

Measurement Note

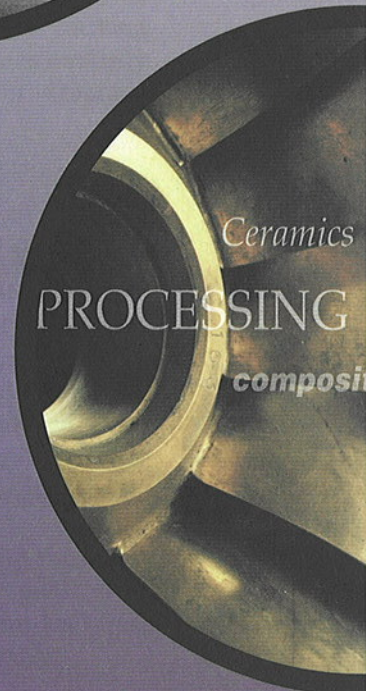
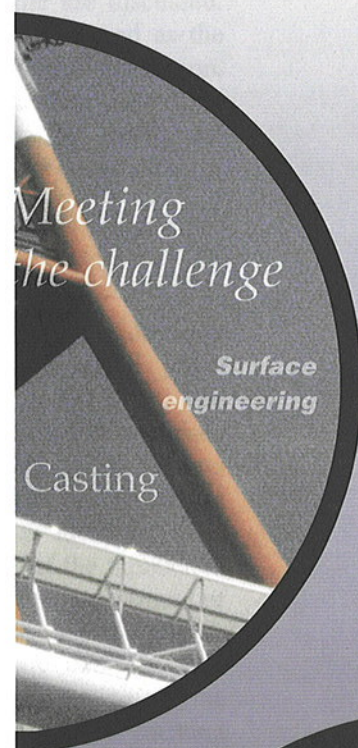
Measurement Note - Shear Strength of Lead-free Solder Joints

SUMMARY

This Note describes the assessment of the reliability of solder joints using accelerated thermal cycling followed by shear strength measurements. It is particularly relevant to the assessment of solder joints assembled using new lead-free solders currently being widely introduced into the electronics manufacturing industry. The test procedures and test requirements are detailed, and the factors influencing the choice of the thermal cycling regime are discussed. The work previously reported (1) has been used as the basis for the comments and discussion, especially regarding understanding of the effects of thermal excursions, ramp rates and temperature dwells on the accumulation of damage in the joints.

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1 INTRODUCTION

Electronics assemblies are manufactured from a range of materials each having a different thermal expansion coefficient (TCE). In normal field use these assemblies experience a variety of temperature/power changes (e.g. power consumption; switching equipment on/off; day/night temperature changes), and these TCE mismatches cause strain and stress in solder joints, which creep and relax over time. Such strains can result in crack initiation (usually in the solder joint under the component), subsequent crack propagation through the solder fillet itself, and finally failure of the joint. The resistance to cyclic strains, called cyclic fatigue resistance, is a material property of an alloy and varies with strain range and strain rate (i.e. applied thermal load).

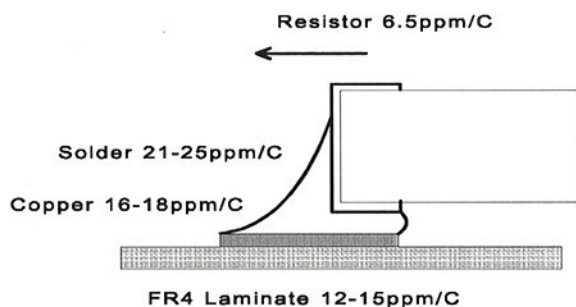


Figure 1: Schematic cross-section of a SM assembly highlighting the CTE mismatches.

In a similar way, deliberately applied thermal cycling also causes cyclic strains, cracks to develop, and weakening of the joint structure by cyclic fatigue. It can therefore be conveniently employed in accelerated testing of solder joints, to assess the joint reliability. Over the past forty years various thermal cycling regimes have been developed and used regularly to assess joints made using lead-based solders (in particular SnPb). For a variety of reasons, however, these may not be appropriate for assessing the performance of lead-free solders (1, 2) currently being introduced into the electronics manufacturing industry. Consequently, recent work focused (1) on evaluating a number of thermal cycling regimes with respect to their applicability for assessing the reliability of joints made using lead-free solders.

This Measurement Note describes the assessment of the reliability of lead-free solder joints using accelerated thermal cycling followed by shear strength measurements. The test procedures and test requirements are detailed, and the factors influencing the choice of the thermal cycling regime are discussed. The previous work (1) has been used as the basis for the comments and discussion, especially regarding understanding the effects of thermal excursions, ramp rates and temperature dwells on the accumulation of damage in the joints.

2 TEST PROCEDURES

The test procedure is essentially simple using devices, known to provide sensitive joints when soldered, mounted on a test PCB. The latter assembly is then subjected to a chosen thermal cycling regime in order to accumulate damage in the solder joints, and the strength of the joint is measured using a shear test. The results are analysed in terms of the number of cycles undertaken, to provide an assessment of the reliability of the joint. Metallographic micro-sectioning is commonly undertaken to provide complementary data regarding the microstructure, extent and nature of cracking etc. The micro-sections can be conveniently examined optically and/or in a scanning electron microscope.

3 TEST REQUIREMENTS

Components : R1206, R0805, R0603 chip resistors – chosen as frequently used, sensitive structures, most likely to fail first in the field due to high CTE mismatches (see Figure 1), and which also lend themselves to shear tests. The terminations should contain no lead, since small additions of lead are known to alter solder properties such as alloy strength (3, 4).

Substrate Finish Selection : FR4 substrates with the ENIG (immersion gold over electroless nickel) finish - they are lead-free, in common usage and widely available.

Test Assembly Design : an example of a suitable PCB layout for shear testing and micro-sectioning is shown in Figure 2. It contains 13 off each of the three types of chip resistors. The board is single-sided FR4, thickness 1.6 mm, copper thickness of 35 μm (copper plating 1 oz/sq.ft) and an ENIG finish.

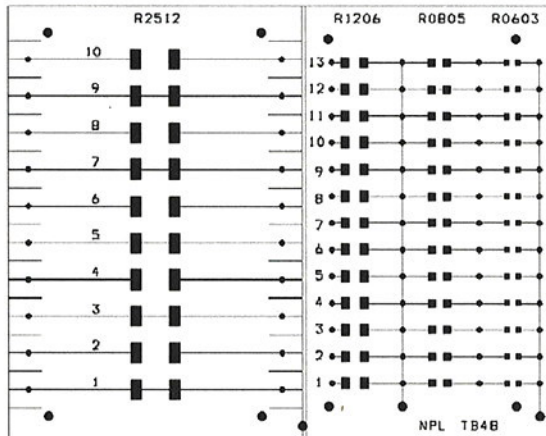


Figure 2: Suggested test board layout (81 $\times$ 65 $\times$ 1.6 mm)

Board Assembly : substrates should be printed with solder paste using a stainless steel stencil with a thickness of 150 μm (0.006"). Two pastes have been found suitable and give broadly similar results (1) for all the six cycling regimes described here i.e. SAC (95.5Sn3.8Ag0.7Cu) and 96.5Sn3.5Ag. An automatic placement system is more likely to provide consistent solder volumes for each joint, and convection reflow assembly is preferred. Reflow temperature profiles should be measured (1) to ensure that the times above 220 $^{\circ}\text{C}$ and 250 $^{\circ}\text{C}$ are not excessive.

4 POSSIBLE THERMAL CYCLING REGIMES

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. The choice will also depend on the requirements of the industry concerned, test equipment and time

available, and 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). There are a few general pointers (1).

- The greater the temperature range and the larger the number of cycles, the greater the damage experienced by a solder joint. Hence if time is of prime importance the regime should incorporate a wide temperature range and a short cycle period.
- Increasing the dwell time does not significantly alter the damage accumulated in the solder joint, a factor which encourages the use of short dwell times. However, longer dwell times are usually considered (5) to cause more damage as they allow the solder to stress relax to a greater extent.
- Damage accumulation is more sensitive to ramp rates than to the dwell times; a slower ramp rate causes more damage than a longer dwell time.
- A dwell at higher temperatures causes more damage than a similar dwell at lower temperatures.
- Ramp rates $>10^{\circ}\text{C}/\text{min}$ cause less damage per cycle than slower rates.
- Thermal shock can give rise to a type of cracking in the joint that is subtly different than that associated with conventional thermal cycling.

Six commonly used thermal cycling regimes are listed in Table 1, and all six were used in the previous study (1). Figure 3 shows a graphical representation of the thermal cycles.

Table 1: Possible temperature cycling regimes ($\pm 4^\circ\text{C}$ is required)

Cycle	Low temp [$^\circ\text{C}$]	High temp [$^\circ\text{C}$]	Ramp [$^\circ\text{C}/\text{min}$]	Dwell min	Period 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

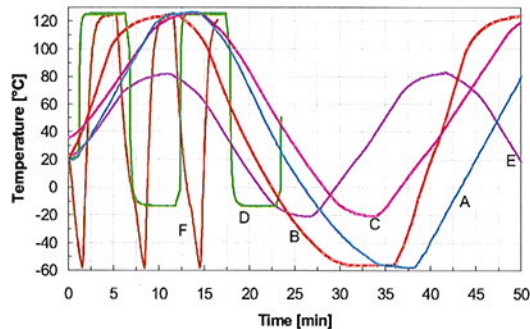


Figure 3: Typical thermal cycling regimes

Cycling Regime A : The common test regime used in military applications - hence it has a wide cycling temperature range (-55°C to 125°C). The ramp rate of $10^\circ\text{C}/\text{min}$ is moderate, but slower than that of a thermal shock regime, which is typically above $20^\circ\text{C}/\text{min}$ (5). The relatively short dwell time of 5 minutes is to minimize the cycle period. In recent years the military and automotive sectors have preferred to use the same cycling regime and this now appears suitable for many, if not all, applications.

Cycling Regime B : A common test regime used in the automotive industry; the wide temperature range reflects under-bonnet uses. The ramp rate of $18^\circ\text{C}/\text{min}$ is just below the thermal shock region. The shorter ramps and the prolonged dwell times mean the overall cycle period is close to that of cycling regime A.

Cycling Regime C : Commonly used in telecoms electronics testing. The ramp rate of $10^\circ\text{C}/\text{min}$ is moderate, safely below that of a thermal shock regime.

Cycling Regime D : Often preferred by the automotive industry - hence the large temperature range. The ramp rate of $65^\circ\text{C}/\text{min}$

is that of a thermal shock regime, and dwell times of 5 minutes gives this a much shorter cycle period than the previous regimes.

Cycling Regime E : A quite benign regime used in consumer electronics testing. The ramp rate of $10^\circ\text{C}/\text{min}$ is moderate. The overall cycle period is intermediate between the short cycles of regimes D and A.

Cycling Regime F : Another example of a thermal shock regime. The damage in solder joints is not caused just by steep temperature ramps but also by the temperature gradient between the substrate and components. This generates stresses, which can highlight short-term manufacturing defects in the electronics.

5 SHEAR TEST

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 4 shows a typical shear test set-up on a Dage Series-4000 modular multi-function bond-tester.

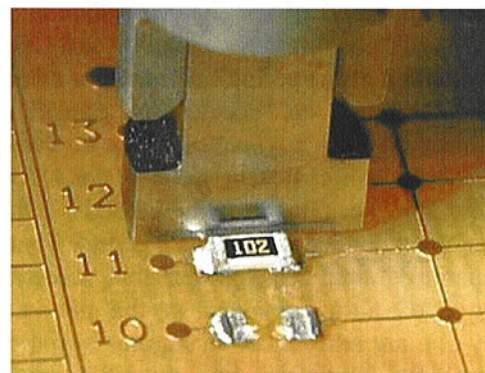


Figure 4: Shear test jig and push-off tool before a shear test

The following steps are useful to assist good shear testing:

- The substrate should be cut into sections suitable for the holding jig, using a water-cooled diamond saw, which produces a clean edge with minimum stress to the board
- The sections should be cleaned using iso-propyl alcohol to remove any contaminant residues from the cutting stage, and then dried using compressed air
- The stand-off height should be set at $h/2$ (typically $80\text{ }\mu\text{m}$) between the bottom of the shear tool and board surface (h is the stand-off height between the component and the board surface). This is the most important test condition
- During each test, the shear tool should be moved forward at an appropriate speed ($200\text{ }\mu\text{m/s}$) against the test component, and the applied force increased until the attachment breaks
- Test data are conveniently analysed in terms of the ultimate shear force (USF) required to rupture the solder joint, and plotted as a function of the number of thermal cycles to which the assembly had been subjected.

Acceleration Effects. A useful method to aid in the comparison of the shear test data is to plot the “acceleration effect” and the “acceleration effect/period” as functions of the cycling regime. The “acceleration effect” is the linear slope approximation of the decrease in USF (in mN/cycle) between 0 and 1200 cycles. The “acceleration effect/period” is the linear slope divided by the cycle period. Some comparative data for chip resistors soldered using SAC alloy, obtained in the previous study (1), are reproduced in Figures 5 and 6. Typical data illustrating how the USF varies, not only with solder type and cycling regime, but also with the size of the component, are presented in Figures 7-9.

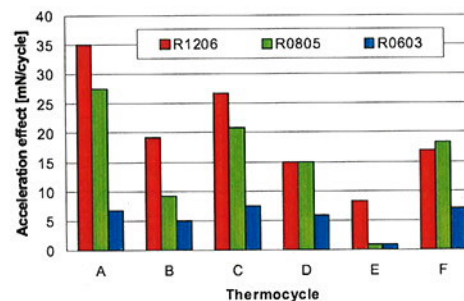


Figure 5: Performance of thermal cycling regimes for SnAgCu solder alloy

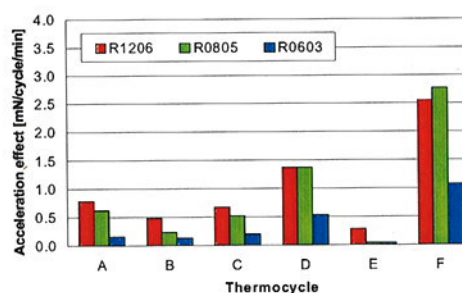


Figure 6: Performance/time of thermal cycling regimes for SnAgCu solder alloy

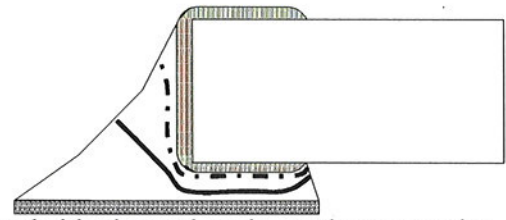
6. CHOICE OF CYCLING REGIME

The choice of cycling regime for accelerated testing of lead-free solders, depends on the industry requirements, but should certainly be a test which reflects the likely service environment.

The cycling regime A (-25 to $+125^{\circ}\text{C}$; ramp rate 10°C/min ; dwell times 5 mins) appears to be suitable for evaluating lead-free solders to be used in most, if not all industrial applications. It not only reflects a severe working environment, but also provides a means of rapid damage accumulation without compromising the failure modes. In the previous work (1) the results from all six cycling regimes exhibited little, if any, differences in the rates of degradation between joints made from SAC or SnAg solders.

Using thermal shocking has the big advantage that damage accumulation in the joint is accumulated about six times faster than in thermal cycling. Hence if test time is a critical factor, test results can be achieved in typically 5-6 days rather than 30-35 days with thermal cycling. However, there is evidence that the

failure modes generated in thermal shocking may be subtly different (1) from those generated in thermal cycling. In particular, the crack propagation paths through the solder fillet exhibit small variations (see Figure 10). For comparative studies this will be of no importance, but if substantive or absolute data are required then the use of thermal cycling conditions is more appropriate. The same is true in those cases where the difference in thermal expansion rates of solder and component are high (e.g. NiFe lead-frame materials).



Probable thermal cycle crack propagation route
 Probable thermal shock crack propagation route

Figure 8 : Probable crack propagation routes

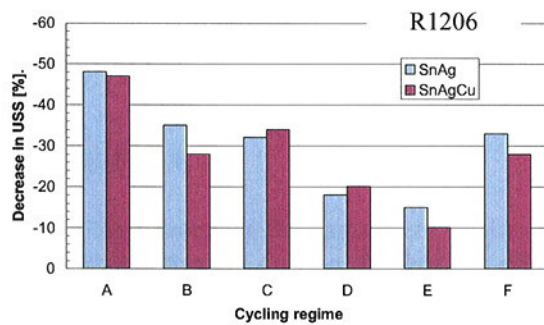


Figure 5 Relative decrease of USS in % after 1200 cycles for 1206 resistors

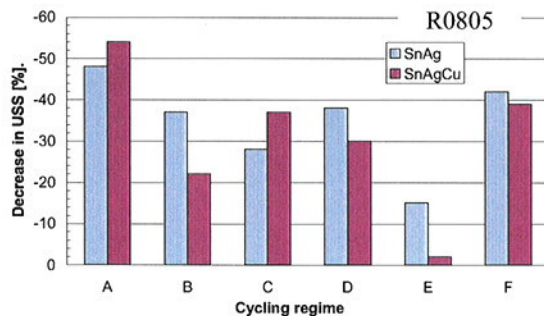


Figure 6 Relative decrease of USS in % after 1200 cycles for 0805 resistors

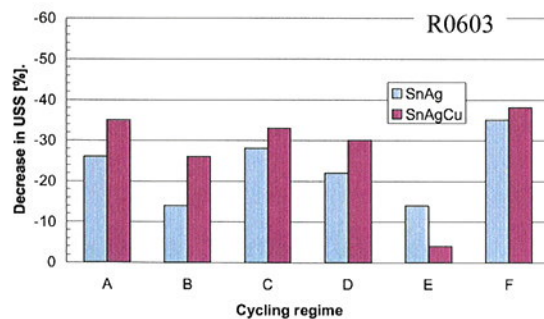


Figure 7 Relative decrease of USS in % after 1200 cycles for 0603 resistors

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