	Conformal Coat	ENIG
D	SAC	Reflow 2x	None	ENIG
E	SAC	Reflow 1x + Wave	None	ENIG
F	SnAg	Reflow 1x	None	ENIG
G	SnAg	Reflow 1x	1000 h @ 125°C	ENIG
H	SnAg	Reflow 2x	None	ENIG
I	SnAg	Reflow 1x + Wave	None	ENIG
J	SnPbAg	Reflow 1x + Wave	None	Ag
K	SAC	Reflow 1x + Wave	None	Ag
L	SAC	Reflow 1x	None	Aramid CTE matched

**Figure 1. Lead-free reflow profile**

All the manufactured assemblies were subsequently subjected to thermocycling. The choice of the cycling regime used to evaluate the reliability of lead-free solder joints is crucial since the relative performance of different solder alloys can change with thermal cycling parameters such as dwell temperatures and times, and the ramp rates between the dwell temperatures [4]. In recent years the military and automotive sectors have preferred to use the same cycling regime (-55°C to +125°C), and this now appears suitable for many high reliability applications. The details of the thermal cycle regime used in this evaluation study, are given in Table 2 and presented graphically in Figure 2.

Table 2. Details of temperature cycling regime with $\pm 4^\circ\text{C}$ temperature tolerance

Low Temperature dwell	High Temperature Dwell	Ramp rate	Dwell time	Period
$^\circ\text{C}$	$^\circ\text{C}$	$^\circ\text{C}/\text{min}$	[min]	[min]
-55	125	10	5	45-48

**Figure 2.** Temperature profile of the thermal cycle

A typical test vehicle is illustrated in Figure 3. Although the PCB layout was designed to enable testing of the continuity of other components during the thermal cycling experiment [5], this report considers only the measurements of shear forces on 1206-type and 0603-type resistor components.

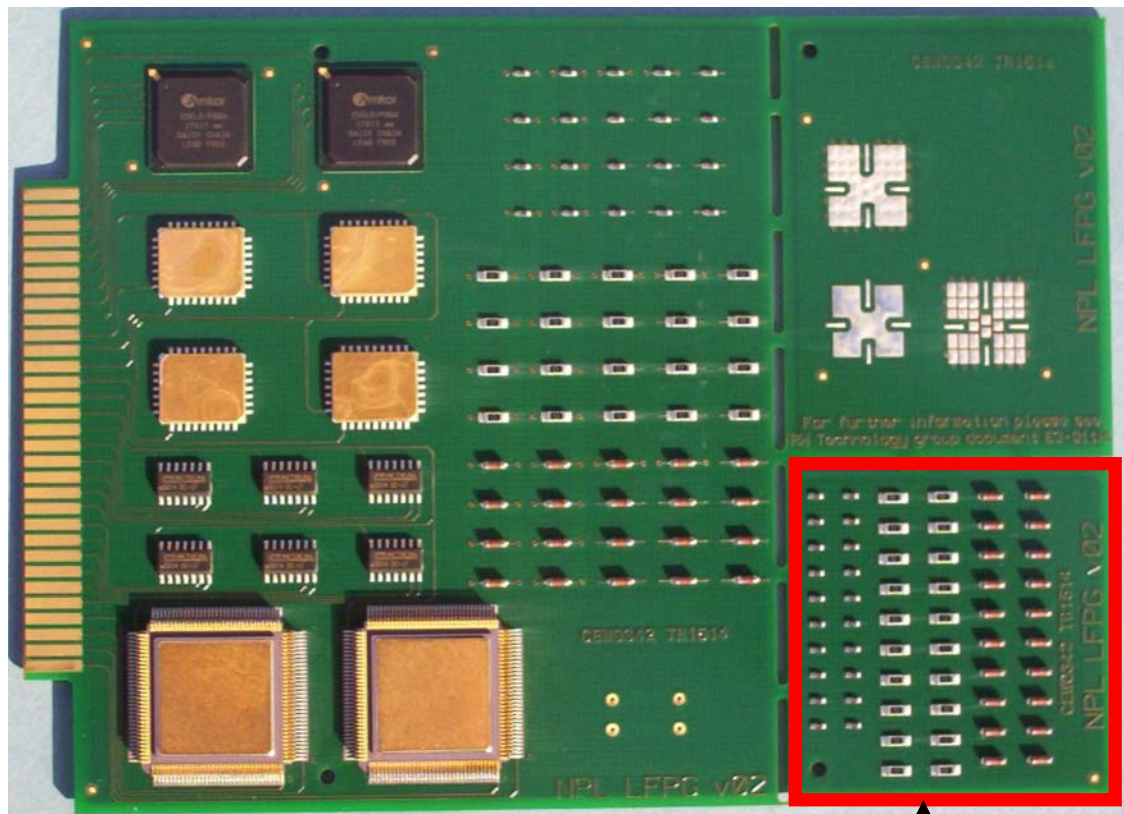


Figure 3 Top side of test vehicle

Shear testing area

3 SHEAR TESTING

Shear testing is an established destructive method for evaluating not only the degree of crack propagation and damage to the solder joint, but also the general strength of the joint. The method is based on the assumption that the presence of cracks in the solder joint, their size and the extent of propagation will influence the strength of a joint. Hence a correlation can be established between the strength of the solder joint and joint failures. Figure 4 shows a typical shear test set up. These shear tests were undertaken at room temperature on a Dage Series-4000 modular multi-function bond-tester.

The data obtained in the test were analysed in terms of the ultimate shear force required to rupture the solder joint, and the results were plotted as functions of the number of thermal cycles to which assemblies had been subjected.

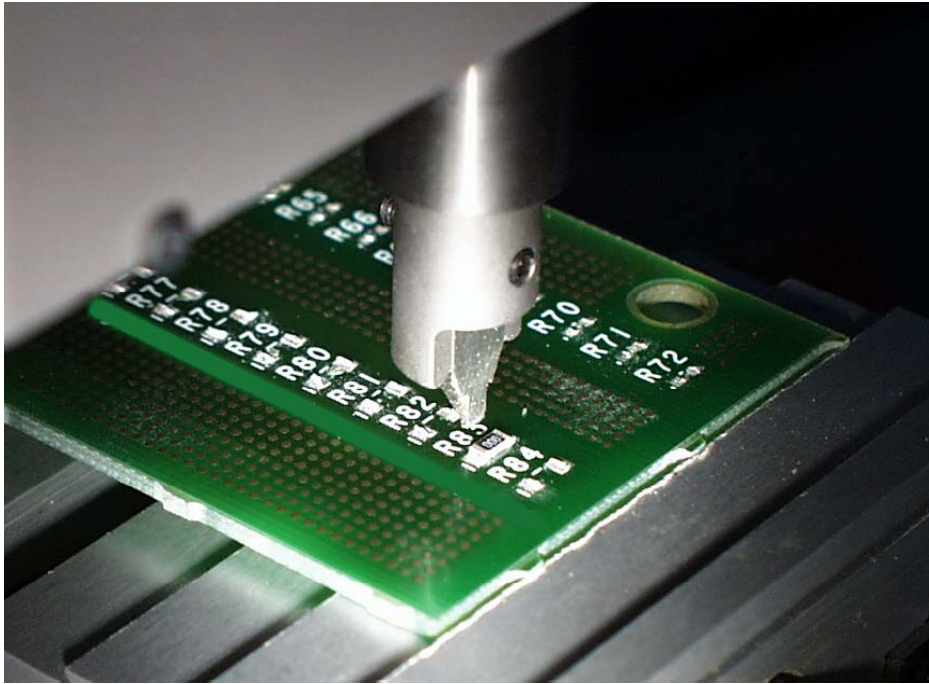


Figure 4. Shear test jig and push-off tool before a shear test

4 STATISTICAL ANALYSIS

The analysis was based on statistical tests procedures, and all tests assumed a confidence interval of 95%. To decide which tests to apply the variances between data sets have to be compared. To perform the hypothesis tests for equality, or homogeneity, of variance between two populations, an F-test can be utilised. Many statistical procedures, including the two-sample t-test, assume that the two samples are from populations with equal variance. The variance F-test procedure tests the validity of this assumption. If the F-test indicates that the samples have similar variances, a **pooled (similar variances) two-sample t-test** is used. If there is a significant difference in variances, a **separated (different variances) two-sample t-test** is used. The criterion as to whether the sample sets are significantly different, is decided via the p-value. **If the p-value of a test is higher than 0.05 the sets are statistically similar i.e. there is no significant difference between tested sets.** Analysis of the variances for the following sample tests were conducted:

- Set E and K – difference between ENIG and immersion silver pad finish
- Set A and L – difference between FR4 and aramid clad invar CTE matched substrate
- Set J and K – difference between SnPbAg and SAC solder alloy
- Set E and I – difference between SAC and SnAg solder alloy

The sample size for all sets was 20, and samples were taken after 0, 500, 1000, 1500 and 2000 thermal cycles.

4.1 PCB FINISH IMPACT ON RELIABILITY (EK)

The measured force values from the shear testing are plotted in box and whisker plots. In Figure 5 measurements taken from 1206-type resistor samples in set E and K are presented. The

only materials difference between these two sets is the pad finish used on the substrate. In the set E solder joints were formed on the ENIG finished PCBs, and in set K they were formed on the immersion silver finished boards.

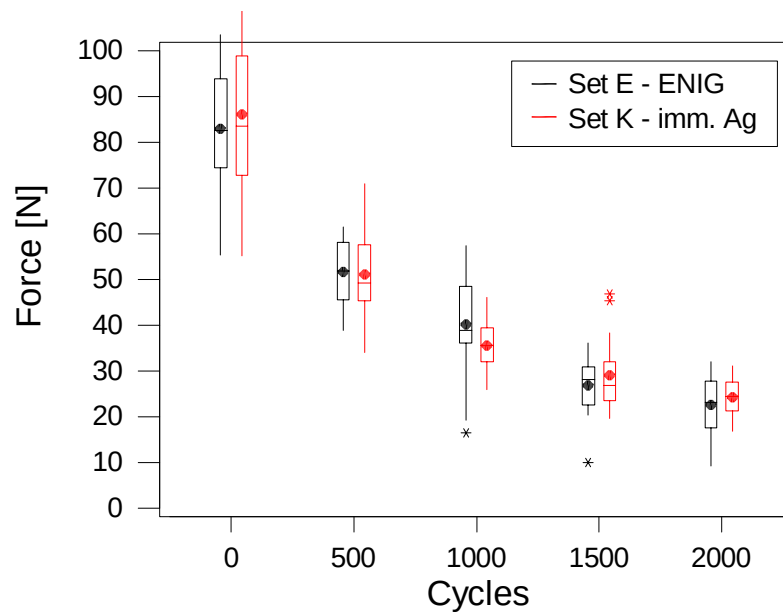


Figure 5. Shear strength of 1206-type resistors mounted on different PCB finishes

A comparison of solder joint degradation for 1206-type resistors during thermal cycling is shown in Table 3. The first two columns describe what set conditions were tested i.e. set E and set K. These sets were tested in couples at the same number of cycles i.e. 0 cycles for E0 and K0, 500 cycles for E500 and K500, etc. The p-value of the F-test for variance comparison is shown in the third column, and the summary result in column four. The “Equal” result of variance test means that there was no statistical difference between variances of tested sets. The “Different” result means that data for one set were measured with a statistically larger or smaller variance (dispersion). This can indicate that there were more factors influencing the measurement technique. The obtained data are still valid but the following t-test has to take account of that. The fifth column shows the *p-value* of the *t-test* for the same sets, resulting in either a positive or a negative answer, i.e. whether $p < 0.05$, and there was a significant difference.

The results in Table 3 indicate that over all the tested cycles, there was no statistical difference between shear forces at joint failure of 1206-type resistors from both sets, since in all cases $p > 0.05$ in column five. The result of the *t test* was therefore negative, and confirmed that there was no statistical significance between the sample sets i.e. these samples could belong to the same set and are not distinguishable. Hence it is concluded that the test pad finish did not influence the joint strength of the 1206-type resistors. This could be explained by the relatively large volume of solder used for these resistor types, for which a thin coating (2-8 μm) on the pads is not limiting solder strength.

Table 3. Statistical analysis of strength of 1206-type resistor solder joints formed on ENIG (E) and immersion silver (K) pad finish

Set R1206		Variance (<i>F</i>) test		Difference (<i>t</i>) test	
E	K	p-value	Result	p-value	Result
E0	K0	0.078	Equal	0.551	No
E500	K500	0.287	Equal	0.866	No
E1000	K1000	0.006	Different	0.097	No
E1500	K1500	0.355	Equal	0.319	No
E2000	K2000	0.161	Equal	0.306	No

The initial shear forces measured on 0603-type resistors were half those on the 1206-type resistors – see Figure 6 and compare with Figure 5. Moreover these forces did not decrease to the final remnant strength at the same rate with thermal cycling as did the 1206-type components. This is due to the component body length being half that of the 1206-type resistors. The longer component body induces larger shear strains during thermal cycling and this is responsible for the higher level of solder joint cracking.

It is apparent from Figure 6 that the mean value of shear strength for joints on the ENIG surface finish was slightly larger than that for the joints on the immersion silver pad finish. In this case the pad finish had influenced the shear strength and statistically significant differences were observed after 500 and 1000 cycles – see Table 4.

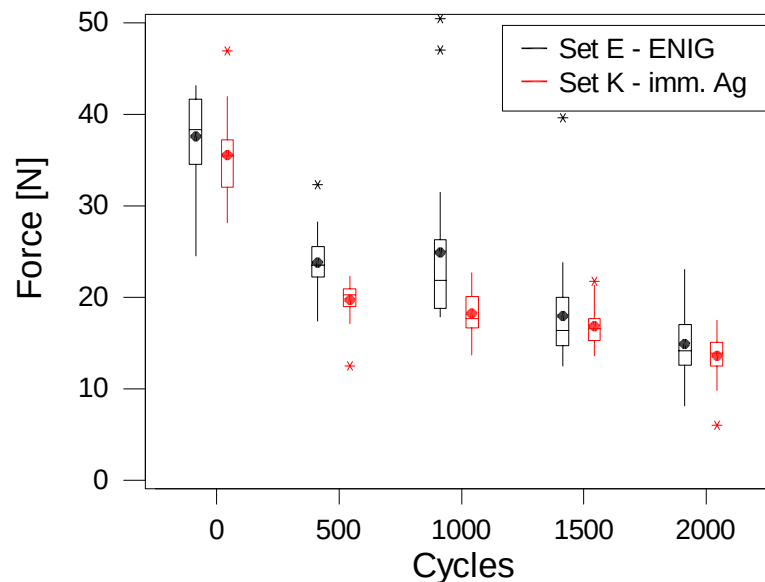
**Figure 6.** Shear strength of 0603-type resistors mounted on different PCB finishes

Table 4. Statistical analysis of the strength of 0603-type resistor solder joints formed on ENIG (E) and immersion silver (K) pad finishes

Set R0603		Variance (<i>F</i>) test		Difference (<i>t</i>) test	
E	K	p-value	Result	p-value	Result
E0	K0	0.685	Equal	0.152	No
E500	K500	0.065	Equal	0.000	Yes
E1000	K1000	0.000	Different	0.004	Yes
E1500	K1500	0.000	Different	0.451	No
E2000	K2000	0.064	Equal	0.218	No

4.2 SUBSTRATE CTE IMPACT ON SHEAR STRENGTH

The impact of substrate coefficient of thermal expansion (CTE) on 1206-type resistor solder joint shear strength is shown in Figure 7. The results of the statistical analysis are presented in Table 5, and these show that the two 1206-type resistor data sets were significantly different, except for the measurement after 500 cycles. The shear strength after 500 cycles is a crossing point for set A, relative to set L. The initial value of shear strength for set L is limited by copper pad adhesion to the epoxy woven aramid, and rarely exceeded 90N. Overall there was no observable degradation in the mean value of solder joint shear strength for set L. By contrast, set A, manufactured using the same solder and pad finish, did develop cracks in the solder joints as thermal cycling progressed.

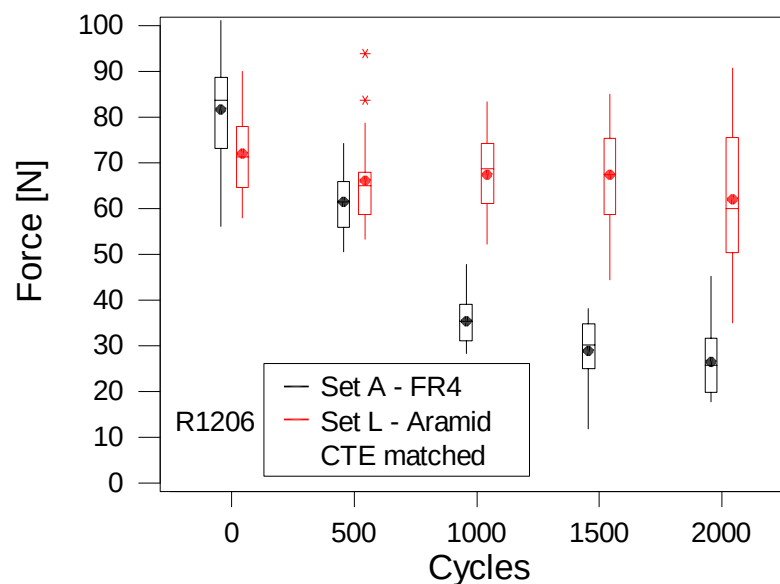
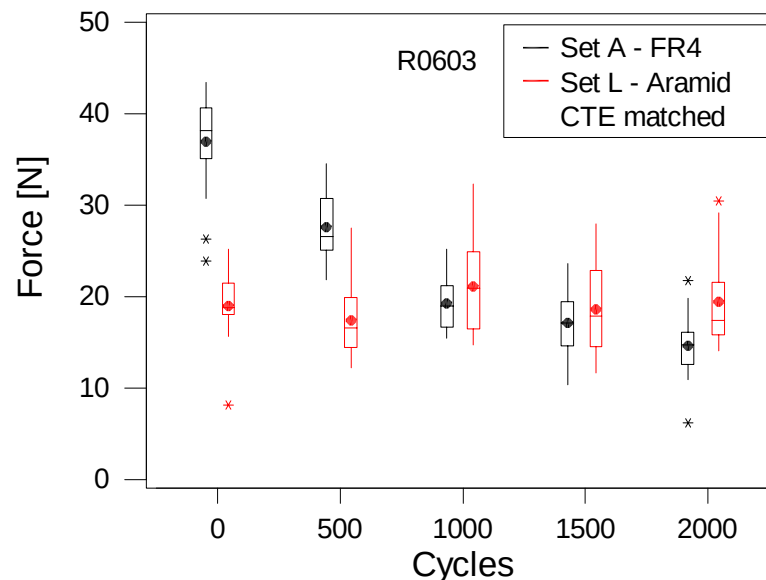
**Figure 7.** Shear strength of 1206-type resistors mounted on different substrates (FR4 and aramid CTE matched)

Table 5. Statistical analysis of the strength of 1206-type resistor solder joints mounted on different substrates (FR4 and aramid CTE matched)

Set R1206		Variance (<i>F</i>) test		Difference (<i>t</i>) test	
A	L	p-value	Result	p-value	Result
A0	L0	0.258	Equal	0.006	Yes
A500	L500	0.015	Different	0.090	No
A1000	L1000	0.029	Different	0.000	Yes
A1500	L1500	0.075	Equal	0.000	Yes
A2000	L2000	0.002	Different	0.000	Yes

The pads for 0603-resistor joints formed on Aramid CTE matched substrate did not exhibit adhesion forces above 30N, and consequently shear testing caused an interface failure between the copper pads and substrate rather than the copper PCB pad and solder joint. As such the measurement of 0603-type resistor shear tests for set L cannot be for compared with those for set A, because the failure modes are different. These data are shown in Figure 8.

**Figure 8.** Shear strength of 0603-type resistors mounted on different substrates (FR4 and aramid CTE matched)

4.3 IMPACT OF SOLDER COMPOSITION ON RELIABILITY (SnPbAg vs. SAC vs. SnAg)

The next sets of tests were used to compare the impact of solder composition on the degradation of shear strength with thermal cycling. Initially, sets K and J (SAC and SnPbAg) were compared, but this was followed by a comparison of sets E and I (SAC and SnAg).

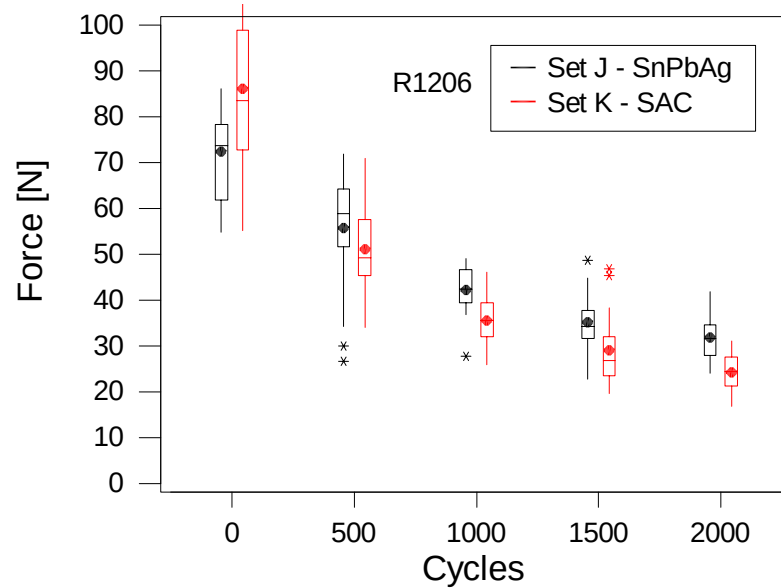


Figure 9. Comparison of SnPbAg and SnAgCu (SAC) solder joint strength of 1206-type resistors

In Figure 9 the results on **1206-type resistors**, set J and K, are compared. These two sets were assembled on the same substrate material (FR4) and with the same pad finish (immersion silver), but with different solder alloys. It is apparent that the mean initial (zero cycles) values of shear strength of SAC alloys (set K) were about 15% higher than those of set J (SnPbAg) alloy. This is in agreement with materials data obtained by tensile measurement [7]. It is interesting to note that all the tests gave equal variance between both sets of data, as shown in Table 6. As the thermal cycling progresses towards 2000 cycles the joints made with SAC solder degraded faster than did those with SnPbAg solder. This is in an agreement with the known fatigue resistance of SAC solder at large strain ranges [6]. The result of the difference test at 500 cycles is negative because there is a crossing point between the data sets.

Table 6. Statistical analysis of strength of 1206-type resistor solder joints (SnPbAg and SnAgCu)

Set R1206		Variance (<i>F</i>) test		Difference (<i>t</i>) test	
J	K	p-value	Result	p-value	Result
J0	K0	0.065	Equal	0.012	Yes
J500	K500	0.223	Equal	0.202	No
J1000	K1000	0.729	Equal	0.000	Yes
J1500	K1500	0.288	Equal	0.005	Yes
J2000	K2000	0.458	Equal	0.000	Yes

Similar data for **0603-type resistors** are shown in Figure 10 and Table 7, and show that the degradation of shear strength of joints made using SnPbAg alloy, was faster than that of the joints made with the SAC alloy, the opposite situation to that observed on joints made with 1206-type resistors. This indicates that the fatigue resistance of SAC alloy joints was better than the SnPbAg alloy joints when the strain range was small, and is in agreement with the known strain range dependencies of these two alloys [6]. Again the result of the difference (*t*) test at 500 cycles is negative because there is a crossing point of both characteristics.

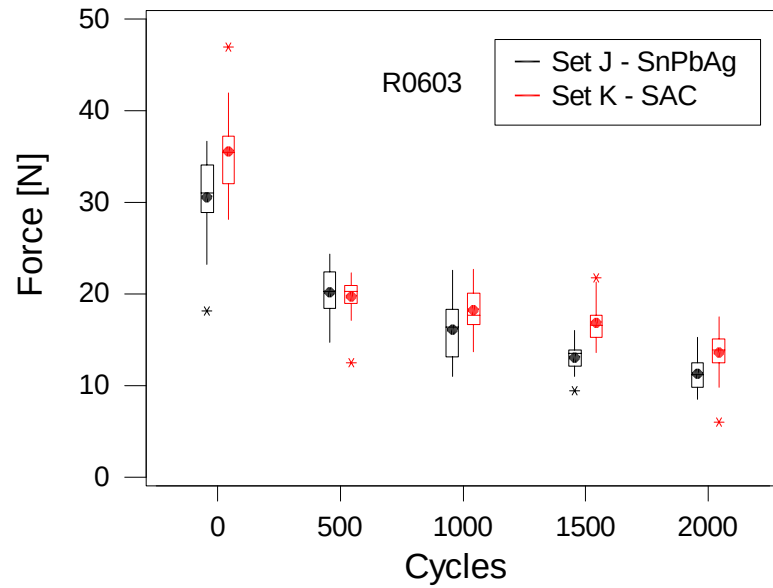


Figure 10. Comparison of SnPbAg and SnAgCu (SAC) alloy solder joint of 0603-type resistors

Table 7. Statistical analysis of strength of 0603-type solder joints (SnPbAg and SnAgCu)

Set R0603		Variance (<i>F</i>)test		Difference (<i>t</i>)test	
J	K	p-value	Result	p-value	Result
J0	K0	0.655	Equal	0.001	Yes
J500	K500	0.294	Equal	0.490	No
J1000	K1000	0.197	Equal	0.023	Yes
J1500	K1500	0.086	Equal	0.000	Yes
J2000	K2000	0.129	Equal	0.003	Yes

Comparing the performance of SAC and SnAg joints in Figure 11 and Table 8, it is apparent that the shear strength of SAC joints was consistently higher than that of SnAg joints (by about 10%). This highlights the positive impact of adding copper in the SAC alloy. The strength degradation rate for both solders is identical, indicating that their resistance to thermal cycling is similar.

Table 8. Statistical analysis of the strength of 1206-type solder joints (SnAgCu and SnAg)

Set R1206		Variance (<i>F</i>) test		Difference (<i>t</i>) test	
E	I	p-value	Result	p-value	Result
E0	I0	0.496	Equal	0.036	Yes
E500	I500	0.023	Different	0.016	Yes
E1000	I1000	0.634	Equal	0.000	Yes
E1500	I1500	0.369	Equal	0.776	No
E2000	I2000	0.188	Equal	0.781	No

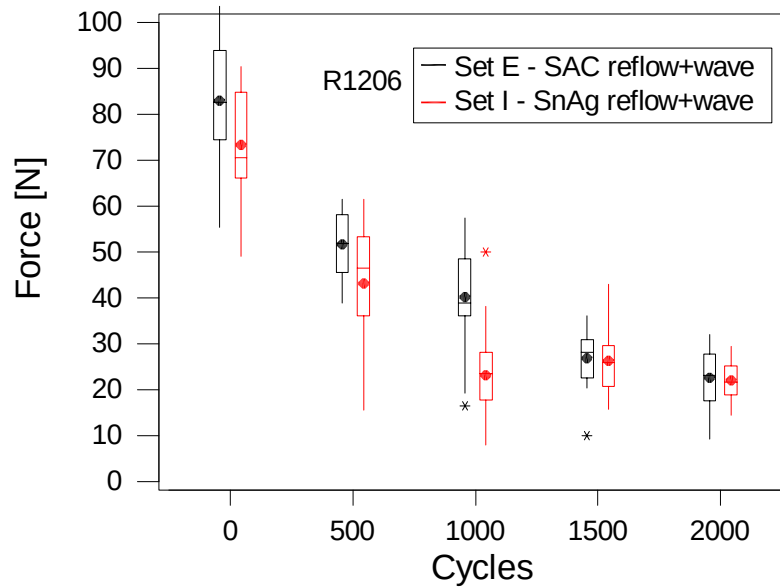


Figure 11. Comparison of SAC and SnAg alloy solder joint strength of 1206-type resistors

For the 0603-type resistors the initial strength of SAC alloy joints was higher than that of SnAg joints – see Figure 12 and Table 9 - and the rate of degradation is very similar for both alloys. Hence there was no crucial difference in terms of fatigue resistance between the two alloys for both component sizes.

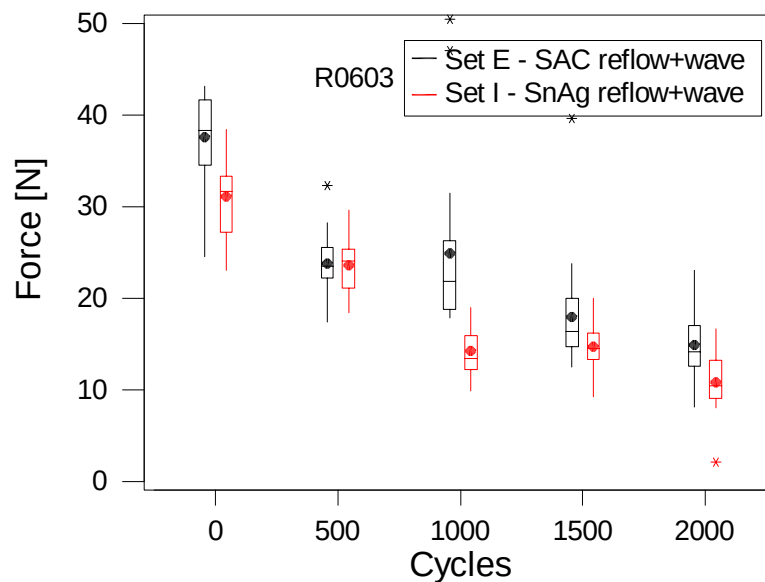


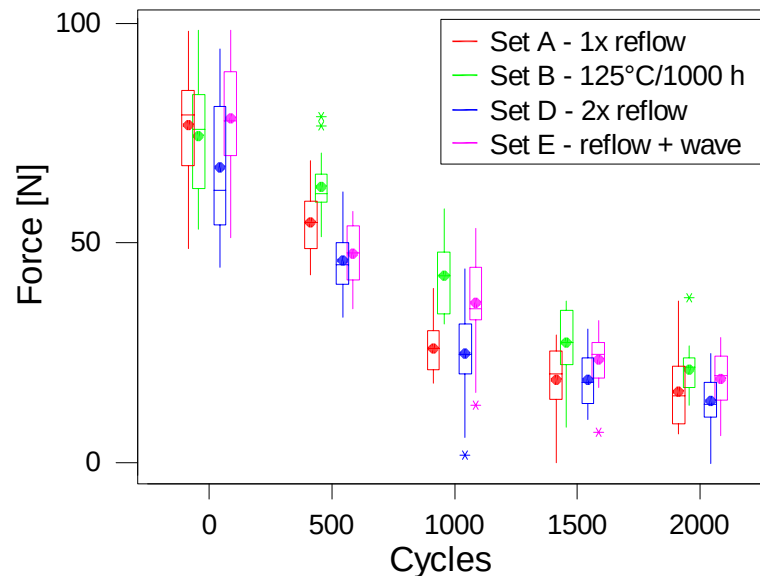
Figure 12. Comparison of SAC and SnAg alloy solder joint strength of 0603-type resistors

Table 9. Statistical analysis of strength of 0603-type resistor solder joints (SnAgCu and SnAg)

Set R0603		Variance (<i>F</i>) test		Difference (<i>t</i>) test	
E	I	p-value	Result	p-value	Result
E0	I0	0.847	Equal	0.000	Yes
E500	I500	0.892	Equal	0.854	No
E1000	I1000	0.000	Different	0.000	Yes
E1500	I1500	0.001	Different	0.037	Yes
E2000	I2000	0.469	Equal	0.001	Yes

5 IMPACT OF THERMAL PROCESSING ON RELIABILITY (SETS A, B, D, E)

To evaluate the impact of processing temperature on the solder joint strength, the results from sets A, B, D and E have to be compared. The shear strength of 1206-type resistors during thermal cycling is plotted in Figure 13. Since four data sets are compared simultaneously the *F* and *t* test can no longer be applied to the group of data.

**Figure 13.** 1206-type resistor solder joint strength after different processing temperature steps

In general the sets B and E have slightly larger values of shear force during 1000-2000 thermal cycles than do sets A and D (lower temperature exposure) i.e. the higher thermal exposure slightly improved the strength and fatigue resistance of solder joints. The gained advantage was quite significant after 1000 cycles, being ~30-50% larger than set A, in terms of shear strength.

The situation is different for the 0603-type resistor solder joints, as shown in Figure 14. The data from set B (long term ageing) indicate that there was a detrimental impact on the copper pad adhesion strength (green box at zero cycles). No other significant differences were observed between the other processing steps.

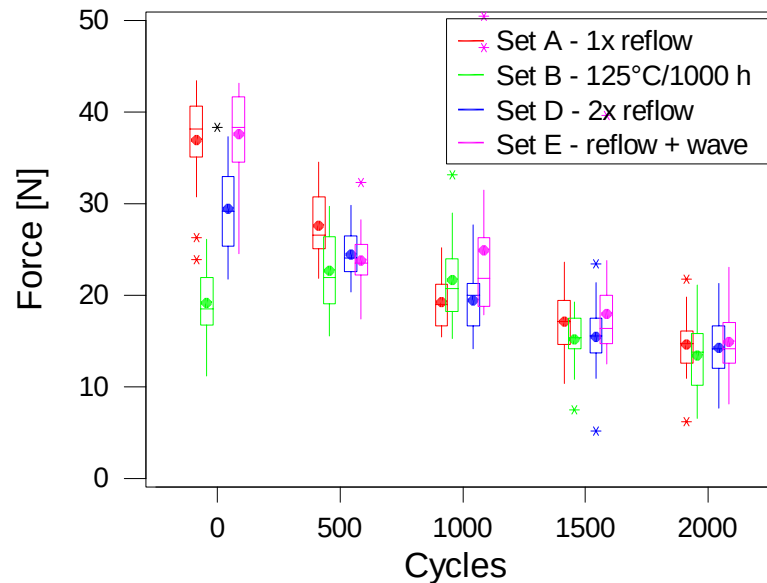


Figure 14. 0603-type resistor solder joint strength after different processing

6 DISCUSSION

The results of the statistical tests are summarised in Table 10. The first column lists the factors studied with respect to their impact on solder joint strength, and strength degradation, during thermal cycling. The second column shows the chip resistor size tested. The third column details the tested sets and their relevant conditions, and the last column presents an evaluation of the performance in terms of solder joint strength and rate of degradation during the thermal cycling. The overall performance is encapsulated in one of three groups: better, worse, or no difference.

The analysis of the first factor, “pad finish”, showed no consistent statistical difference between ENIG and immersion silver finishes throughout the 2000 thermal cycles for both resistor sizes. Hence the relative performance is marked as “0”.

For the factor, “substrate material”, the CTE-matched substrate delivered superior performance, with the reduced CTE of aramid laminate and its invar core helping to decrease the strain range exerted on the solder joints during thermal cycling. This increases the resistance of the solder to fatigue cracking, and hence the solder joints remain stronger over the same number of thermal cycles (marked + in the fourth column).

Statistical analysis of “alloy effect” on the strength of 1206-type resistor solder joints showed that SnPbAg solder accommodated strains cycles better than did the SnAgCu alloy. In the case of 0603-type resistors (i.e. for a smaller strain range) the SnAgCu alloy exhibited a better performance than that of SnPbAg solder. Comparison of the data for SnAgCu and SnAg joints shows that the SAC out-performed the SnAg joints.

The last factor “thermal process treatment” proved to be inconclusive. Changes due to thermal treatment were more pronounced with the larger chip resistors. For these components the behaviour following single and double reflow processing, was noticeably poorer than either that following simple reflow after thermal ageing, or that following reflow and wave soldering

processing. In the case of the 0603-type resistors, with the exception of thermal ageing (100 hours at 125°C), the thermal exposure made no significance difference to the performance

The aim of this work had been to create a model, using multiple regression analysis, for the impact that certain factors (pad finish, thermal heat treatment, laminate material and solder alloy) might have on the joint strengths of chip resistors. As can be seen from the analysis of the results given above, and summarised in Table 10, there were no clear trends for the chosen factors, other than for the solder alloy, and a relationship for this dependence had been provided previously [2]. This disappointing outcome prevented the meaningful use of multiple regression analysis and the construction of the last planned model.

Table 10. Summary of statistical tests

Factor	Resistor size	Tested set - condition	Relative performance
Pad Finish	1206	Set E - ENIG	0
		Set K - immersion Ag	0
	0603	Set E - ENIG	0
		Set K - immersion Ag	0
Substrate material	1206	Set A - FR4	-
		Set L - CTE matched	+
	0603	Set A - FR4	X
		Set L - CTE matched	X
Solder	1206	Set J - SnPbAg	+
		Set K - SAC	-
	0603	Set J - SnPbAg	-
		Set K - SAC	+
Solder	1206	Set E - SAC	+
		Set I - SnAg	-
	0603	Set E - SAC	+
		Set I - SnAg	-
Thermal process treatment	1206	Set A - 1x reflow	-
		Set B - 1000h/125°C	+
		Set D - 2x reflow	-
		Set E - 1 reflow + 1 wave	+
	0603	Set A - 1x reflow	0
		Set B - 1000h/125°C	-
		Set D - 2x reflow	0
		Set E - 1x reflow + 1x wave	0

+	better performance
-	worse performance
0	no difference
x	data not available

7 CONCLUSIONS

This report describes the third stage of an investigation of various aspects of the reliability of joints made using lead-free solders. The possible impact that certain chosen factors (pad finish, thermal heat treatment, laminate material and solder alloy) might have on the strength of chip resistors, has been studied using accelerated ageing and shear testing techniques. The shear strength data were encouraging and indicated that:

- the joint strength data did not exhibit any dependence on the pad finishes studied, a finding of comfort to board assemblers
- the joint strength was dependent on the solder used, and the findings of different behaviours of the joints of the small and larger chip resistors, confirm those in the literature
 - for 1206-type chip resistors, SnPbAg solder joints accommodated strain better than SAC solder joints
 - for 0603-type resistors, SAC solder joints performed better than SnPbAg solder joints
- the joint strength was dependent on the type of substrate, again confirming literature data i.e. CTE-matched boards did not generate the large strains associated with FR4 boards
- the joint strength data did not exhibit any dependence on the thermal process treatments studied
 - however, there was an indication of a better performance for the 1206-type resistor joints after reflow and thermal ageing, and after reflow and wave soldering
 - in the case of the 0603-type resistor joints, the ageing treatment did hinder adhesion of the small copper pads.

Statistical tests have been applied to all four sets of materials data in order to ascertain whether or not differences, or trends, between data sets existed, and hence whether or not subsequent regression analysis could be undertaken. The statistical t tests indicated that only in one case, the “solder factor” data, did such differences exist. Moreover, the statistical tests indicated that none of the materials data sets were sufficient or adequate enough to allow meaningful multiple regression analysis.

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