NPL REPORT
DEPC-MPR 039

The Analytical Model II for Predicting Solder Joint Shape and Volume Impact on Life-time

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NOT RESTRICTED

NOVEMBER 2005

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ABSTRACT

The reliability of electronics assemblies is highly dependent on the quality of solder joints, and the latter's response to temperature excursions. As part of its work to investigate many aspects of lead-free soldering, NPL has an on-going programme to characterise the thermal fatigue in lead-free solder joints. In this programme the effects on joint integrity of thermal cycling, thermal pre-treatment, solder volume, joint design, component types, PCB finishes, and solder alloy are being studied as part of the development of an analytical model for predicting lead-free solder joint reliability. The work encompasses a wealth of data, and although they can be used widely in a comparative sense, in this work (stage 2 of the project) they are also used to extend their usability by fitting to a linear descriptive formula. This approach has been applied to solder joint variables (inc volume, design, component size, stencil thickness) taking the ultimate shear strength of solder joints of chip resistors, after ageing and thermal cycling, as the degradation metric. The analysis showed that of the variables investigated, component size had the strongest effect on joint reliability. The number of thermal cycles also had a major influence, but stencil thickness had only a minor effect. There was no significant influence arising from varying the PCB design or the solderability of the component/PCB finishes.

ISSN 1744-0270

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1 INTRODUCTION

In the electronics industry, thermal cycling is commonly used as an integral part of assessing the reliability of electronics assemblies, which is itself known to be highly dependent on the quality of the solder joints. Any electronics assembly subjected to temperature changes expands, and because of the difference in coefficients of thermal expansion of the various materials used, localised stresses and strains are generated between the components and substrate. Solder, as the joining medium, has to accommodate these stresses and strains in order to provide both mechanical and electrical functionality. Unfortunately, the mechanical properties of solders can vary considerably with temperature. Consequently the thermo-mechanical performances of solder joints have to be examined over various temperatures and temperature cycling rates.

As part of its work to investigate many aspects of lead-free soldering, NPL has an on-going programme to characterise the thermal fatigue in lead-free solder joints. In this programme the effects on joint integrity of thermal cycling, thermal pre-treatment, solder volume, joint design, component types, PCB finishes, and solder alloy are being studied as part of the development of an analytical model for predicting lead-free solder joint reliability. The work encompasses a wealth of data and although they can be used widely in a comparative sense, in this work (stage 2) they are also used to extend their usability by fitting to a linear descriptive formula. This approach has been applied to solder joint variables (inc volume, design, component size, stencil thickness) taking the ultimate shear strength of solder joints, of chip resistors after ageing and thermal cycling, as the degradation metric.

In this work, not only was the solder volume varies using three stencil thicknesses, but the joint was also modified by altering the pad design, changing the pad dimensions and inter-pad gap. The work described here follows a previous project that modelled the results after various thermal cycling treatments, and is known [1] as Model I.

2 EXPERIMENTAL

The test vehicle design contained two types of chip resistors, i.e. 1206 and 0603. The substrate was fabricated from a double-sided FR4, thickness 1.6 mm, copper thickness of 35 µm (copper plating 1 oz/sq.ft) and immersion gold over electroless nickel (ENIG) pad finish.

Substrates were stencil printed with solder paste using three stainless steel stencils with thicknesses of 100, 150 and 200 µm. Table 1 lists the pad designs for 1206-type resistors and 0603-type resistors. The pad dimension modifications were based on the IPC-SM-782 revision A - August 1993. The definitions for pad dimensions are given in Figure 1. The recommended pad sizes from the IPC standard are given in groups A and F (1206- and 0603-type resistors respectively). However, in order to study the influence of increasing inter-pad gap, groups B and C (for 1206-type resistors) and groups G and H (for 0603-type resistors) were also used. Similarly groups D and E, and groups I and J, were used to investigate the influence of pad length on fillet formation.

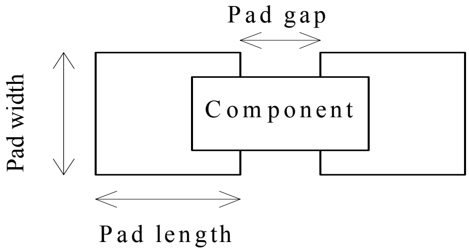


Figure 1. Definitions of pad dimensions

Table 1. Dimensions (mm) for various pad designs.

R1206	**IPC (A)**	**IPC+gap (B)**	**IPC+gap 2 (C)**	**Long pad (D)**	**Short pad (E)**
Pad gap	1.20	1.60	2.00	1.20	1.20
Pad width	1.80	1.80	1.80	1.80	1.80
Pad length	1.60	1.60	1.60	1.92	1.28
Differences	0%	+33%(gap)	+67%(gap)	+20%(length)	-20%(length)
R0603	**IPC (F)**	**IPC+gap (G)**	**IPC+gap 2 (H)**	**Long pad (I)**	**Short pad (J)**
Pad gap	0.60	0.76	0.92	0.60	0.60
Pad width	1.00	1.00	1.00	1.00	1.00
Pad length	1.10	1.10	1.10	1.32	0.88
Differences	0%	+27%(gap)	+53%(gap)	+20%(length)	-20%(length)

Figure 2 shows the actual pad designs on the PCB without components present.

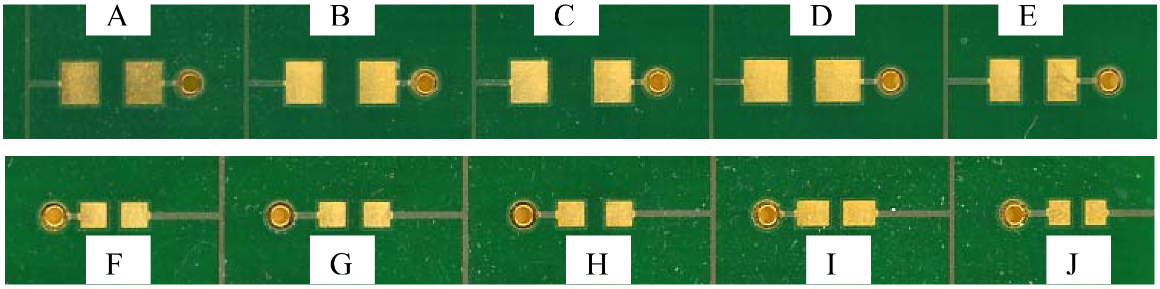


Figure 2. Variations of pad designs for 1206- type (top row) and 0603-type resistors (bottom row)

The assembly was processed using a **95.5Sn3.8Ag0.7Cu** solder paste with a no-clean type flux. Components were placed onto the substrates using an automatic placement system, ensuring a regular solder joint volume. Reflow of the lead-free solder paste was achieved in a convection reflow oven. The peaks of reflow temperature profiles were between 245 and 260 °C, and 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, and the technique used to characterise level of damage in solder joints, was again shear testing [2].

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 [1]. 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. Table 2 lists the values of the thermal cycling parameters used in this evaluation study, and these are presented graphically in Figure 3.

Table 2. Temperature cycling parameters with ± 4°C temperature tolerance

Low Temperature Dwell	**High Temperature Dwell**	**Ramp Rate**	**Dwell Time**	**Period**
[°C]	[°C]	[°C/min]	[min]	[min]
-55	125	10	5	45-48

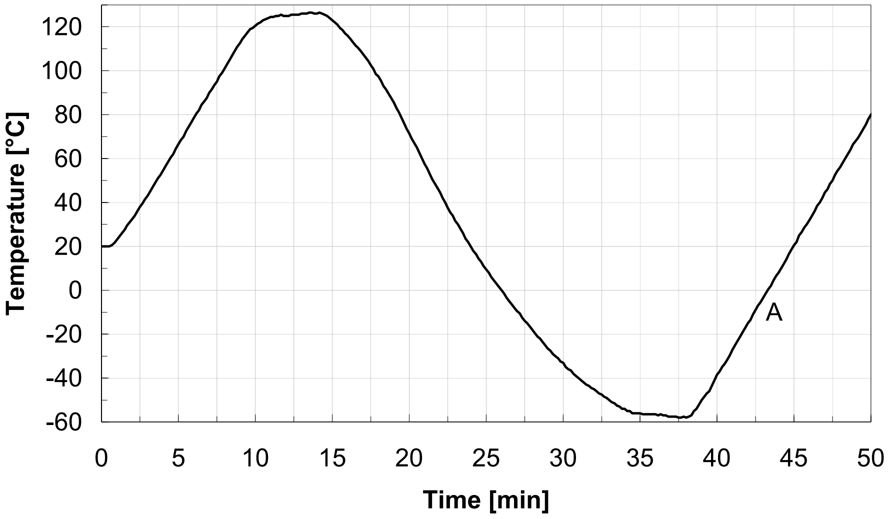


Figure 3. Thermal cycling temperature profile

In Figure 3 the top side board design of the test vehicle is presented. Although the PCB design included a continuity test of the resistors and other components during the thermal cycling, this report only considers the measurements of shear forces on 1206- and 0603-type resistors.

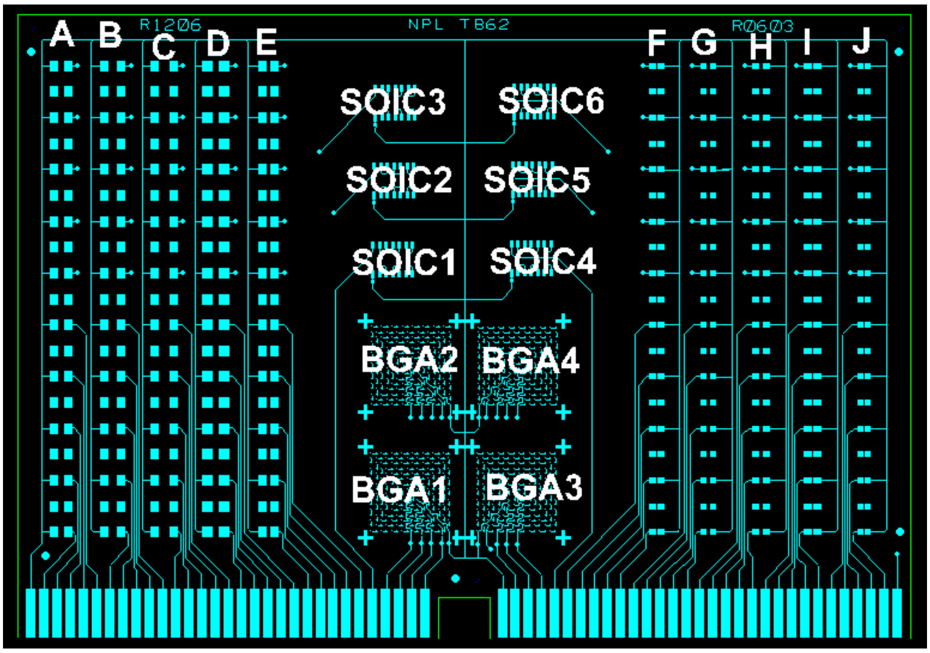


Figure 4. Test vehicle PCB design

In Figure 5 typical photographs of R0603-type resistors after the reflow process are presented. (NB. Notice that the pad gap in design H is equivalent to the gap between the plated terminations on the component.

3 SHEAR TESTING

Shear testing is an established destructive method for evaluating the degree of crack propagation and damage to the solder joint, and also provides a measure of the joint strength [3]. The method is based on the assumption that the presence of a crack in the solder joint, its 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 5 shows a typical shear test set up. In this work these tests were undertaken using 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 [see Appendix 1].

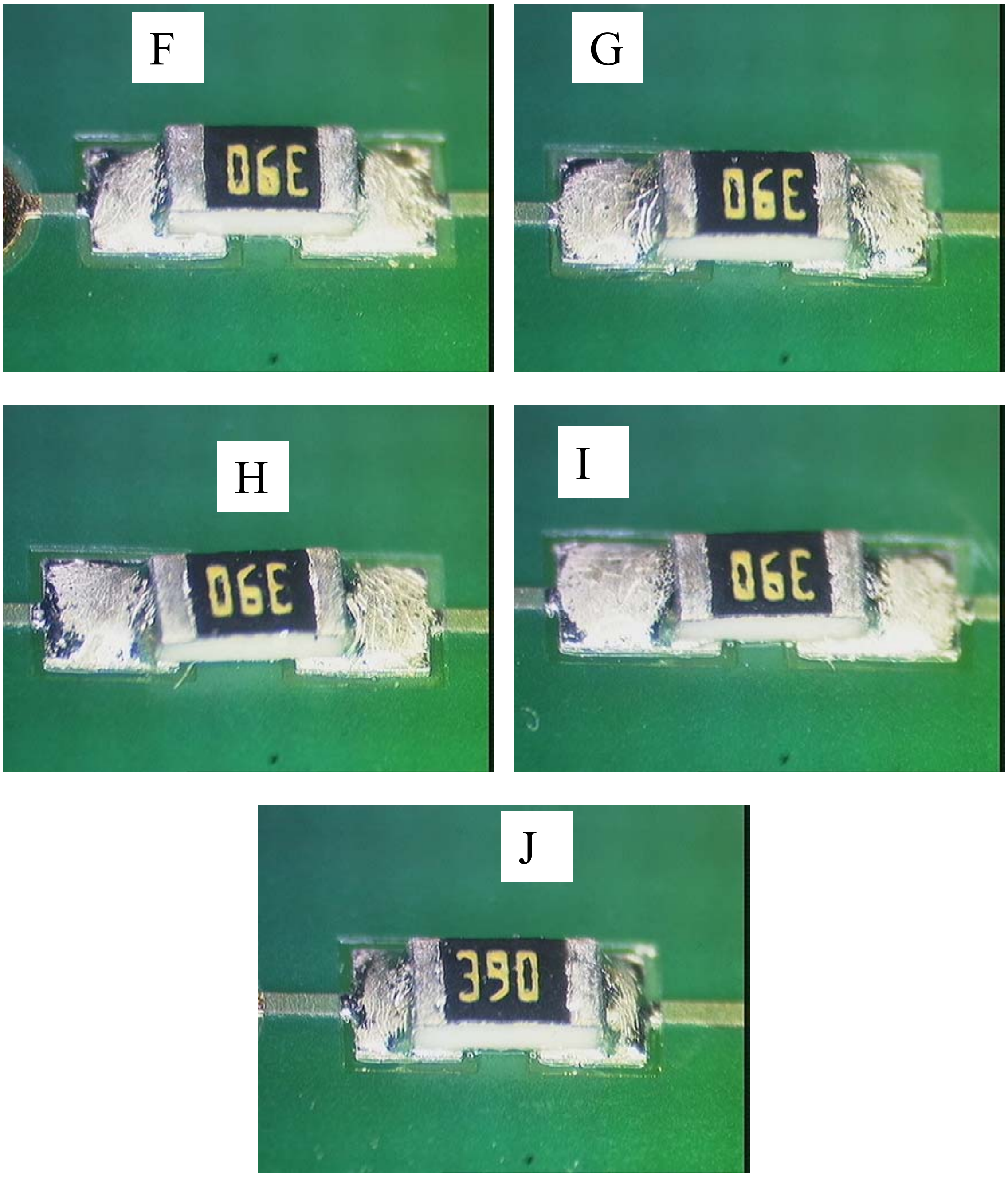


Figure 5. Images of soldered 0603-type resistors with 5 different pad designs

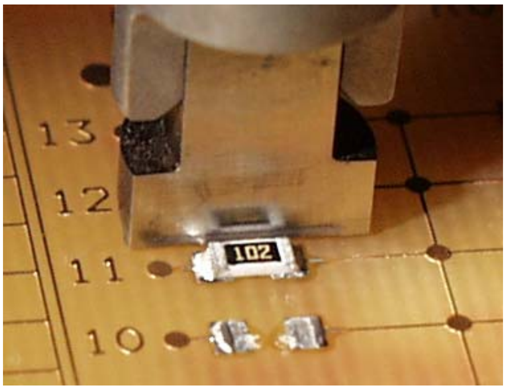


Figure 6. Shear test jig and push-off tool before a shear test

4 MODEL II – REGRESSION ANALYSIS

To characterise the impact of component size and stencil thickness on solder joint shear strength, a linear fit model was proposed. The standard statistical approach of multiple regression analysis is applied here using the push off shear forces, which are presented in Appendix 1. Three predictors are considered here, component size, number of thermal cycles, and stencil thickness. Other predictors were ignored since they were not statistical significant, this is established in Appendix 2.

A linear polynomial equation was applied with predictors and predictors' coefficients as shown in Equation 1.

$$Y=b0+b1*X1+b2*X2+b3*X3 \qquad \textbf{Eq 1}$$

Where:
Y- response variable (solder joint strength USS Force)
b0 – intercept
b1 – coefficient of predictor 1 (component size)
b2 – coefficient of predictor 2 (number of thermal cycles)
b3 – coefficient of predictor 3 (stencil thickness)
X1 – predictor 1 (component size)
X2 – predictor 2 (number of thermal cycles)
X3 – predictor 3 (stencil thickness)

In this model the response variable is shear strength (USS) of solder joint, and the predictors (b1, b2, b3) are:

- Component size (length of component body) = 3.1 mm (1206), 1.6 mm (0603)
- N (number of thermal cycles) = 0, 500, 1000, 1500, 2000
- Stencil thickness = 100, 150 and 200 μm
- Pad design (not statistically significant)
- Solderability (not statistically significant, Appendix 2)

Equation 2 is the linear equation with coefficients for the chosen predictors, and the fit matches 74% of the measured data (details are given in Appendix 3). The error of the model is 26% i.e. 26% of the measured data do not fit the model. If the model functionality was increased the fit could be improved, but at this level of error the simple linear fit is considered acceptable.

USS Force [N] = - 10.8 - 0.0159*Cycles + 0.0525*Stencil [µm]+ 23.2*Component size [mm] **Eq 2**

5 DISCUSSION

The ultimate shear strength data formed the statistical base for a simple linear regression model. The statistical fit was performed on three predictors: number of cycles, stencil thickness, and component size. The coefficients in the linear polynomial equation were estimated by multiple regression analysis. From all the predictors, the pad size and solderability did not show any significant impact on the resulting shear strength of solder joint (Appendix 2).

From the Main Effects plot (see Appendix 4) and the data in Table 3, it is evident that component size causes the biggest span (range) in the response; hence it has the strongest effect (up to 48%) on actual shear strength of a solder joint. The second, and nearly equivalent effect, was observed with the number of thermal cycles (up to 44%). The stencil thickness has only a minor effect with only 7% contribution to the predicted shear force.

It has to be noted that neither the variation of pad design nor the solderability, had any statistical effect in contributing to response variable of shear force. The constant in Equation 2 has no physical meaning and only offsets the mentioned trends.

Table 3. Assessment of predictor strength based on predictor's range

Predictors	Max	Min	Max Force	Min Force	Max-Min	%
Cycles	0	2000	0.0	-31.8	31.8	44%
Stencil	200	100	10.5	5.3	5.3	7%
Component size	3.1	1.6	71.9	37.1	34.8	48%
Intercept	-	-	-10.8	-10.8	0	0%
		Total Response =	71.6	-0.2	71.9	100%

6 CONCLUSION

This report describes the second stage (of three) in the development of an analytical model for predicting lead-free solder joint reliability. The model is based on shear strength measurements, which reflect the damage induced by thermal cycling inside solder joints. Analysis of factors influencing the solder joint integrity shows that, of the variables investigated, component size had the strongest effect. The number of thermal cycles also had a major influence on joint integrity, but stencil thickness had only a minor effect. There was no significant influence in terms of ultimate shear strength, of varying the PCB design or the solderability of the component/PCB finishes.

7 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.

8 REFERENCES

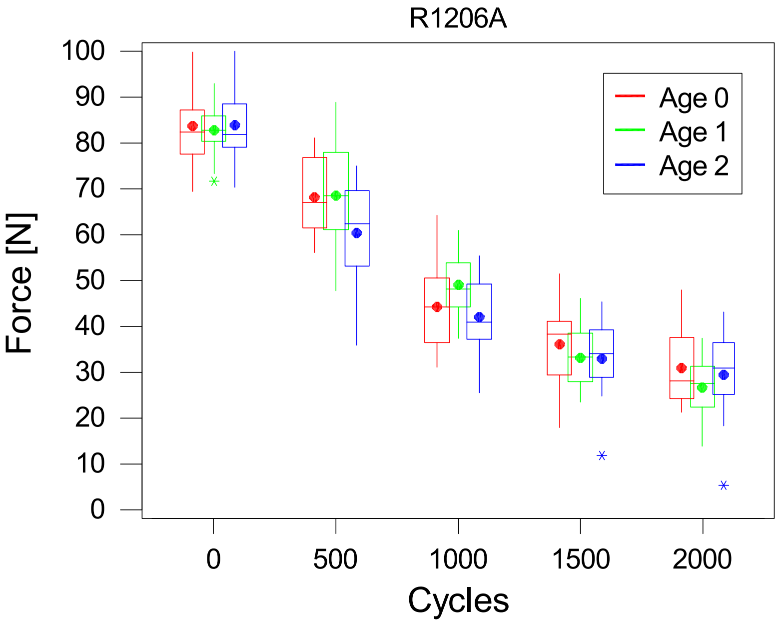
[1] Dusek, M., and Hunt, C., "*Analytical Model for Thermal Cycling*" NPL Report MATC(A)163, March 2004

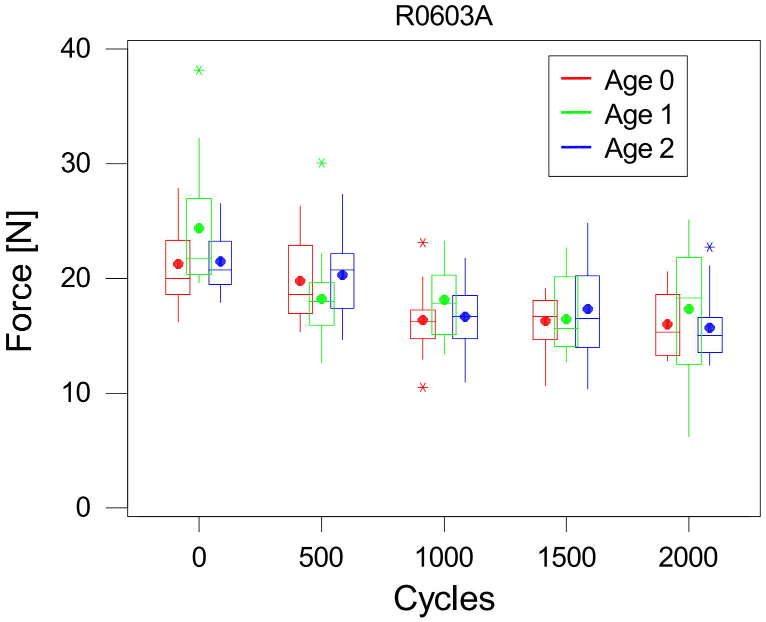
[2] Dusek, M., Wickham, M., Hunt, C: "*The Impact of Thermal Cycle Regime on the Shear Strength of Lead-free Solder Joints*", NPL Report MATC(A)156, November 2003

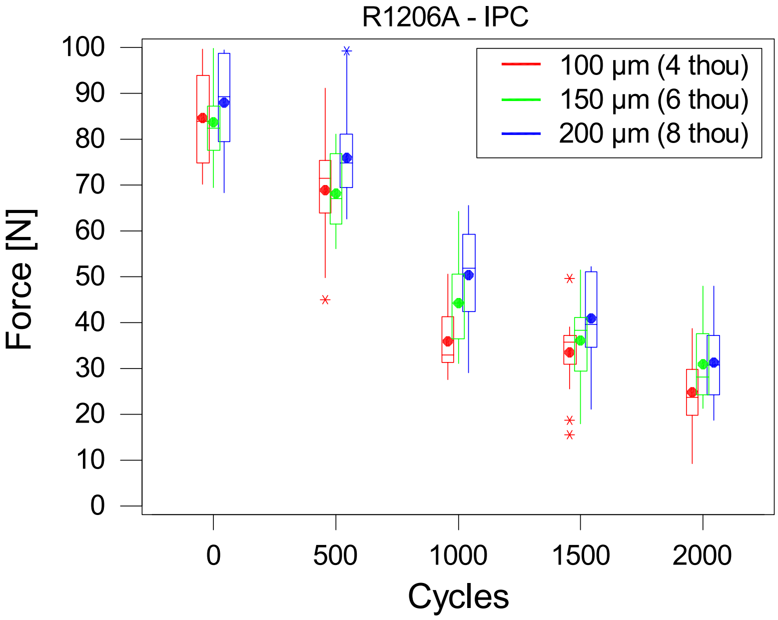
[3] Dusek, M., and Hunt, C., "*Crack Detection Methods For Lead-free Solder Joints*", NPL Report MATC(A)164, March 2004

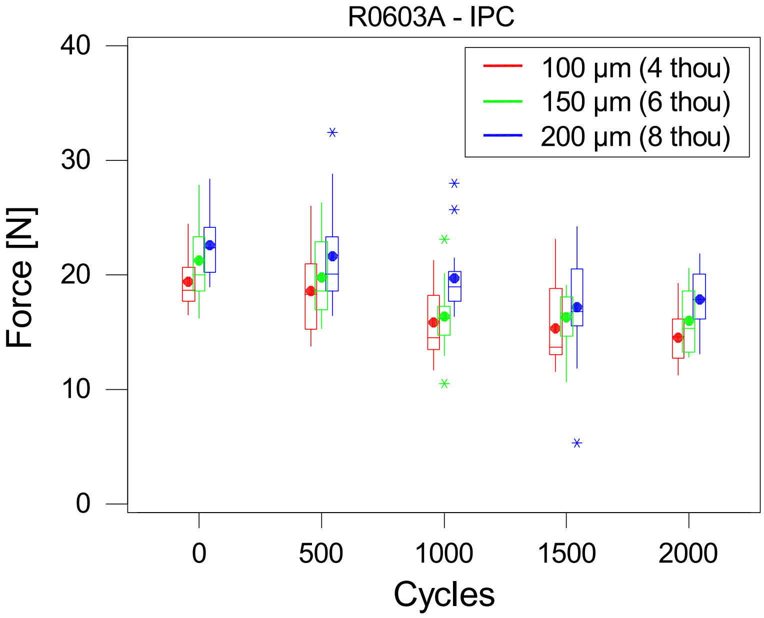
APPENDIX 1

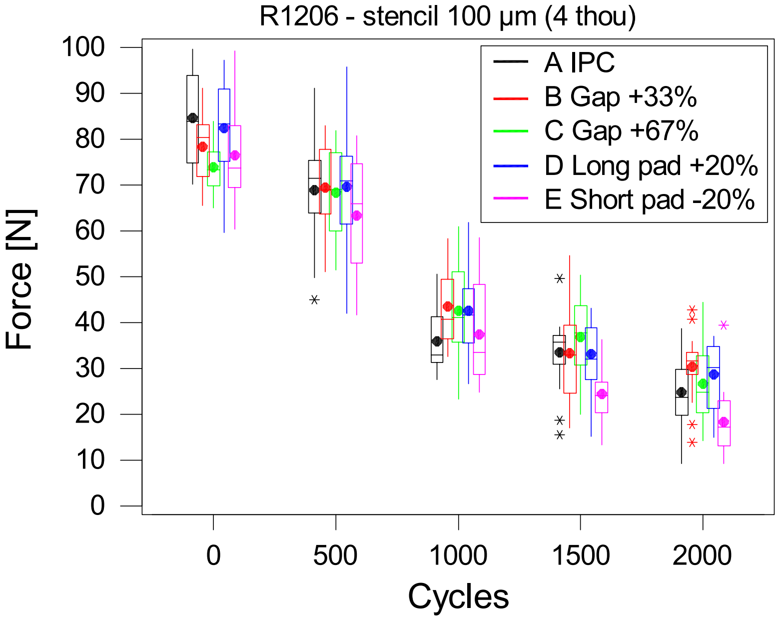
Ultimate shear force required to rupture the solder joint as a function of the number of cycles to which the assembly had been subjected. The ageing condition for Age 0, Age 1 and Age 2 was 155 ºC, and the duration for each age was 0, 72 and 200 hours respectively.

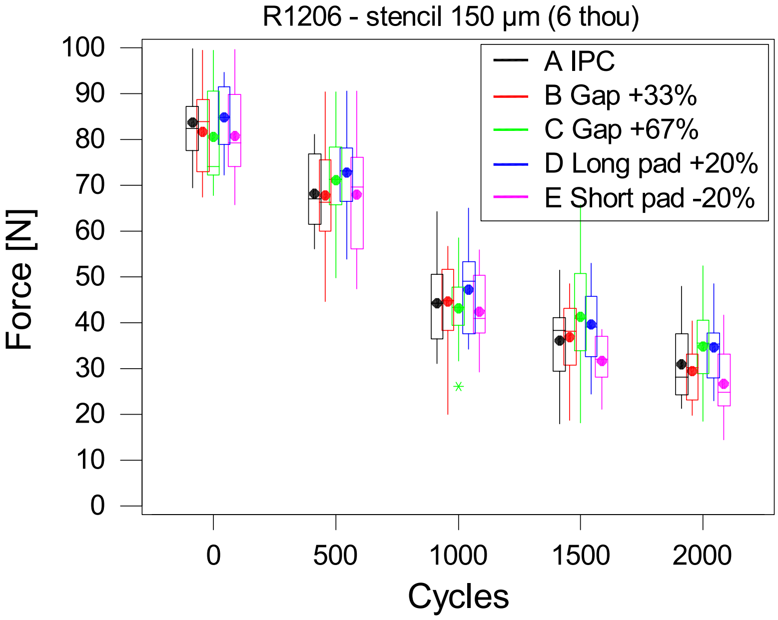


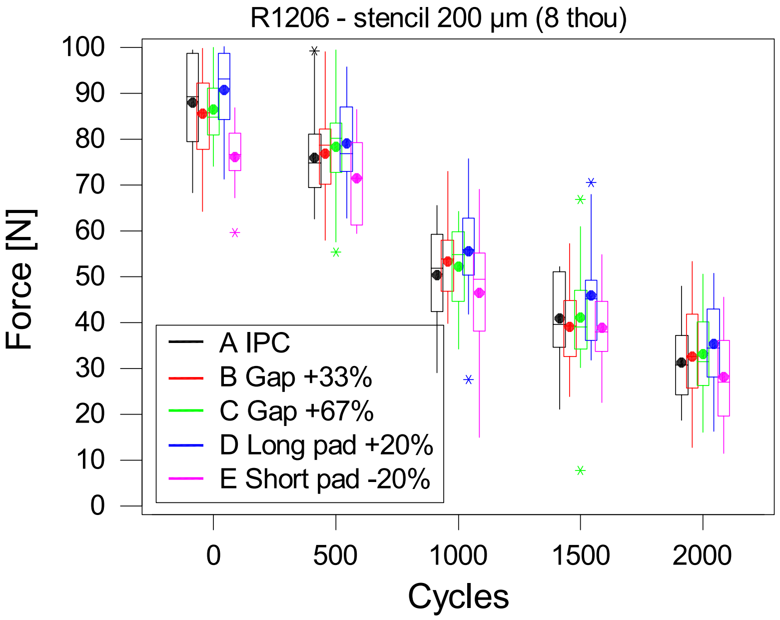


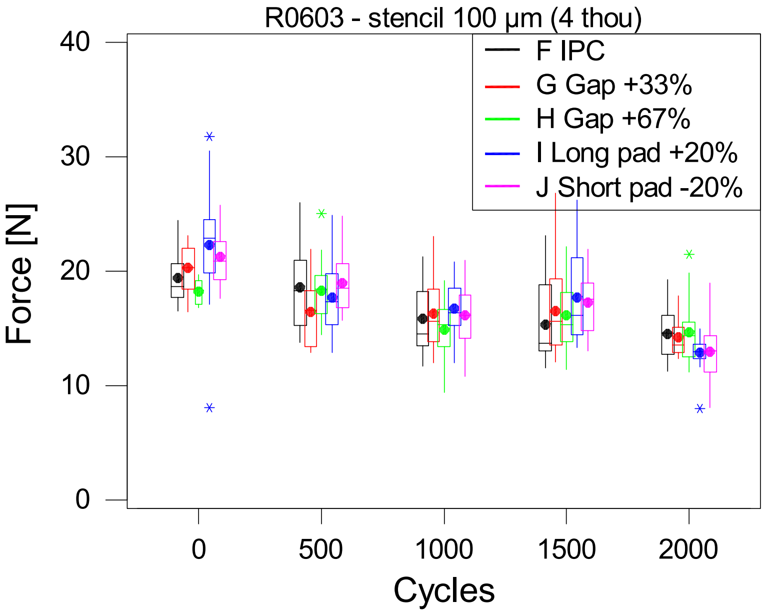

R1206A - IPC
100 µm (4 thou)
150 µm (6 thou)
200 µm (8 thou)
Force [N]
100
90
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
Cycles

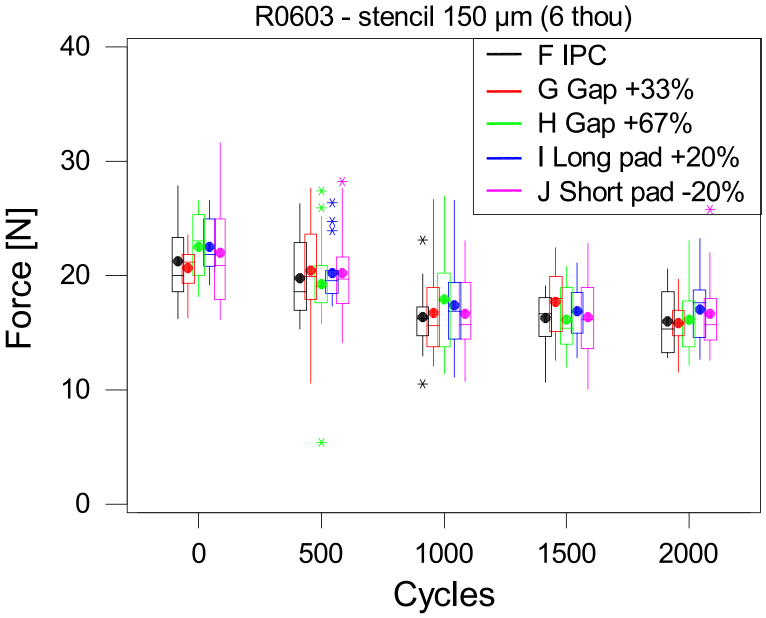

R0603A - IPC
100 µm (4 thou)
150 µm (6 thou)
200 µm (8 thou)
Force [N]
40
30
20
10
0
0
500
1000
1500
2000
Cycles

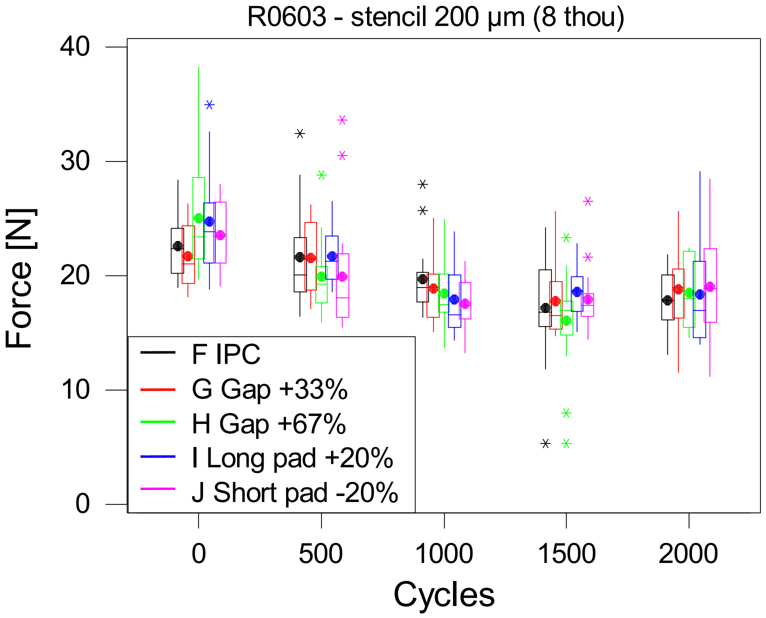

R1206 - stencil 100 µm (4 thou)
Force [N]
100
90
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
Cycles
A IPC
B Gap +33%
C Gap +67%
D Long pad +20%
E Short pad -20%


R1206 - stencil 150 µm (6 thou)
Force [N]
100
90
80
70
60
50
40
30
20
10
0
0
500
1000
1500
2000
Cycles
A IPC
B Gap +33%
C Gap +67%
D Long pad +20%
E Short pad -20%


R1206 - stencil 200 µm (8 thou)
Force [N]
Cycles
0
10
20
30
40
50
60
70
80
90
100
0
500
1000
1500
2000
A IPC
B Gap +33%
C Gap +67%
D Long pad +20%
E Short pad -20%


R0603 - stencil 100 µm (4 thou)
Force [N]
Cycles
0
10
20
30
40
0
500
1000
1500
2000
F IPC
G Gap +33%
H Gap +67%
I Long pad +20%
J Short pad -20%


R0603 - stencil 150 µm (6 thou)
Force [N]
40
30
20
10
0
0
500
1000
1500
2000
Cycles
F IPC
G Gap +33%
H Gap +67%
I Long pad +20%
J Short pad -20%


R0603 - stencil 200 µm (8 thou)
Force [N]
40
30
20
10
0
0
500
1000
1500
2000
Cycles
F IPC
G Gap +33%
H Gap +67%
I Long pad +20%
J Short pad -20%

APPENDIX 2

It is self evident that multiple regression analysis is only applied when there is a trend. For the data looking at solderability and pad design, it is not clear whether such a trend exists. Hence to establish if there is a statistically significant difference the t-test is used. But firstly the F-test is run to establish whether to use the equal variance or pooled variance t-test.

The results of the statistical analysis are given in Table A2.1 and A2.2 for the 1206 and 0603 respectively. Within each table the Age 1 and Age 2 are compared with the Age 0 zero data.

In both Table A2.1 and A2.2 the first two columns list age group and cycle number for the shear test result. The third column shows the p-value of the variance F-test, if this is less than 0.05 the variance are different. Column 4 indicates this result. If the variance test results as "variance equal" the final t-test is two-sample t-test with equal variances. If the variance test results as "variance different" the final two-sample t-test is with pooled variance. The result of statistical test is a p-value. If the p-value is smaller than 0.05 the test is confirming that there is no statistical difference between tested sample sets (null hypothesis). If the p-value is bigger than 0.05 the tested sample groups are not statistically different with confidence limit of 95%. Inspection of the p value results of the two sample t-tests prove that there is no statistical significance (measurable difference) in the shear strength of solder joints from the three aged groups of both sizes of resistors. The differences observed for the 1206 are isolated and insufficient to construct a regression analysis.

Table A2.1: Results of F-test and t-test for aged 1206 resistors

		F-test for Variance		Two sample t-test	
Set 1_cycle	Set 2_cycle	F-p	Variance test	p	Difference? test
Age 0_0	Age 1_0	0.035	Different	0.713	No
Age 0_500	Age 1_500	0.29	Equal	0.907	No
Age 0_1000	Age 1_1000	0.204	Equal	0.107	No
Age 0_1500	Age 1_1500	0.237	Equal	0.255	No
Age 0_2000	Age 1_2000	0.432	Equal	0.116	No
Set 1_cycle	Set 2_cycle	F-p	Variance test	p	Difference? test
Age 0_0	Age 2_0	0.577	Equal	0.983	No
Age 0_500	Age 2_500	0.233	Equal	0.037	Yes
Age 0_1000	Age 2_1000	0.864	Equal	0.477	No
Age 0_1500	Age 2_1500	0.855	Equal	0.282	No
Age 0_2000	Age 2_2000	0.448	Equal	0.665	No
Set 1_cycle	Set 2_cycle	F-p	Variance test	p	Difference? test
Age 1_0	Age 2_0	0.113	Equal	0.662	No
Age 1_500	Age 2_500	0.887	Equal	0.045	Yes
Age 1_1000	Age 2_1000	0.271	Equal	0.016	Yes
Age 1_1500	Age 2_1500	0.315	Equal	0.95	No
Age 1_2000	Age 2_2000	0.137	Equal	0.39	No

Table A2.2: Results of t-test for 0603 resistors

		F-test for Variance		Two sample t-test	
Set 1_cycle	Set 2_cycle	F-p	Variance test	p	Difference? test
Age 0_0	Age 1_0	0.051	Equal	0.066	No
Age 0_500	Age 1_500	0.609	Equal	0.267	No
Age 0_1000	Age 1_1000	0.729	Equal	0.127	No
Age 0_1500	Age 1_1500	0.196	Equal	0.874	No
Age 0_2000	Age 1_2000	0.014	Different	0.354	No

Set 1_cycle	Set 2_cycle	F-p	Variance test	p	Difference? Test
Age 0_0	Age 2_0	0.44	Equal	0.862	No
Age 0_500	Age 2_500	1	Equal	0.69	No
Age 0_1000	Age 2_1000	0.602	Equal	0.776	No
Age 0_1500	Age 2_1500	0.026	Different	0.391	No
Age 0_2000	Age 2_2000	0.56	Equal	0.808	No
Set 1_cycle	Set 2_cycle	F-p	Variance test	p	Difference? test
Age 1_0	Age 2_0	0.009	Different	0.071	No
Age 1_500	Age 2_500	0.624	Equal	0.155	No
Age 1_1000	Age 2_1000	0.391	Equal	0.173	No
Age 1_1500	Age 2_1500	0.35	Equal	0.52	No
Age 1_2000	Age 2_2000	0.054	Equal	0.289	No

As seen in Table A2.3 there are results of the statistical analysis are given 1206 resistors designs A and B. The results of the tests are showing no statistical difference between A and B designs with 150 µm stencil. Based on the plots in Appendix 1 there is no evidence that other pad designs combinations show any difference.

Table A2.3: Results of t-test for 1206 resistors designs A and design B (150 µm stencil)

Design_cycle	Design_cycle	F, p-value	Variance test	p-value	Difference? test
A0	B0	0.933	Equal	0.531	No
A500	B500	0.147	Equal	0.921	No
A1000	B1000	0.823	Equal	0.936	No
A1500	B1500	0.664	Equal	0.818	No
A2000	B2000	0.276	Equal	0.557	No

APPENDIX 3

Regression Analysis: Force [N] versus Cycles, Stencil, Component size

Below is the output from the statistical software package.

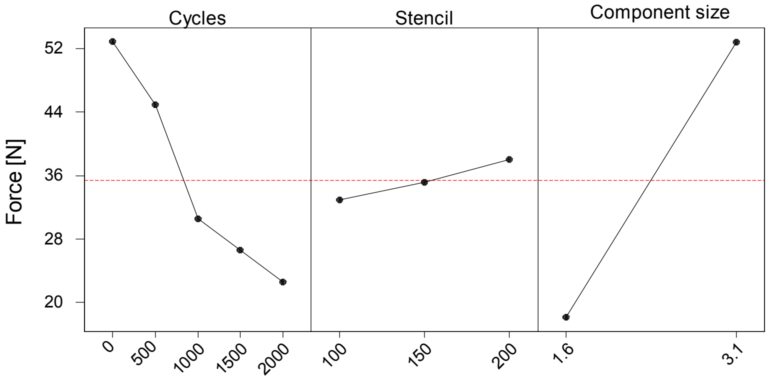
```
The regression equation is
Force [N] = - 10.8 - 0.0159*Cycles + 0.0525*Stencil + 23.2*Component size

Predictor        Coef     SE Coef          T        P       VIF
Constant      -10.836       2.906      -3.73    0.000
Cycles     -0.0159153   0.0008010     -19.87    0.000       1.0
Stencil       0.05253     0.01388       3.78    0.000       1.0
Component size23.1821      0.7552      30.70    0.000       1.0

S = 12.32              R-Sq = 74.1%         R-Sq(adj) = 74.0%
PRESS = 72492.9        R-Sq(pred) = 73.63%

Analysis of Variance

Source            DF          SS          MS         F         P
Regression         3      203795       67932    447.75    0.000
Residual Error   469       71155         152
  Lack of Fit     26       49612        1908     39.24    0.000
  Pure Error     443       21543          49
Total            472      274951


Durbin-Watson statistic = 0.64

Lack of fit test
Possible curvature in variable Cycles (P-Value = 0.000)
Possible interactions with variable Cycles (P-Value = 0.000)
Possible curvature in variable Component size (P-Value = 0.000)
Possible interactions with variable Component size (P-Value = 0.000)
Possible lack of fit at outer X-values       (P-Value = 0.000)
Overall lack of fit test is significant at P = 0.000
```

General Linear Model: Force [N] versus Cycles, Stencil, Component size

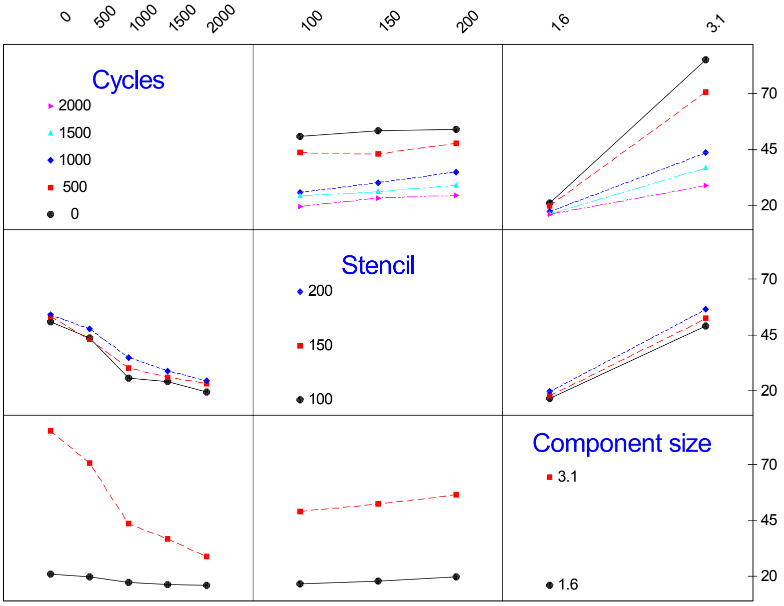
```
Factor              Type   Levels Values
Cycles              fixed      5  0  500 1000 1500 2000
Stencil             fixed      3  100 150 200
Component size      fixed      2  1.6 3.1

Analysis of Variance for Force [N, using Adjusted SS for Tests

Source              DF     Seq SS     Adj SS     Adj MS     F       P
Cycles              4      62403      63783      15946  110.26  0.000
Stencil             2       2147       2251       1125    7.78  0.000
Component size      1     143155     143155     143155  989.91  0.000
Error               465    67246      67246        145
Total               472   274951
```

APPENDIX 4

This appendix contains two plots, the Main Effects and the Interaction Plot. The Main Effects plot shows the response of each variable, as shown by the push off force, with the other variables held at its average value. This clearly shows the smaller effect of stencil thickness.


Main Effects Plot - Data Means for Force [N]

The Interaction Plot shows the response between the different variables. The data in any one cell is the response from the intersecting labelled cell. Hence the middle cell on the top row is the interaction between "cycles" and "stencil", and so on for the other cells. This plot shows there is a strong interaction between "cycles" and "component size", but a weak interaction between "stencil" and "component size".


Interaction Plot - Data Means for Force [N]