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The Analytical Model for Thermal Cycling

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ABSTRACT

The reliability of electronics assemblies is highly dependent on quality of solder joints. To assess a solder joint quality and its life-time several techniques were evaluated [1] showing that destructive techniques still represent major source of reliable data. Shear testing is used to measure thermal cycling induced damage in a form of internal cracks inside a solder joint. Main issue is to find a universal descriptive formula summarising effect of thermocycling parameters on a degradation variable. In this report the degradation variable is represented by ultimate shear strength of a solder joint.

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Head, Materials Centre

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1. Introduction

Thermocyling is a most common reliability testing used in electronic industry. An electronic assembly submitted to temperature changes expands and due to the variability in materials and their coefficient of thermal expansion (CTE) localised stresses and strains concentrate between components and substrate. Solder, as a joining material has to withstand these stresses and strains for electronic components to provide mechanical and electrical function. Hence thermo-mechanical performance of solder joints has to be tested at various temperatures and temperatures rates. Unfortunately mechanical properties of solders vary considerably with temperature.

2. Experiment

The test vehicle design used here contains three types of chip resistors 1206, 0805 and 0603. This is fabricated from a single-sided FR4, thickness 1.6 mm, Cu thickness of 35 µm (Cu plating 1 oz/sq.ft) and immersion Au over electroless Ni (ENIG).

Substrates were stencil printed with solder paste using a stainless steel stencil with a thickness of 150 µm (0.006”). The pastes used were **95.5Sn3.8Ag0.7Cu and 96.5Sn3.5Ag**. Components were placed onto the substrates using an automatic placement system. These processes ensured a regular solder joint volume. Reflow of the lead-free solder paste was achieved in a convection reflow oven and the soldering profile was measured at 5 different locations. Reflow of the lead-free solder paste was achieved in a convection reflow oven and the soldering profile was measured at 5 different locations on the substrate. The peaks of reflow temperature profiles were between 245 and 260°C. The time above the 220°C temperature was between 1 and 1.5 min.

The manufactured assemblies were subjected to thermocycling and life-time assessment. The technique used to characterise level of damage in solder joints was shear testing [1].

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 [6]. The greater the temperature range and the larger the number of cycles, the greater the damage experienced by a solder joint. But it is vital that the regime selected should reflect the likely working environment of the product(s) of interest (e.g. military, automotive, consumer etc). In recent years the military and automotive sectors have preferred to use the same cycling regime (-55^{o}C to 125^{o}C), and this now appears suitable for many, if not all, applications. Table 1 lists the thermal cycle regimes used in this evaluation study, and these are presented graphically in Figure 1.

Table 1 Shape parameters for 6 thermal cycles

Cycle	Low temp	High temp	Ramp	Dwell	Period
	[°C]	[°C]	[°C/min]	min	min
A	-55	125	10	5	45
B	-55	125	18	10	40
C	-20	125	10	5	40
D	-12	125	65	5	11
E	-20	80	10	5	30
F	-55	125	55	0	6.6

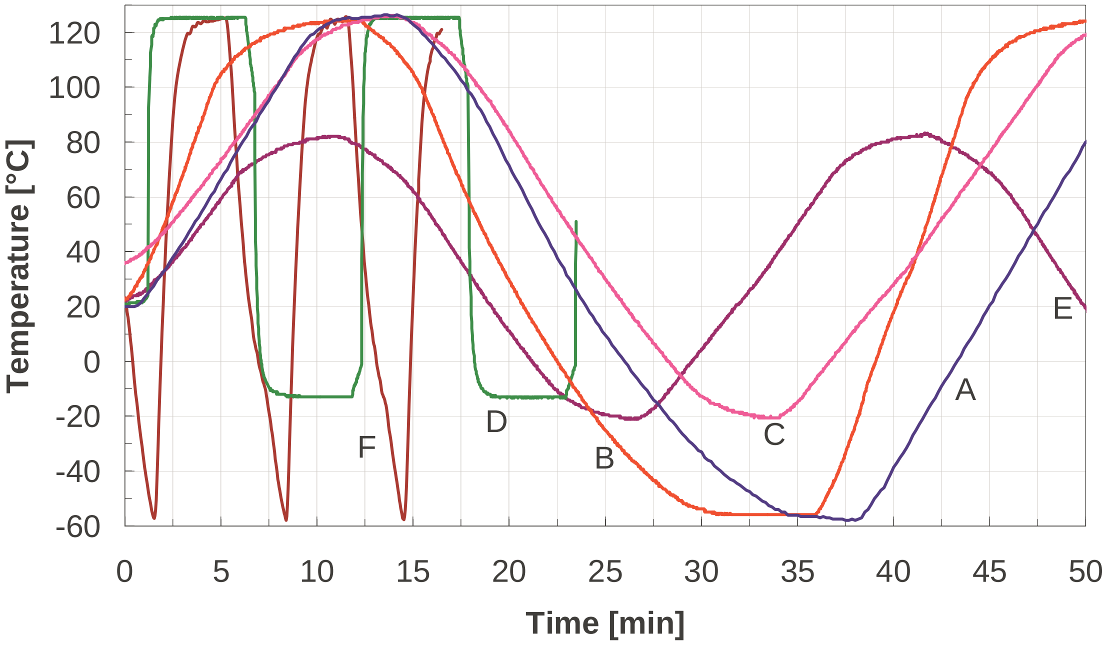


Figure 1 Temperature profiles of 6 different thermal cycles

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 a crack in the solder joint, its size and the extent of its 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 2 shows a typical shear test set up. These tests were undertaken 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 then plotted as a function of the number of thermal cycles to which the assembly had been subjected [Appendix 1].

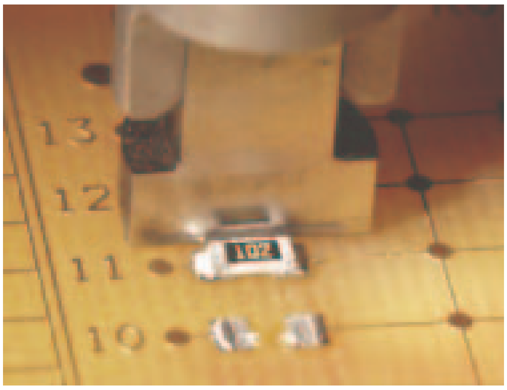


Figure 2: Shear test jig and push-off tool before a shear test

Resistor’s solder joints are formed on Cu pads on the surface of a printed circuit board. To measure resistor solder joint areas the image in Figure 3 was taken after removing the components. The area or rupture is measured from top view and plotted against the pad area in Figure 4. A close correlation was found between these two measurements meaning that either of the two measures can be used for characterisation of stress inside solder joints when force to rupture a solder joint is applied. In the later analysis the ruptured solder area size was used as a predictor variable.

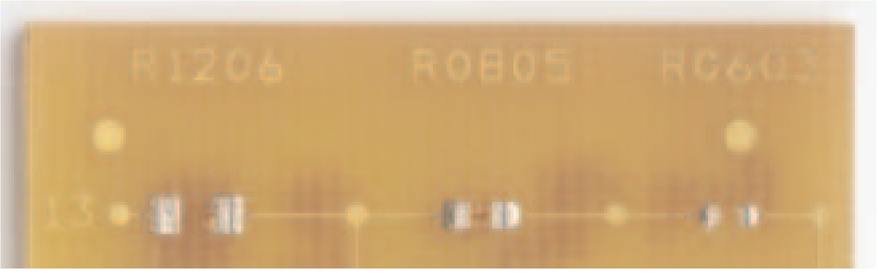


Figure 3 PCB showing solder joint after shear test

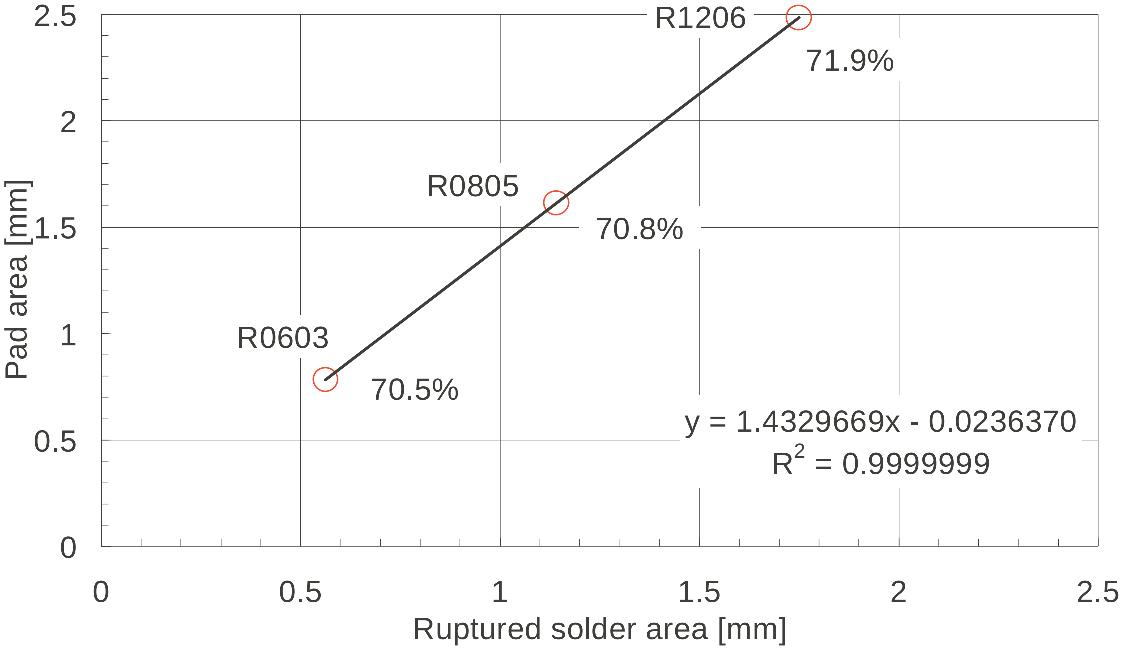


Figure 4 Correlation of pad area and solder joint area

3. Model I – Regression Analysis

To characterise impact of thermal cycling on shear strength of solder joint six linear fit models are proposed each for different thermal cycle regime. These linear polynomial equations are applied with predictors and predictors' coefficients as seen in Equation 1.

$$Y=b0+b1*X1+b2*X2+\ldots \qquad \text{Equation 1}$$

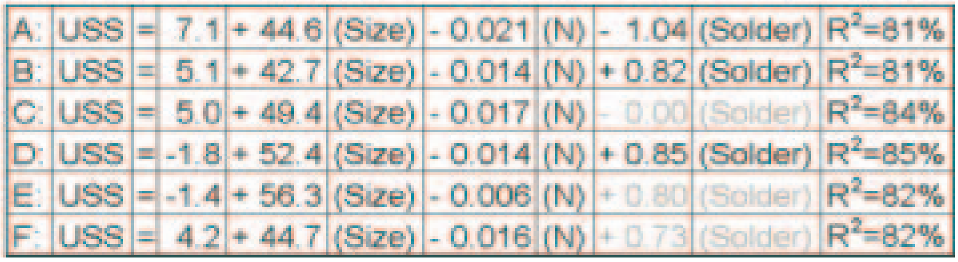
Where:
Y- response variable
b0 – intercept
b1 – coefficient of predictor 1
b2 – coefficient of predictor 2
X1 – predictor 1
X2 – predictor 2

In this model the response variable is ultimate shear strength (USS) of solder joint, and predictors are:

- Size of solder joint (ruptured area) = 1.75 (1206), 1.14 (0805) , 0.56 (0603) mm^2
- N (number of thermal cycles) = 0, 300, 600, 900, 1200
- Solder alloy = -1 (SnAg), + 1 (SAC)

In Table 2 there are 6 equations each for different thermal cycle (Figure 1). The coefficients for predictor solder in case of cycle C, E and F are printed in grey are they are not statistically significant. The fit was performed by the least square method and percentage of data following the linear model between 81-85%.

Table 2 Coefficients after linear fit



A:	USS	=	7.1	+ 44.6	(Size)	- 0.021	(N)	- 1.04	(Solder)	R^2=81%
B:	USS	=	5.1	+ 42.7	(Size)	- 0.014	(N)	+ 0.82	(Solder)	R^2=81%
C:	USS	=	5.0	+ 49.4	(Size)	- 0.017	(N)	- 0.00	(Solder)	R^2=84%
D:	USS	=	-1.8	+ 52.4	(Size)	- 0.014	(N)	+ 0.85	(Solder)	R^2=85%
E:	USS	=	-1.4	+ 56.3	(Size)	- 0.006	(N)	+ 0.80	(Solder)	R^2=82%
F:	USS	=	4.2	+ 44.7	(Size)	- 0.016	(N)	+ 0.73	(Solder)	R^2=82%

In Figure 5 there are coefficients for number of cycles predictor plotted for all 6 thermal cycles. The maximal absolute value i.e. the biggest impact on degradation of solder joints during thermocyling is observer with cycle profile A. This means that after one thermal cycle A damage in solder is by 33% bigger than after one thermal cycle B. Similarly with cycles C-F including the cycle E showing the lowest sensitivity for the number of cycles predictor.

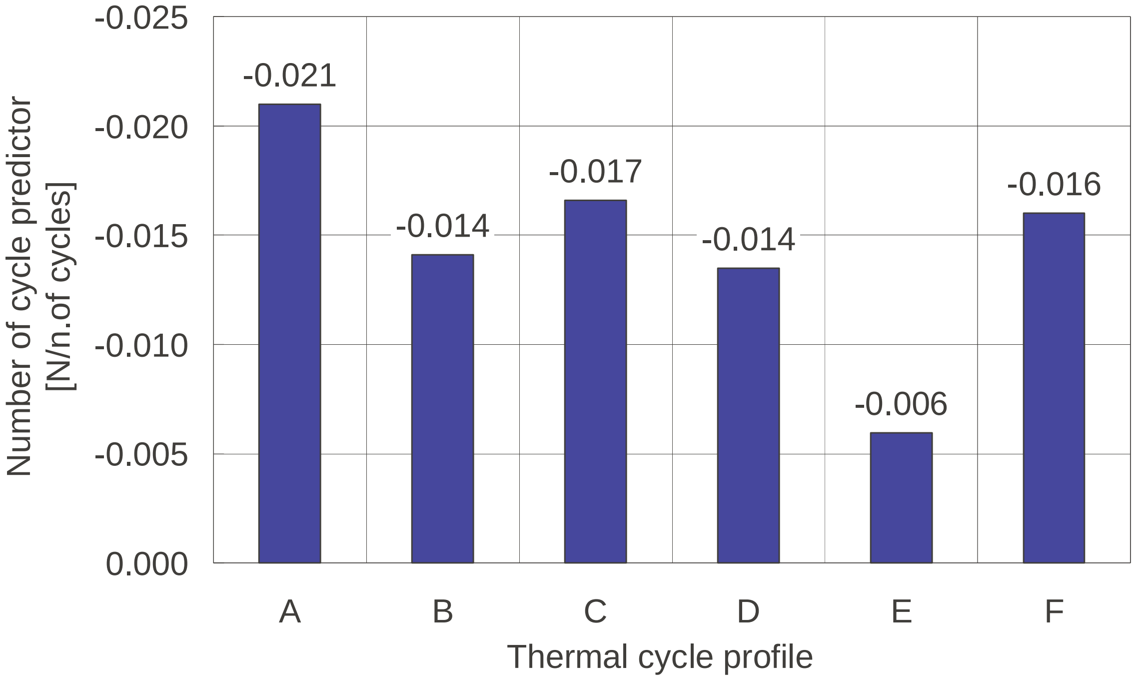


Figure 5

In Figure 6 there are coefficients for solder joint size predictor plotted for all 6 thermal cycles. It shows more even spread around the averaged value than the number of cycles predictor. This means that the impact of this factor is strong but more or less similar for various cycles.

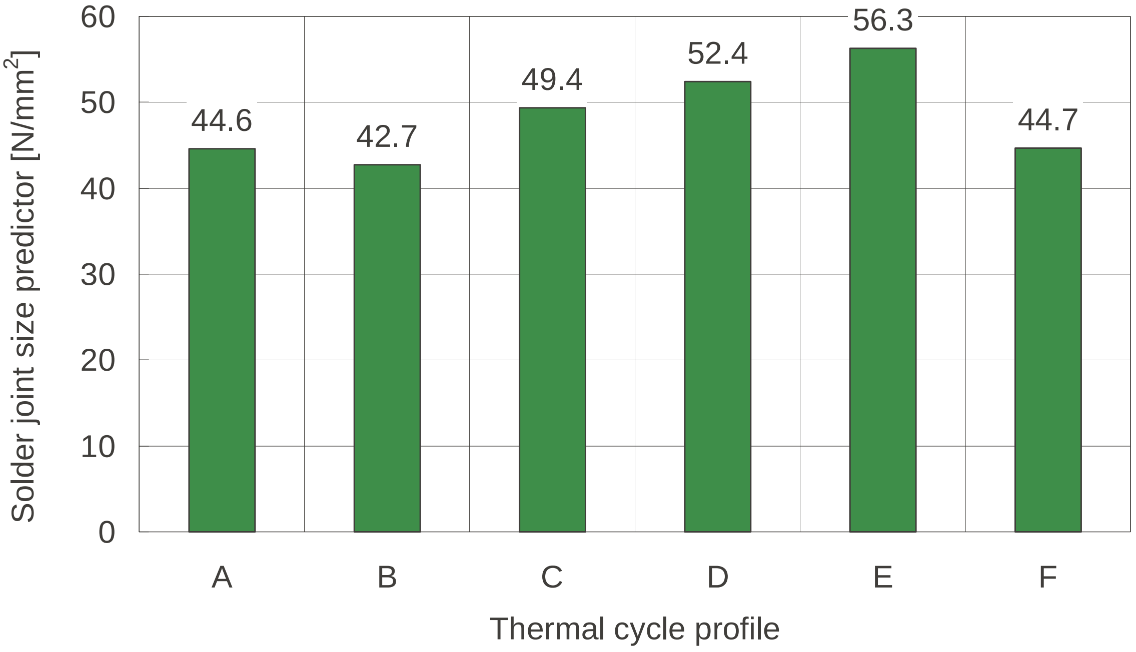


Figure 6 Coefficients of Solder joint size predictor

It has to be noted that the coefficients for number of cycle predictor and solder joint size predictor, these two contribute the most to the predicted value of USS. The solder predictor has got statistically insignificant impact on the resulting value of joint strength between the chosen solders. The constant in Formula 1 has no physical meaning and only offsets the mentioned trends.

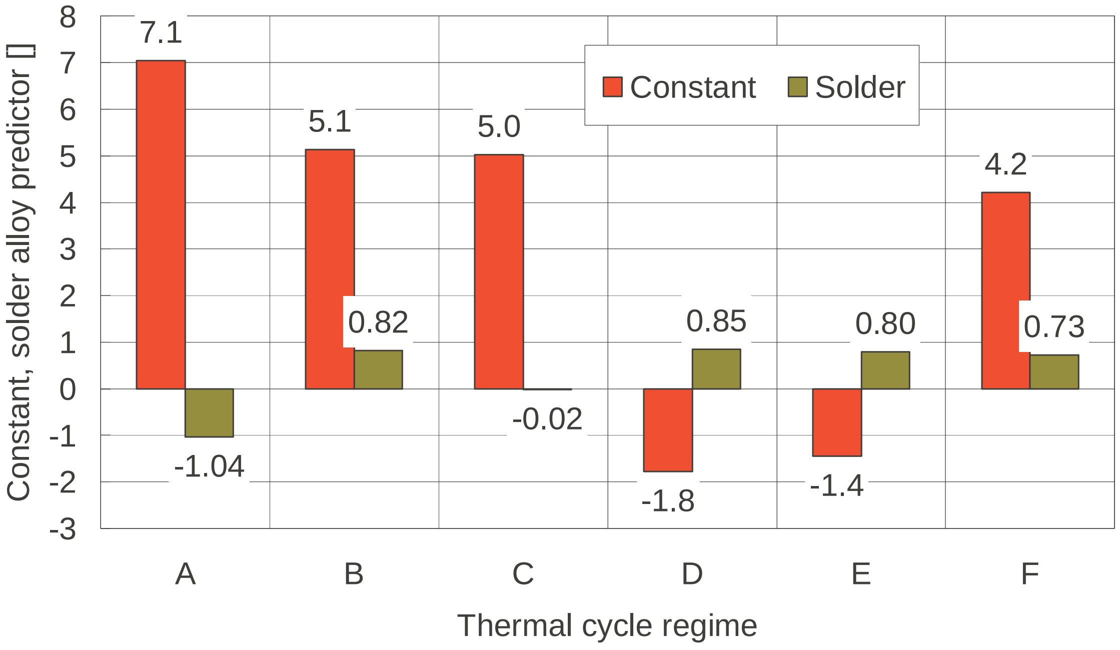


Figure 7 Magnitude of constant and solder predictor

4. Discussion

The ultimate shear strength data formed statistical base for a simple linear regression model. The statistical fit was performed on six sets of data for each thermal cycling profile. The identified predictors were number of cycles, solder joint size and solder alloy. The coefficient in the linear polynomial equation were estimated by least square method. From all of the predictors, the solder alloy did not show any significant impact on the resulting shear strength of solder joint. With all thermal cycles the strength of solder joint decreases with increasing number of cycles.

5. Conclusion

This report describes first stage in the development of analytical model for predicting lead-free reliability. The model is based on the shear strength measurements, which reflect the damage induced by thermal cycling inside solder joints. Analysis of factors influencing the solder joint integrity shows that there is no significant difference between SnAg and SnAgCu solder joints in terms of ultimate shear strength.

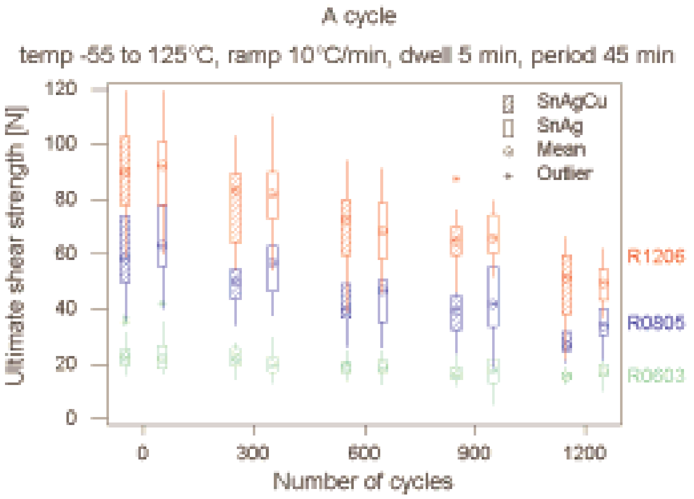
6. Acknowledgments

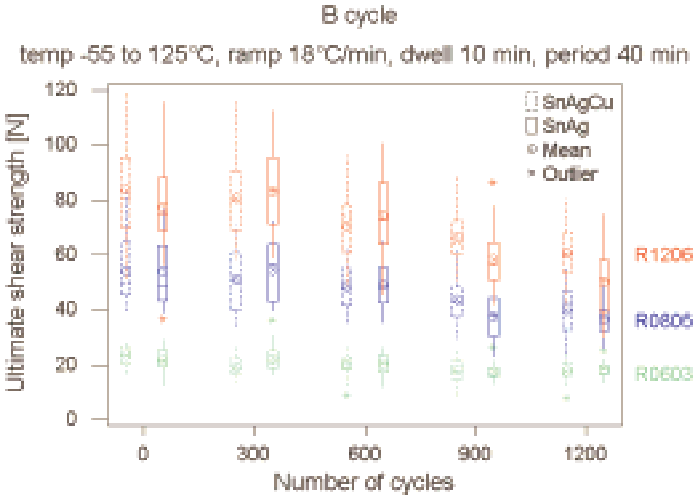
The work was carried out as part of a project in the Materials Processing Metrology Programme of the UK Department of Trade and Industry.

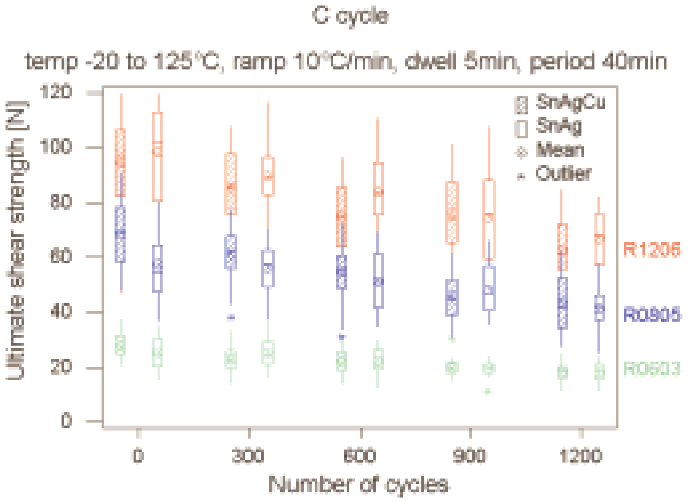
7. References

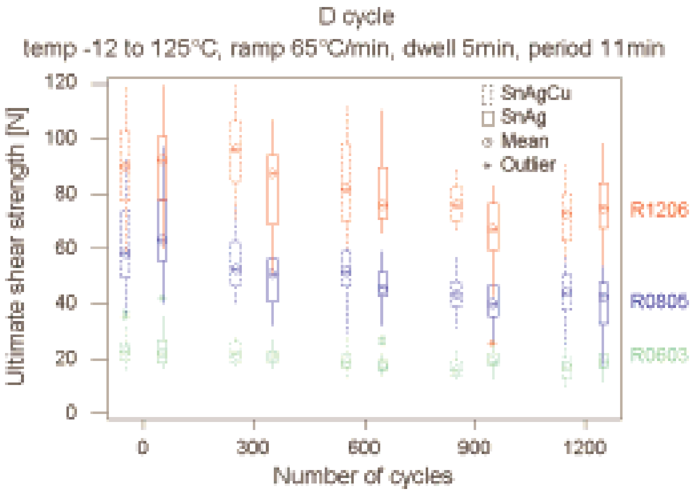
[1] Dusek, M., Wickham, M., Hunt, C: The Impact of Thermal Cycle Regime on the Shear Strength of Lead-free Solder Joints, November 2003, NPL report MATC(A)156
[2] Dusek, M., Hunt, C., “Crack Detection Methods For Lead-free Solder Joints”, NPL MATC(A) report 164, March 2004

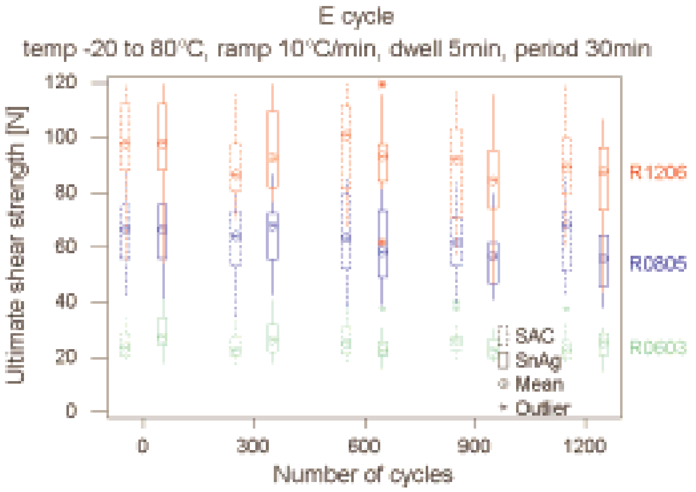
8. Appendix 1

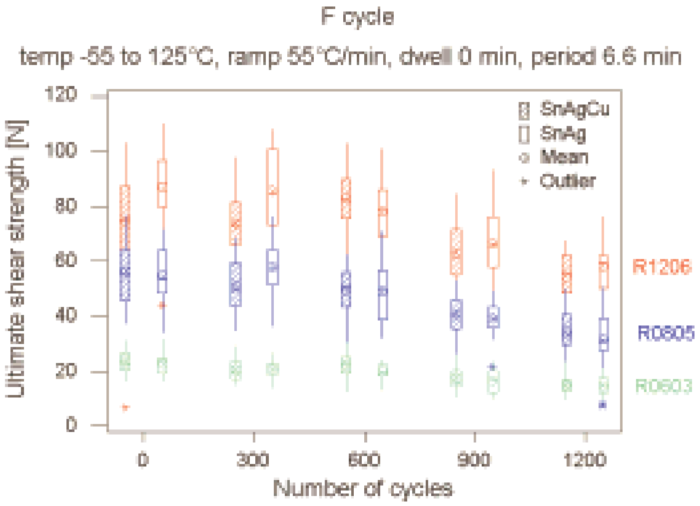

A cycle
temp -55 to 125°C, ramp 10°C/min, dwell 5 min, period 45 min
Ultimate shear strength [N]
120
100
80
60
40
20
0
0
300
600
900
1200
Number of cycles
SnAgCu
SnAg
Mean
Outlier
R1206
R0805
R0603


B cycle
temp -55 to 125°C, ramp 18°C/min, dwell 10 min, period 40 min
Ultimate shear strength [N]
120
100
80
60
40
20
0
0
300
600
900
1200
Number of cycles
SnAgCu
SnAg
Mean
Outlier
R1206
R0806
R0603

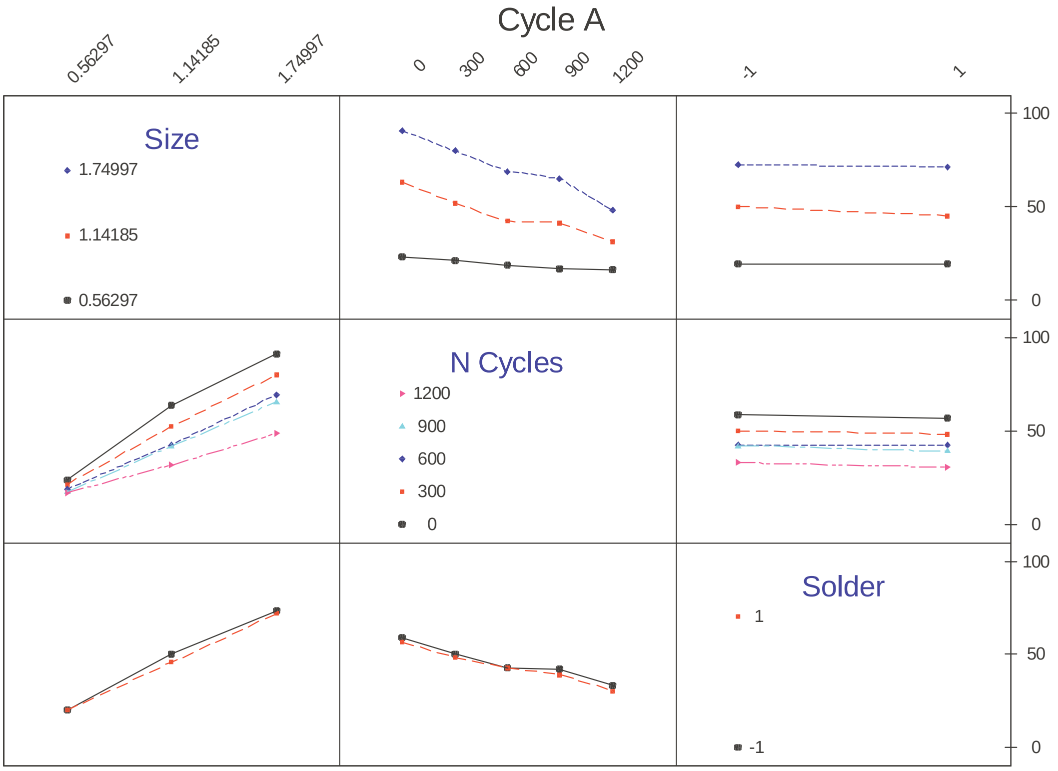

C cycle
temp -20 to 125°C, ramp 10°C/min, dwell 5min, period 40min
Ultimate shear strength [N]
120
100
80
60
40
20
0
0
300
600
900
1200
Number of cycles
SnAgCu
SnAg
Mean
Outlier
R1206
R0805
R0603

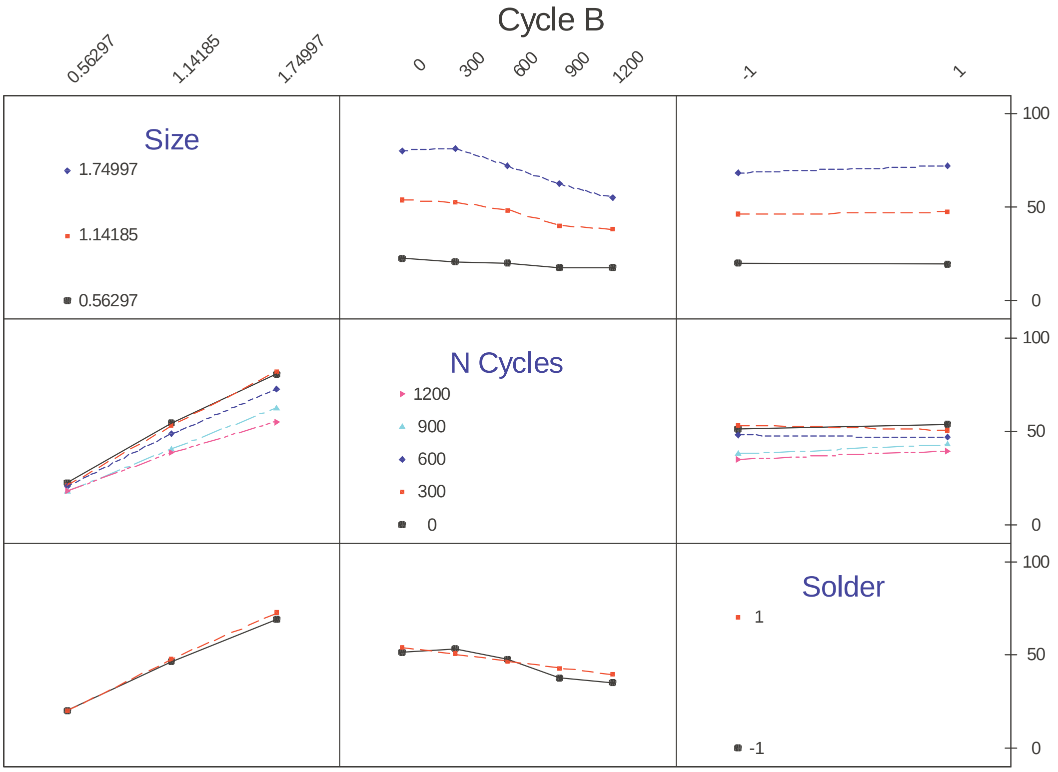

D cycle
temp -12 to 125°C, ramp 65°C/min, dwell 5min, period 11min
Ultimate shear strength [N]
120
100
80
60
40
20
0
0
300
600
900
1200
Number of cycles
SnAgCu
SnAg
Mean
Outlier
R1206
R0805
R0603

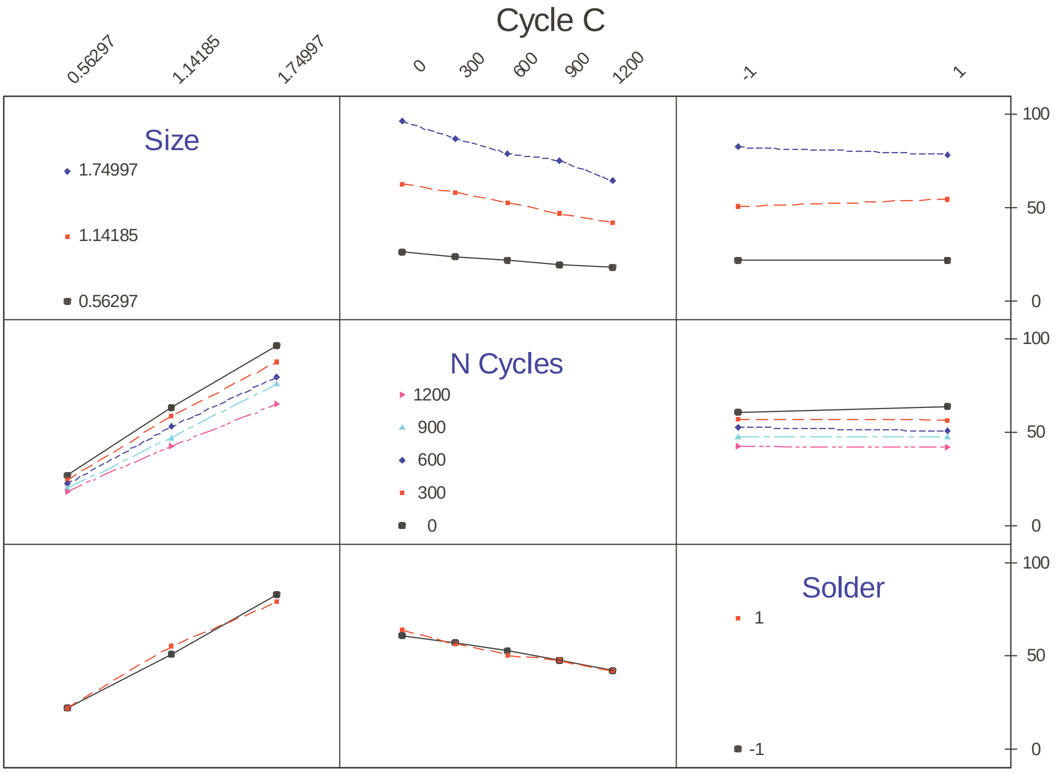

E cycle
temp -20 to 80°C, ramp 10°C/min, dwell 5min, period 30min
Ultimate shear strength [N]
120
100
80
60
40
20
0
0
300
600
900
1200
Number of cycles
SAC
SnAg
Mean
Outlier
R1206
R0805
R0603

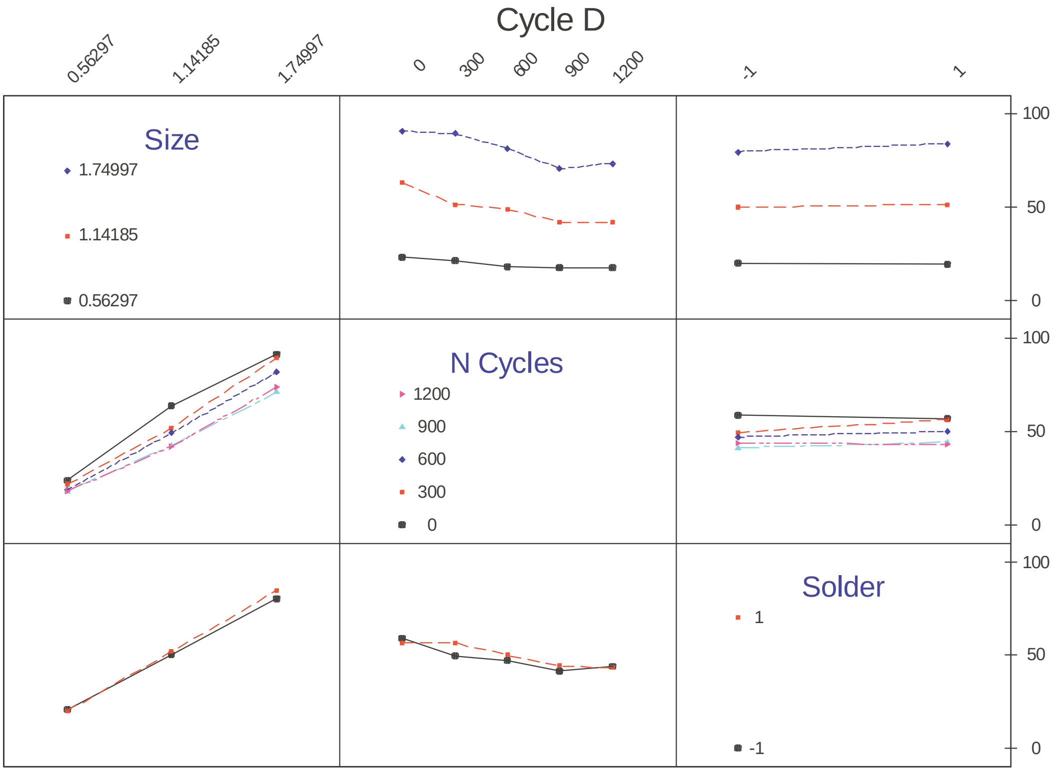

F cycle
temp -55 to 125°C, ramp 55°C/min, dwell 0 min, period 6.6 min
Ultimate shear strength [N]
120
100
80
60
40
20
0
0
300
600
900
1200
Number of cycles
SnAgCu
SnAg
Mean
Outlier
R1206
R0805
R0603

9. Appendix 2

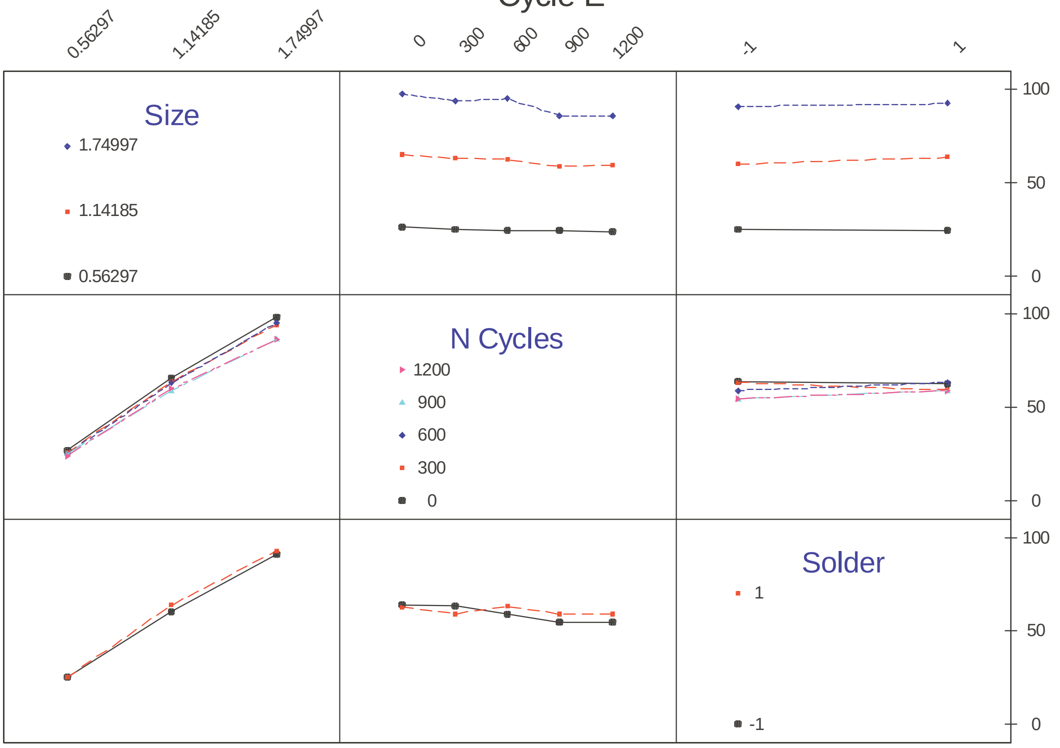

Cycle A
0.56297
1.14185
1.74997
0
300
600
900
1200
-1
1
Size
1.74997
1.14185
0.56297
N Cycles
1200
900
600
300
0
Solder
1
-1
100
50
0


Cycle B
0.56297
1.14185
1.74997
0
300
600
900
1200
-1
1
Size
1.74997
1.14185
0.56297
N Cycles
1200
900
600
300
0
Solder
1
-1
100
50
0


Cycle C
0.56297
1.14185
1.74997
0
300
600
900
1200
-1
1
Size
1.74997
1.14185
0.56297
N Cycles
1200
900
600
300
0
Solder
1
-1
100
50
0
100
50
0
100
50
0


Cycle D
0.56297
1.14185
1.74997
0
300
600
900
1200
-1
1
Size
1.74997
1.14185
0.56297
N Cycles
1200
900
600
300
0
Solder
1
-1
100
50
0
100
50
0
100
50
0

Cycle E



Cycle F