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Reliability of Joints Formed with Mixed Alloy Solders

Alan Brewin, Christopher Hunt .
Milos Dusek & Jaspal Nottay

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Alan Brewin, Christopher Hunt, Milos Dusek & Jaspal Nottay
Materials Centre
National Physical Laboratory
Teddington, Middlesex
UK. TW11 0LW

ABSTRACT

The introduction of lead-free solders into the re-work arena will potentially involve the mixing of a wide variety of alloys in the resulting joints. This report investigates the effect on joint reliability of mixing alloys likely to be used in production and rework during the transition to lead-free soldering technologies.. SnPb, SnPbAg, SnCu, SnAgCu and SnAgBiCu alloys were used in a range of mixtures to make surface mount joints. The reliability of the joints was assessed using thermal cycling with continuity monitoring, and shear testing.

The continuity data is fitted to a Weibull distribution and ‘first failure’ reliability is defined as the number of thermal cycles at which 1% of the population of solder joints tested has failed (equivalent of first joint failure on a board of 100 solder joints). The results indicate that when solder alloys are mixed the resultant joints exhibit a general improvement in first failure reliability as compared with those soldered using the single alloys. This finding suggests that concerns about mixing of alloys in rework situations, may be unfounded.

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National Physical Laboratory
Teddington, Middlesex, UK. TW11 0LW

Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Materials Centre

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1 INTRODUCTION

The impending introduction of lead-free solders across the printed circuit assembly arena is likely to be relatively un-harmonized, with different manufacturers using different alternative alloys. Thus for those reworking parts of a circuit board the assumption that the joint was made from tin-lead alloy can no longer be made.

In consequence, where sub-assemblies are manufactured at various locations, and possibly reworked or repaired with alternative solders, the possibility of creating solder mixtures has significantly increased. The consequence of creating alloys differing from the original specification will be that new phases and intermetallics may be formed that may enhance or degrade solder joint reliability.

This report investigates the effect on joint reliability of mixing alloys likely to be used in production and rework during the transition to lead-free soldering technologies.

2 EXPERIMENTAL

The manufacture of the test boards was performed using the procedure outlined in report MATC(A) 73 [1]. There were five different solder alloys used in the experiment in combinations of two lead-based solders and three lead-free solders. Table 1 lists the alloys together and their melting points.

Table 1: Solder alloy description

Solder	Composition	Melting Point (^{o}C)
A	63.1Sn/36.9Pb	183
B	95.8Sn/3.5Ag/0.7Cu	217
C	93.3Sn/3.7Ag/2.1 Bi/0.8 Cu	210
D	99.3Sn/ 0.7Cu	227
E	63Sn/37Pb/2Ag	~179

Table 2 outlines the matrix of solder mixtures used in the study; half the Table is blanked out as it simply repeats diagonally the bottom half. The occurrence of 5 in a cell indicates that 5 assemblies were built of this combination.

Table 2: Solder alloy combinations

(%)	**ID**	A 25	A 50	A 75	B 25	B 50	B 75	C 25	C 50	C 75	D 25	D 50	D 75	E 0	D 0
SnPb	A														
SnAgCu	B	**5**	**5**	**5**											
SnAgBiCu	C	**5**	**5**	**5**	**5**	**5**	**5**								
SnCu	D	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**					**5**
SnPbAg	E			**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	

Thermal cycling and continuity data collection were undertaken using the method described in NPL Code of Practice 49 – ‘Compatibility of Lead-free Solders with PCB Materials’ [2]. Continuity data were collected for the 2512 chip resistors, the SOIC components and TH-resistors.

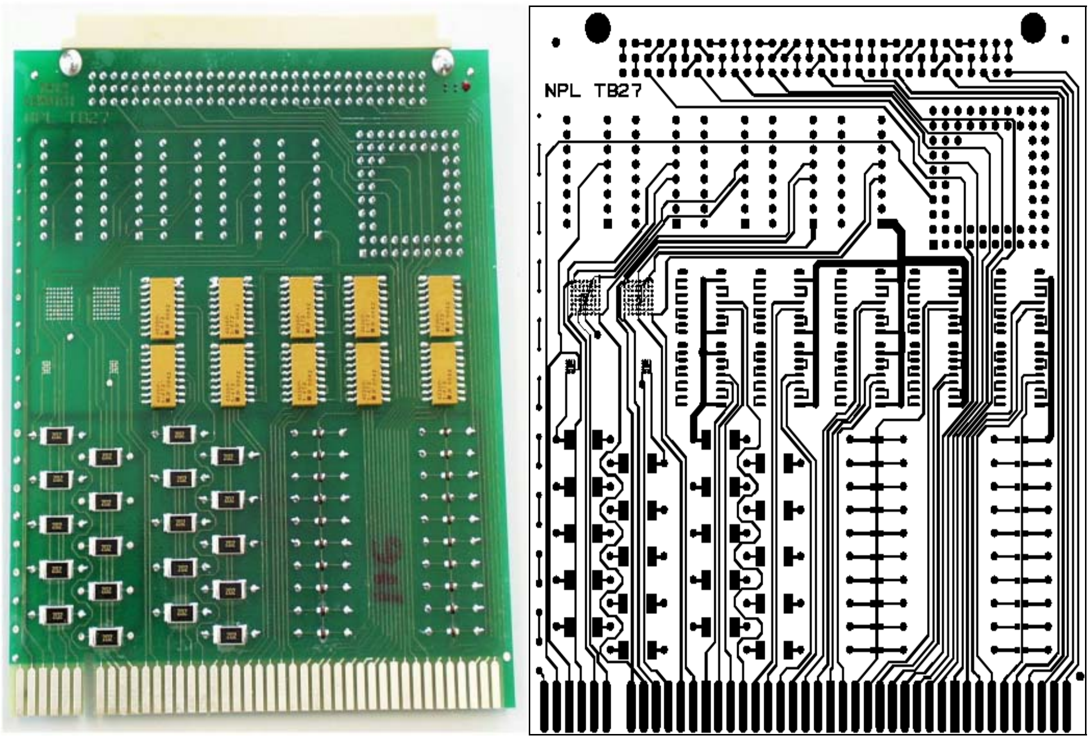


Figure 1. Test PCB layout and design

3 RESULTS

3.1 Continuity Data

There were no continuity failures detected for any of the SOIC or TH resistor joints, hence the data below are for the 2512 chip resistors only.

The work was intended to follow a previous reliability study [3] utilising the data collected on solder alloys as references. Processing issues have meant that the test boards, although identical in design and surface finish, have behaved like separate batches. The data collected from the two experimental runs cannot be directly compared with the result that only data for the single alloys SnCu and SnPbAg are available.

Table 3. Results for Thermal Cycling Continuity Testing

Alloy 1	%	Alloy 2	%	Beta	Nf62.3	Nf/Beta	Cycles to 1% Faliure
SnAgBiCu	25	SnAgCu	75	2.8	1876	678.25	356
SnAgBiCu	50	SnAgCu	50	2.0	3635	1817.38	364
SnAgBiCu	75	SnAgCu	25	2.2	3067	1371.39	392
SnAgBiCu	25	SnPb	75	3.7	1378	376.62	392
SnAgBiCu	50	SnPb	50	4.6	2139	467.94	782
SnAgBiCu	75	SnPb	25	1.7	4020	2423.72	251
SnAgCu	25	SnPb	75	4.2	1920	461.94	635
SnAgCu	50	SnPb	50	3.2	2025	642.76	470
SnAgCu	75	SnPb	25	3.1	1457	463.67	337
SnAgPb	25	SnAgCu	75	4.4	2126	482.71	748
SnAgPb	50	SnAgCu	50	4.0	2349	587.23	744
SnAgPb	75	SnAgCu	25	4.0	2215	553.73	701
SnCu	25	SnAgBiCu	75	1.3	2138	1609.44	67
SnCu	50	SnAgBiCu	50	2.3	1671	718.17	231
SnCu	75	SnAgBiCu	25	4.9	1338	275.47	519
SnCu	25	SnAgCu	75	3.2	1253	391.68	297
SnCu	50	SnAgCu	50	3.7	1366	368.39	395
SnCu	75	SnAgCu	25	4.6	1255	274.20	460
SnCu	25	SnPb	75	1.9	2693	1427.14	235
SnCu	50	SnPb	50	3.1	1443	470.24	322
SnCu	75	SnPb	25	2.5	1059	418.33	172
SnPbAg	25	SnAgBiCu	75	2.4	2394	1010.53	344
SnPbAg	50	SnAgBiCu	50	4.0	2535	633.84	803
SnPbAg	75	SnAgBiCu	25	4.0	2596	648.95	822
SnPbAg	25	SnCu	75	2.8	1820	643.43	358
SnPbAg	50	SnCu	50	2.9	2909	1017.61	582
SnPbAg	75	SnCu	25	4.4	2555	576.71	905
		SnCu	100	2.5	952	380.99	151
		SnPbAg	100	1.2	3491	2985.05	68

3.2 Joint Shear Strength Data

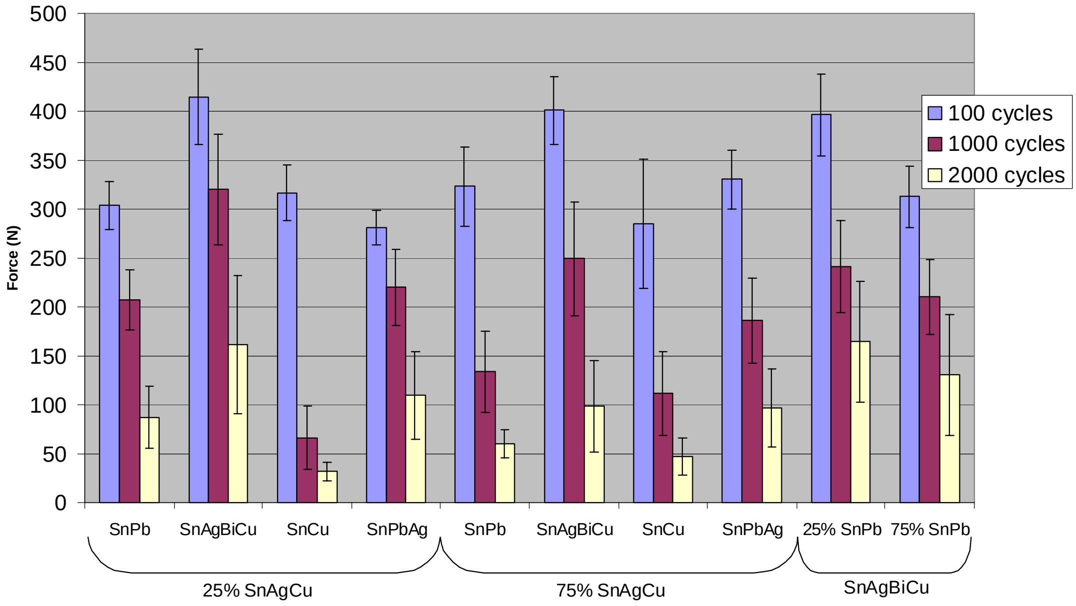


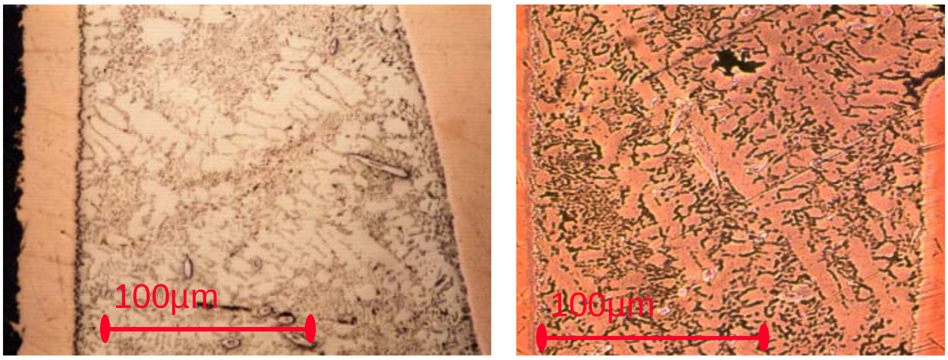
Figure 2. Ultimate Joint Shear Strength Data

The ultimate shear strength (USS) results for the alloy mixtures tested are shown in Figure 2. The approach is from the point of view of reworking a joint, (originally made from SnPb, SnAgBiCu, SnCu or SnPbAg) with SnAgCu (SAC) alloy solder wire. The main point to note is the poor performance for SnCu-containing alloys after only 1000 cycles, indicating the poor performance of SnCu solder joints reworked with SnAgCu solder.

In addition the bismuth-containing joints show an improved USS over similar joints after rework with the tertiary SAC alloy after all levels of cycling.

3.3 Joint Sectioning

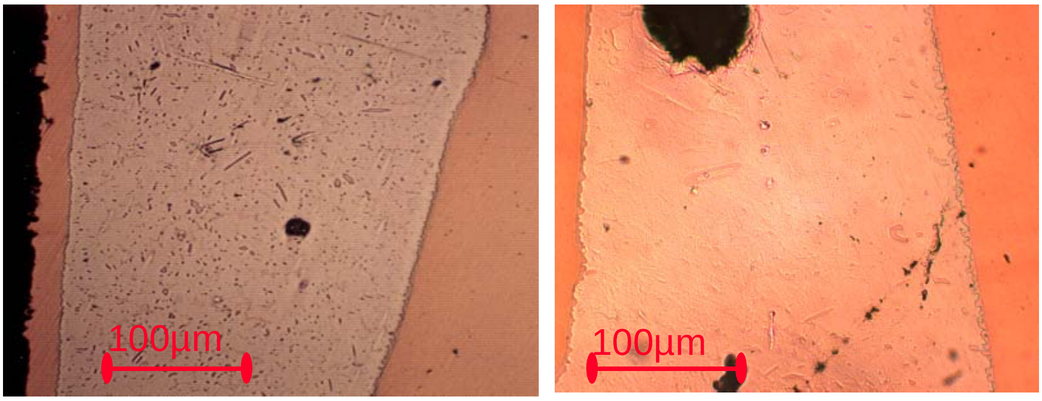
Generally there was a coarsening of the microstructure as the joints were thermally cycled. This is illustrated in Figure 3.



100 Cycles 1000 Cycles

Figure 3. Coarsening of microstructure with cycling, 25% SnAgCu, 75% SnPb

The thermal cycling did not change the amounts or types of intermetallic phases present. For example Cu_6Sn_5 and Ag_3Sn intermetallic phases were present in both 100 and 1000 cycled (25% SnAgCu, 75% SnPb) through-hole joints (Figure 4).



100 Cycles 1000 Cycles

Figure 4. Cu_6Sn_5 and Ag_3Sn phases in 25% SnAgCu, 75% SnPb through-hole joints

The SM joints with Bi present in the mixture were sometimes found to behave in a brittle manner, with failure at the interface with the component termination (Figure 5). Those with increasing levels of Pb behaved in a ductile manner, with crack propagation within the bulk of the joint (Figure 6).

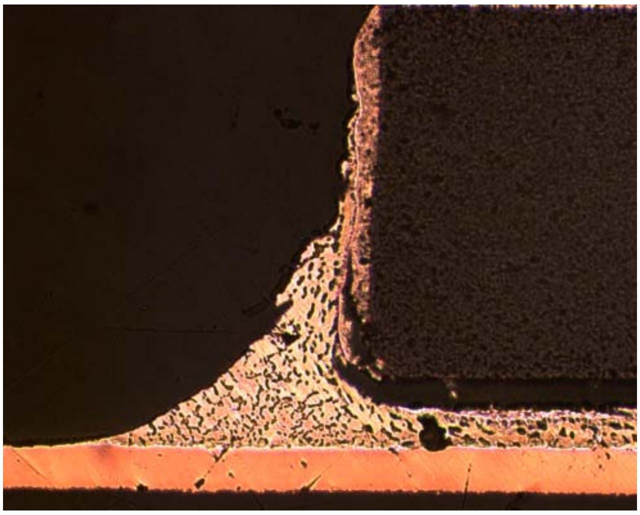


Figure 5. 25% SnAgBiCu/75% SnPb cracking at SM joint/component interface

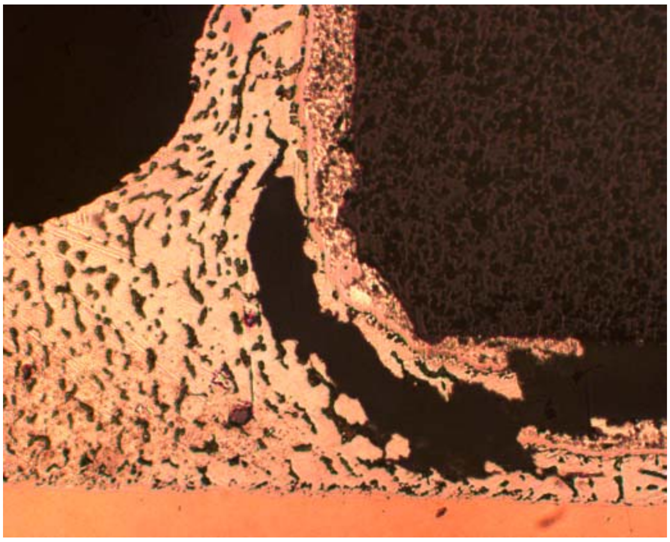


Figure 6. 25% SnAgCu/ 75% SnPb SM joint cracking within joint bulk

With alloy mixtures solidification may take place over wider range of temperatur than with the eutectic alloys. This involves partial solidification as the joints form in separate phases, increasing the risk if fillet lifting. Fillet tearing was observed on through hole joints of the following alloy mixtures:

- 25% SnPbAg/ 75% SnAgCu
- 75% SnAgBiCu/ 25% SnPb
- 25% SnAgCu/ 75% SnPb

All the fillet tearing defects were benign and did not impact on joint continuity.

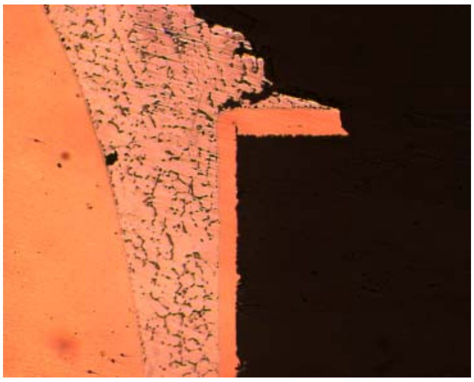


Figure 7. 25% SnPbAg/ 75% SnAgCu TH joint, fillet tearing

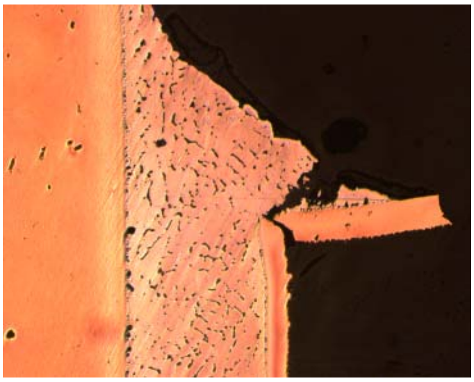


Figure 8. 75% SnAgBiCu/ 25% SnPb TH joint, fillet lifting, and evidence of pad lifting

Figure 8, shows the potentially serious failure mechanism of pad lifting. If this occurs at the connection to a trace, continuity will be broken, and failure will be deemed to have occurred. Figure 9 illustrates the more benign fillet tearing mechanism.

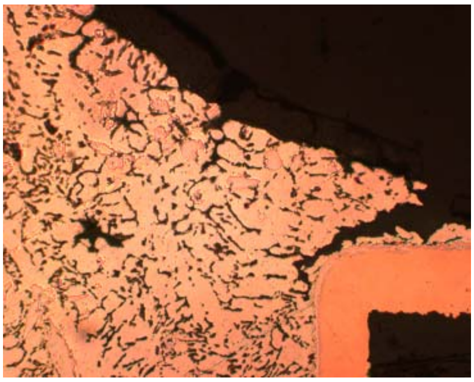


Figure 9. 25% SnAgCu/ 75% SnPb TH joint, fillet lifting

4 DISCUSSION

4.1 Weibull Distribution – N_f(62.3%), Beta and 1% Failure

The failure rate with time data is fitted to the Weibull distribution model to obtain the values given in Section 3. To help visualise the significance of the N_f and Beta values it is useful to look at the shape of representative Weibull distribution curves (Figure 10).

N_f, or the 'characteristic number of cycles to failure' is the number of thermal cycles needed to cause 62.3% of the solder joints to fail. It is commonly quoted as a measure of the relative solder joint reliability.

Beta is the gradient of the curve at the N_f point. A larger Beta (high gradient) essentially means that failures occur within a smaller range of cycles. A lower Beta indicates that failures occur over a wider range.

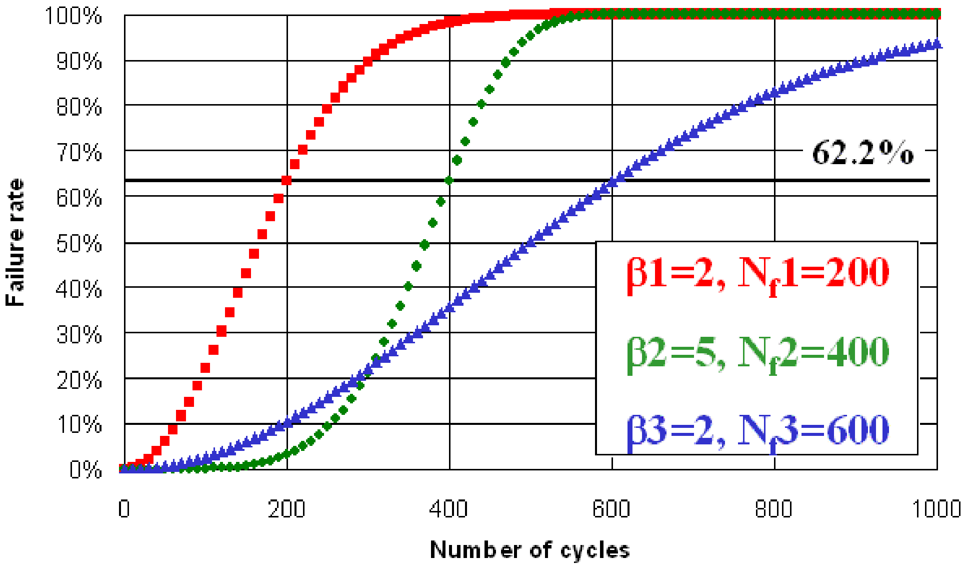
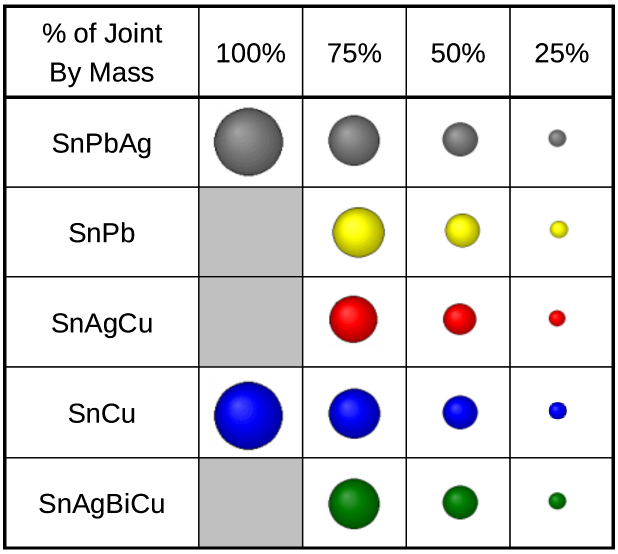


Figure 10. Weibull distributions for example N_f and Beta values.

It only takes one solder joint to fail for an electronic device to malfunction or stop working all together. For the end user of an electronic product, therefore, the values of N_f and Beta are less important than the number of cycles needed to produce just one joint failure. This point was highlighted by the NPL's MPM Industrial Advisory Group, consisting of industry members.

For this reason the continuity data for each alloy mix are fitted to a Weibull distribution and 'first failure performance' (FFP) is defined as the number of thermal cycles at which 1% of the population of solder joints tested has failed (arbitrarily chosen as the equivalent of a first joint failure on a board of 100 solder joints). Data are plotted in the following figures using N_f and the number of cycles to 1% failure, rather than Beta.

The spheres used in the following plots to represent alloys mixtures are colour and size coded as follows:



% of Joint By Mass	100%	75%	50%	25%
SnPbAg	●	●	●	●
SnPb		●	●	●
SnAgCu		●	●	●
SnCu	●	●	●	●
SnAgBiCu		●	●	●

Figure 11. Legend for rework reliability plots.

Although mixing solder pastes prior to reflow created the alloys mixes, the results are grouped according to the rework scenario for each wire type. This makes the data easier to apply practice. The diagrams are shaded to illustrate the area of best performance (high 1% performance and high N_f i.e. top right).

4.2 Additions of Tin/Lead (modelling use of SnPb solder wire)

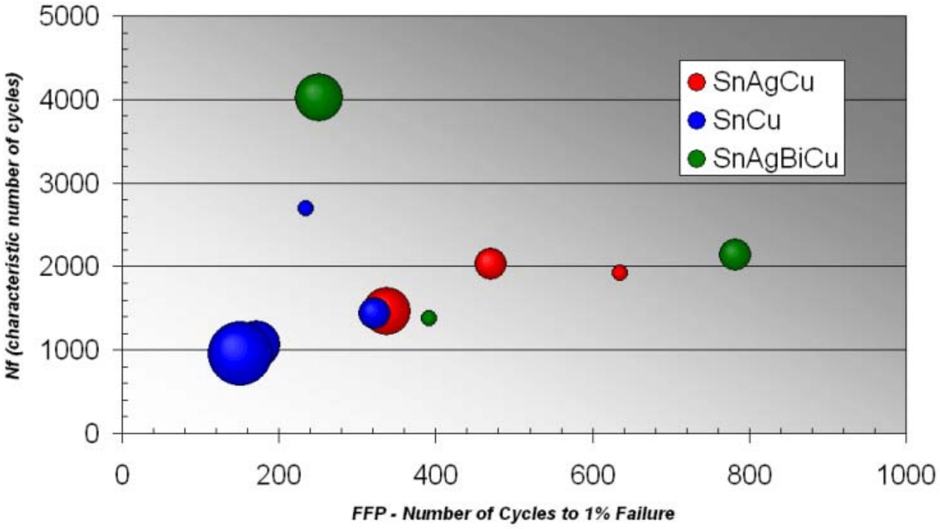


Figure 12. Effects of addition of Tin/Lead

An increase in the amount of SnPb in a SnAgCu or SnCu joint can be seen to increase the FFP without a significant effect on N_f. Whilst additions to the bismuth alloy decreases the N_f of the joint.

4.3 Additions of Tin/Lead/Silver (modelling use of SnPbAg solder wire)

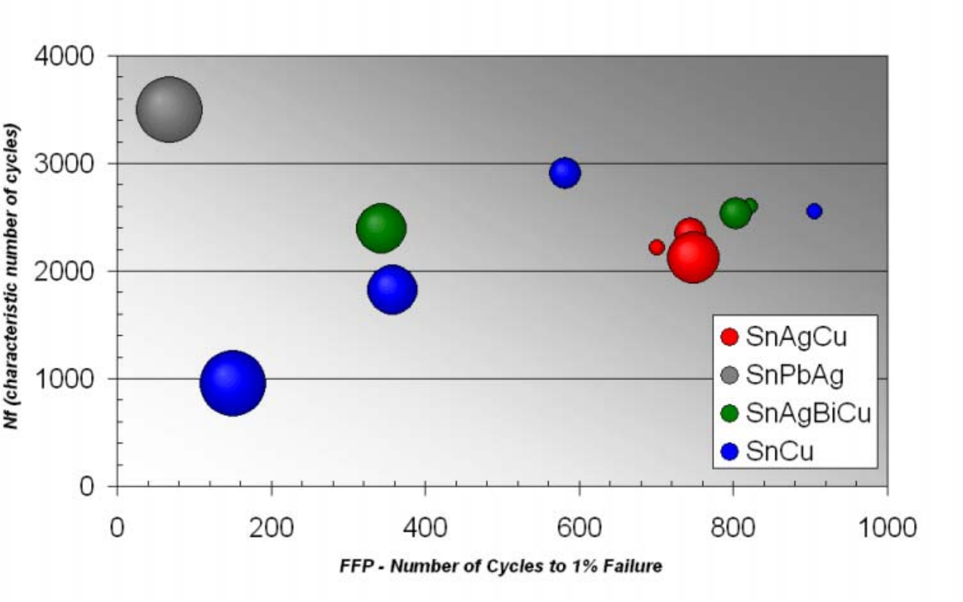


Figure 13. Effects of addition of Tin/Lead/Silver

Addition of SnPbAg to SnCu and SnAgBiCu increases the FFP of the alloy mixture. Additions of SnPbAg to SAC alloy improve the FFP drastically. It can be noted that the single SnPbAg and SnCu alloys exhibit the earliest no cycles to 1% failure.

4.4 Additions of Tin/Silver/Copper (modelling use of SnAgCu solder wire)

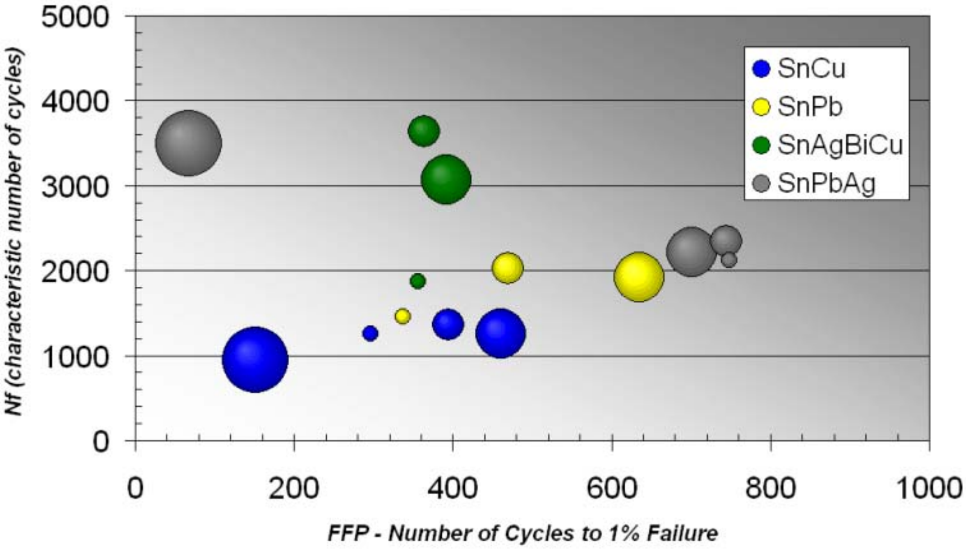


Figure 14. Effects of rework for a Tin/Silver/Copper Joint

Mixtures of the SAC alloy with SnPbAg shows a very good FFP (over 700 cycles) compared to pure SnPbAg (68 cycles). The mixing of SAC with SnAgBiCu in any amount results in around 400 cycles to 1% failure, despite variation in the N_f performance of the joints. SAC with SnPb mixtures all have an N_f of around 2000 cycles, but first FFP increases with the amount of lead-containing alloy present.

Addition of SAC to SnCu at 25% increases the no. cycles to 1%, failure in relation to the single SnCu alloy (from 151 to 460 cycles). Further additions whilst not effecting N_f result in a decrease in FFP (back to 297 cycles).

4.5 Additions of Tin/Silver/Copper/Bismuth (modelling use of SnAgBiCu solder wire)

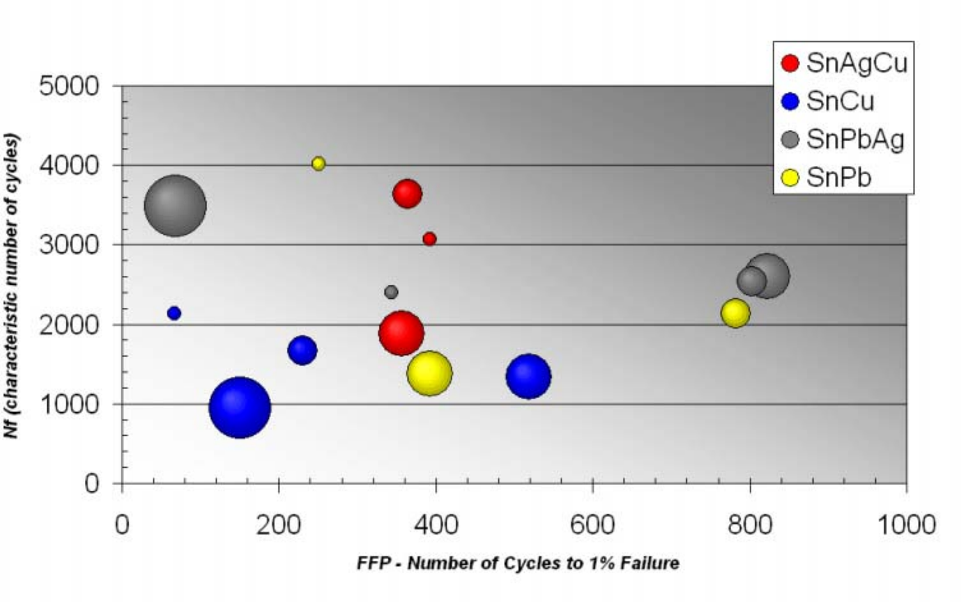


Figure 15. Effects of rework for a Tin/Silver/Copper/Bismuth Joint

Mixtures with SAC all produce a FFP of around 400 cycles. The addition to SnCu at 25% increases with FFP from 151 cycles up to over 500. Further additions of SnAgBiCu decreases the number of cycles to 1% failure right down to only 67 cycles for a composition with 75% of the bismuth-containing alloy.

Similar trends are seen with the SnPbAg alloy, although when it is mixed with the SnAgBiCu provides better FFP than the single SnPbAg alloy results in all cases.

4.6 Additions of Tin/Copper Joint (modelling use of SnCu solder wire)

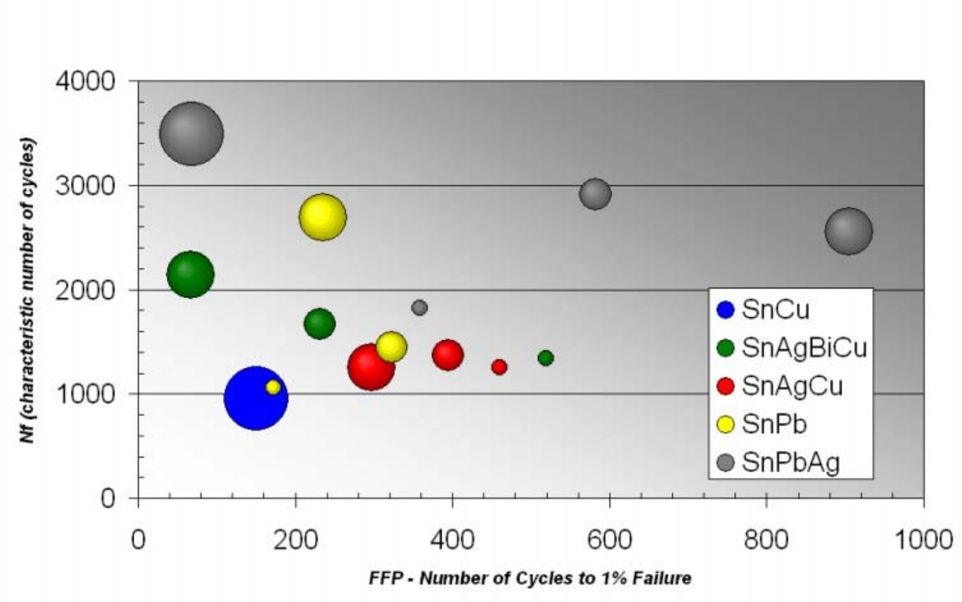


Figure 16. Effects of rework for a Tin/Copper Joint

The addition of SnCu to other alloys to is generally shown to improve FFP, whilst decreasing or having a negligible effect on N_f. Again the mixture with 75% of the bismuth-containing alloy stands out, exhibiting a very low FFP of only 67.

4.7 Trends and the formation intermetallic compounds

Although it is difficult to identify universal trends for any of the mixtures, in defined regions some trends are apparent. Groupings can be identified using N_f data, but trends are seen more clearly in the 1% failure data.

In general, the alloy mixtures do not show poor N_f or first failure performance. This may be explained by the fact that mixtures will produce precipitates within the joint that may impart structure and strength. The chosen alloys themselves of eutectic composition in order to minimise the ‘pasty range’ of the alloy during reflow, not because a eutectic alloy has any particular advantages in reliability.

There are clear trends to be seen as the ratio of the alloys in mixtures is changed (an example is shown by the full red line in Figure 17). The single alloys often do not appear where predicted by the trend (as represented by dotted line). This can be explained by the fact that the variation in FFP is due to changing amounts of intermetallic precipitate in the mixtures that impart additional structure and strength to the solidified joint (for example $AgSn_3$, seen in the micro-sections, see Section 3.3). The single alloy itself will not produce any of the intermetallic in joints, and so the microstructure is very different, leading to the behaviour seen in the above diagrams.

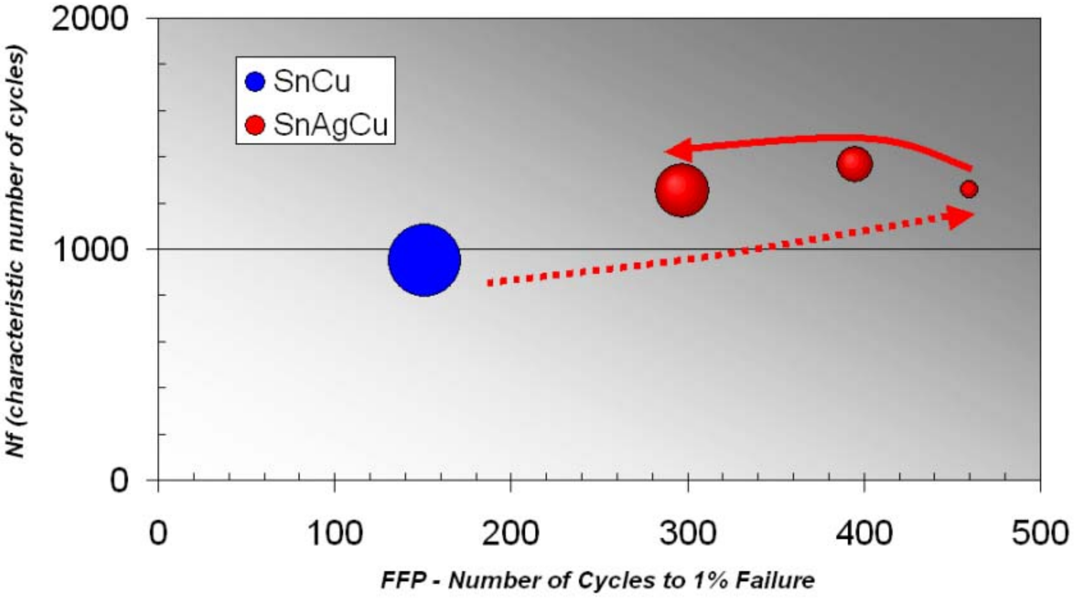


Figure 17. Trend for mixing of SnAgCu into SnCu

4.8 Confidence if FFP data

Confidence in the data collected during the first cycles is better than for later cycles. This is due to a decreasing joint population effectively under test as joints fail, represented in Figure 18.

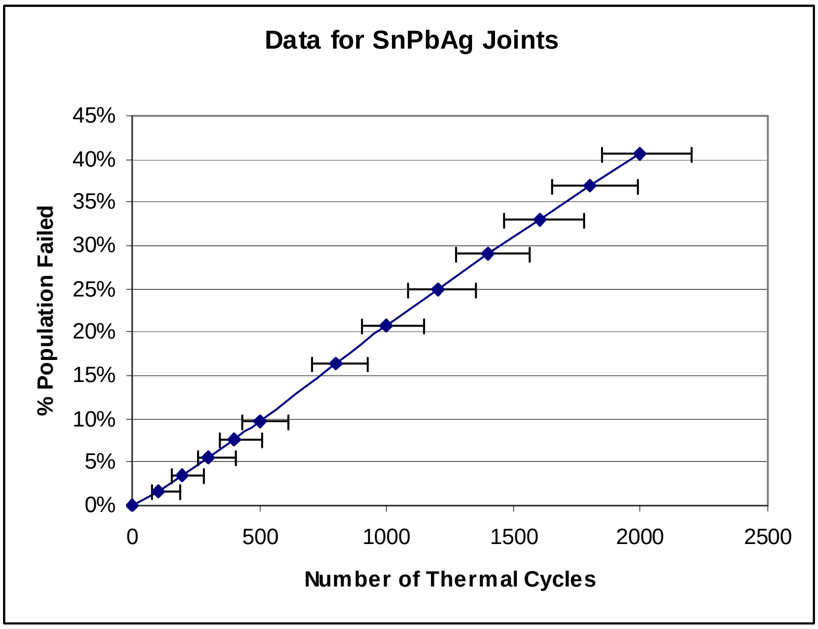


Figure 18. Error bars showing standard deviation on joint failure data

The data in this report is all based upon 2512 resistor solder joints representing a high strain environment for the solder. Previous studies have shown that the lead-free solder alloys (SnAgCu, SnAgBiCu) perform best in low-strain environments. This reinforces the conclusion that mixing alloys in rework will not compromise reliability.

4.9 Correlation between Continuity and Shear Data

Shear testing is quicker and cheaper than continuity testing, and so there is great value in establishing a correlation between ultimate shear strength and reliability from fitting continuity data to the Weibull model.

Figure 19 shows data of N_f against the ultimate shear strength for all the alloys shear tested. Although there is a degree of scatter in the data, a trend can be seen in which alloys with higher cycles to failure exhibit greater shear strengths.

However, a different behaviour is apparent if the USS values are plotted as a function of the FFP (see

Figure **20**). In this case an alloy with a high number of cycles to 1% failure will exhibit lower ultimate shear strength.

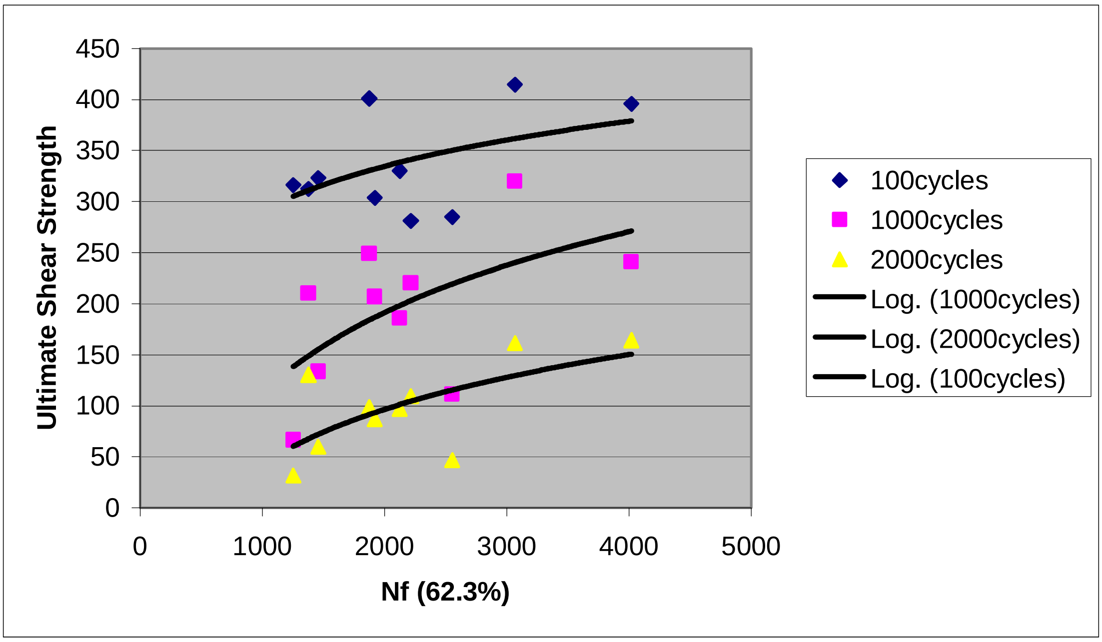


Figure 19. Correlation between N_f and USS

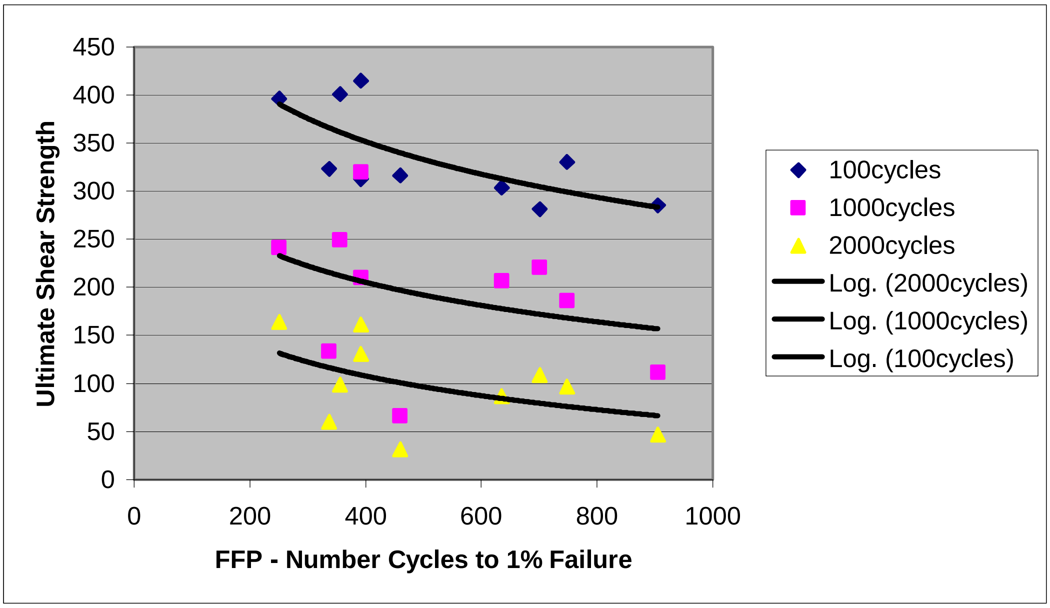


Figure 20. Correlation between FFP and USS

This contrast in behaviour is consistent with the observation that the 1% failure values in Sections 4.2 to 4.6 show different trends and rankings to the N_f values.

5 CONCLUSIONS

- Using the plots in this report the likely effect on reliability of reworking joints with a lead free alloy can be predicted
- In terms of product reliability 1% failure is more relevant than N_f data
- Joints with lower ultimate shear strength will generally give the better first failure performance
- The ranking and trends seen with 1% failure performance do not always match with N_f
- Mixed alloy joints in this study generally gave better or equal first failure performance relative to the original alloys
- There is a potential for increased fillet tearing and pad lifting with alloy mixtures, although the defects proved benign in the NPL study on mixing rework alloys

6 ACKNOLWEDGMENTS

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. NPL Report - MATC(A) 73 ‘Reworking Solder alloy Mixtures of Lead-free and Tin-Lead Alloys’, *Jaspal Nottay, Milos Dusek, Martin Wickham and Christopher Hunt*
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