NPL Report CMMT(A)274

Best Practice Guide for Thermocycling and Reliability Assessment of Solder Joints

Miloš Dušek and Christopher Hunt

July 2000

July 2000

Best Practice Guide for Thermocycling and Reliability Assessment of Solder Joints

Miloš Dušek and Christopher Hunt

Centre for Materials Measurement and Technology

National Physical Laboratory

Teddington, Middlesex, UK, TW11 0LW

ABSTRACT:

This guide recommends best practice used for short-term accelerated thermal cycling as a method for assessing solder joint reliability. Three techniques (shear testing, and electrical continuity measurements, complemented with microstructural investigations) are described.

ISSN 1361-4061

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

Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Centre for Materials Measurement and Technology

CONTENTS

1 INTRODUCTION

Thermal cycling accelerates the development of cracks and structural changes that will weaken a solder joint. This failure mechanism can be major source of circuit failures for electronics that have been in the field for some time. Since electronics assemblies are manufactured from various materials with different thermal coefficients of expansion (TCE), shear strains are placed on the various components in the assembly as it is taken through a thermal cycle. Temperature cycling during service induces stresses due to the TCE differences between the mounted component and base substrate. It is a function of the materials used in assemblies that this strain is relieved in the solder joint, which becomes damaged as a consequence of continual cycling. This is shown schematically in Figure 1.

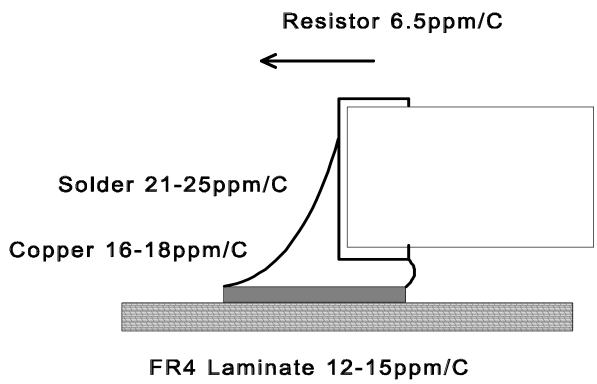

Figure 1. TCE (X-axis) mismatches in SM assemblies

A conventional method for assessing reliability has been to use electrical continuity measurements. Although this method provides a technique in which a large number of joints can be monitored, it is dependent on a complete electrical open circuit occurring before any failure is registered. This can be a severe handicap when over 5000 cycles may be required to reach a failure.

A complementary technique is the measurement of the solder joint strength, which will be a complex function of microstructural damage, and specifically the degree of crack propagation. A method based on shear testing for the evaluation of accelerated thermocycling is one that has been used recently for reliability assessment and lifetime prediction [1].

2 TEST ASSEMBLIES

The key to any reliability assessment of solder joints is the design of the test vehicle and many aspects must be taken into account at this critical design stage.

2.1 DESIGN

The approach to adopt in designing a test vehicle is to eliminate as many variables as possible, so ending up with a closely focused test. The features of this test will then be the solder material, joint geometry, component solderability, or any other experimental parameter that needs to be investigated. The design of a test vehicle is mainly dependent on the materials used for the base substrate, components and solder.

The selection of materials may restrict the number of component types that can be used, since component termination finishes are only available in limited alloys (first elimination stage). The solder and base material selection will mainly influence the reliability over the long-term, whereas the component selection can be far more significant and influence reliability over a much shorter term.

The choice of alloy is commonly associated with reliability over the longer term, as mentioned above. This provides the opportunity to accommodate minor changes, for example variations in solder joint geometry design as a function of pad design.

The physical aspects of components can have a very significant effect on reliability and so dominate the experimental response when assessing reliability. This can be usefully put to advantage so that solder joint failures occur over a wide range of thermal cycles.

2.2 COMPONENT SELECTION

The selection of components should be focused on the so-called “weak links”, using the most vulnerable components. This typically means using ceramic resistors (or capacitors) and BGAs. The gull wing or “J” leaded parts are far more robust due to the compliant nature of the lead.

Components that are commonly used in reliability assessments of solder alloys are briefly discussed below:

Chip resistors: These components are often used, since their rigid alumina bodies have a significantly different TCE from the pcb base material (FR4), and hence are more prone to fail from stress accumulation in the solder joints. The magnitude of this effect is of course dependent on the component size, typically the largest available today is the 2512 type, and it is prudent to complement this choice with more frequently used size of component such as a 0603-type. The other advantage of using SM chip resistors as test devices is the simplicity in joint failure detection. High resistance or an open circuit is easily recognised by direct current measurement (DC). There are currently two different termination finishes commercially available and used as resistor termination materials, Sn and SnPb.

Chip capacitors: The use of chip capacitors can bring a number of component production problems as well as the requirement for a more complicated detection method (AC or pulse-response detection). There are two main chip capacitor types: multilayer (bipolar) chip capacitor and tantalum (unipolar) electrolytic capacitor. Both types of capacitors are sensitive to high temperatures and their (component) reliability can be lower than their solder attachment reliability. The size issue relating to resistors also applies to capacitors.

SOIC, QFP, PLCC: The attachment design is based on the gull wing or J-lead types. This is probably the most common type of lead attachment used in SM components. The focus of attention is on the heal of a solder joint, this being an indicator of wetting acceptability and hence was utilised for visual inspection purposes. As this type of lead attachment is compliant, the reliability of this type of solder attachment is considered high, providing that proper wetting characteristics are achieved [2]. Use of these components is limited to daisy-chained types since this pattern makes DC continuity failure detection possible. SOIC components with gull wing leads are widely available with different surface finishes some of them being lead-free.

BGA, Flip-chip: The bump or ball type of attachment method is a space-saving option for solder attachment especially for high-density packages. The solder bumps tested can be made from the identical solder to that used in soldering other components to the boards, or can be made from different solder. There are some high melting point solders used on a few BGA designs. As is the case with the previous component types a daisy-chained pattern between solder balls is desirable and it is essential that there is a silicon die inside the component. The die significantly influences the stresses within the package, which will impact on the solder joint performance. Care should also be taken in selecting the component with regards to the layout and population of solder balls with the BGA, which again can affect the reliability response.

2.3 COMPONENT NUMBERS

Clearly there are requirements regarding the number of parts to be tested. It is important to have a sufficient number of parts to make the results statistically significant. The planned number of experimental variables together with factors such as the chamber size, will also determine the final experimental plan.

From purely statistical considerations the optimal number of uniform samples is 110. This estimate is based on the binomial distribution and assumes 95% confidence interval. A 5% uncertainty interval is achieved when only one failure occurs in 110 uniform samples [2].

2.4 PCB DESIGN

The design of the pcb is a key element in generating the test. Not only should the substrate material be representative of the assemblies being evaluated, but the design of the pads and tracking will also need to meet the functional requirements of the components to be tested. In particular this requires the boards to match the daisy-chained aspect of the parts to be tested. Other issues that require consideration include how parts will be cut from the pcb for later microsectioning and shear testing.

An example of a suitable pcb layout is shown in Figure 4. It is a single sided 1.6 mm thick FR4 board with Cu tracks 35 µm thick. The design incorporates 20 off 0805-type resistors, 20 off 2512-type resistors, four PBGAs and 12 SOICs. In this design the resistors and PBGAs have circuitry to the board main connector, to facilitate continuity measurements.

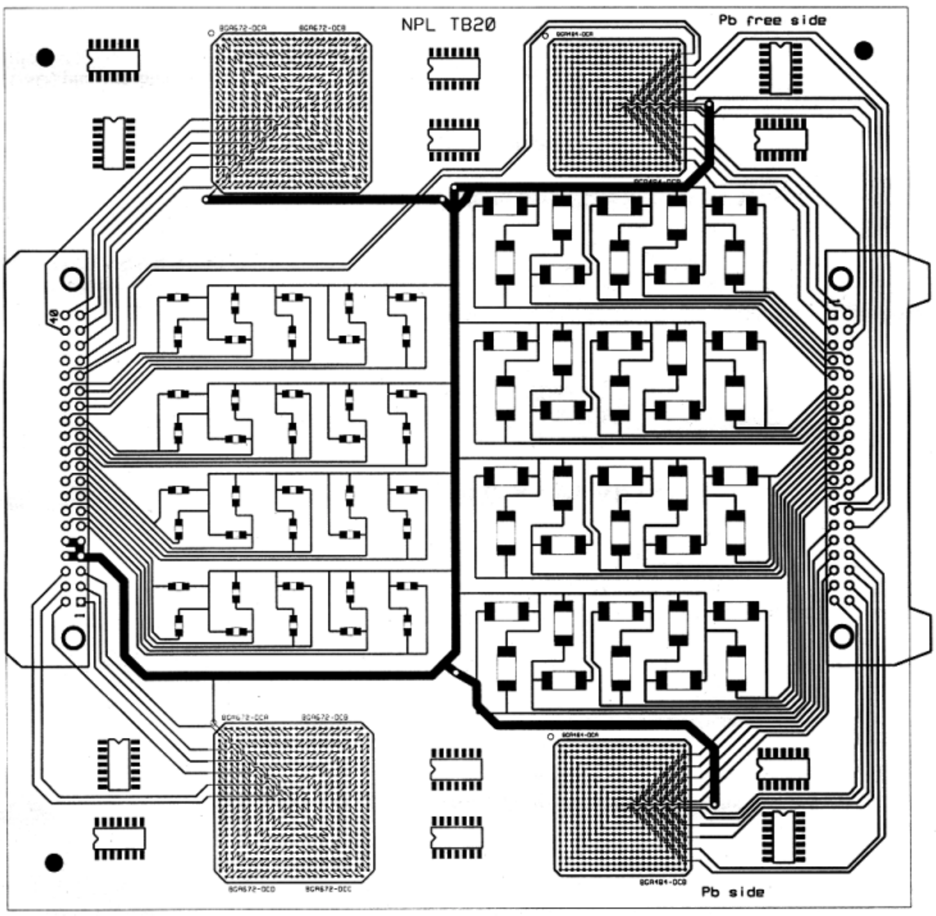

Figure 2. Example of test pcb layout, size 152 x 152 x 1.6 mm

2.5 PCB MANUFACTURE

The techniques used to manufacture the test vehicles should be representative of those used for the assemblies being evaluated. Care should be taken to ensure that all the test vehicles are manufactured under identical conditions, and ideally in one batch. This avoids introducing any further variables into the manufacture that may influence the reliability.

The number of boards built will clearly depend on the number of parts on each board and the number of variables being considered. Consideration should also be given to the number of samples that are required for microsectioning and shear testing, as this will require pcbs to be removed form the experiment. Clearly enough pcbs should remain for the continuity measurements.

2.6 THERMOCYCLING

The thermocycling regime used to evaluate the reliability of the solder joints is very important, and care should be exercised in making the selection. Clearly the greater the range in temperature the more severe the stress placed on the solder joint. But it is important that the regime selected should reflect the application environment.

In a recent experiment at NPL [5] the solder joints were thermally cycled according to the profile in Figure 5 selected on the basis of being representative of what industry currently uses when they require a tough test. There were two temperature set points, -55 °C and +125 °C, with 5 minutes dwells. The 5 min dwell was defined as the time during which the temperature in the oven was within ± 5°C of the set value.

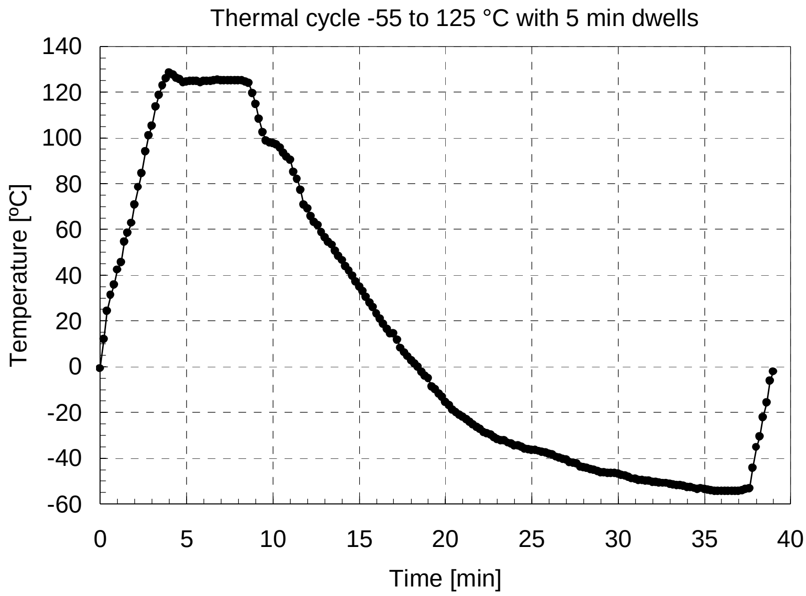

Figure 3. Temperature cycle load used

When samples (pcbs) are tested in a thermocycling chamber the temperature distribution in the chamber should be minimal. Forced airflow circulation is strongly recommended, as this will achieve a more uniform temperature distribution in the chamber. To minimize the impact of temperature variations within the chamber and different heating and cooling rates, the samples should be regularly moved around inside the oven.

3 DATA ANALYSIS

Three analysis techniques are discussed that can be used to evaluate the effect of thermal cycling and thermo-mechanical fatigue in solder.

3.1 MICROSECTIONING

Microsectioning is a destructive method that requires the pcb to be cut into sections, and hence they must be extracted from the experiment. This should be included in the original plan, so that sufficient pcbs remain for the continuity experiment.

Microsectioning is particularly useful since it shows the evolution of microstructure with thermocycling and the development of the cracks. Although no failure data can be obtained, qualitative information on how the solder fails can be extracted from the micrographs.

3.1.1 Specimen preparation.

Any of the components used in the test vehicle can be microsectioned for metallurgical analysis.

Samples can be cut out individually from the boards using a liquid-cooled conventional diamond saw. This method of cutting is employed to ensure that the soldered joints do not heat to a level that would affect the joint properties.

Once cut, the components can be cleaned using conventional IPA (iso-propyl alcohol) to ensure that any residue present from the cutting stage has been sufficiently cleaned from the joint region. The samples can then be mounted in a cold curing epoxy.

3.1.2 Metallography.

Once cured, the samples can be removed from their respective moulds to be ground and polished, using silicon carbide of 120 to 4000 grit paper on an automated machine, and polished with diamond-containing pastes/sprays 15 to 0.25µm in size. Diamond impregnation of the cloth should be kept to a maximum in order to ensure the best cutting rate of the surface. Final polishing of the samples can be achieved by hand using a gamma aluminide powder suspended in lapping fluid, as this has been found to give the best finish.

3.1.3 Etching

Etching can be carried out to enhance the microstructure, and for the lead-containing solder systems, can be accomplished using a solution containing 2 ml hydrochloric acid and 98 ml industrial methylated spirits. With this solution a polish-etch technique is achieved 0.25 µm diamond paste as the polishing medium.

The lead-free alloy can be etched using a solution of 2 ml nitric acid, 2 ml hydrochloric acid and 96 ml distilled water.

3.1.4 Micrographs

A standard optical bench microscope is suitable for examination up to magnifications of 200-500x, and a method for recording the images is desirable.

3.2 SHEAR TESTING

Shear testing is a very useful method for evaluating the degree of crack propagation and damage to the solder joint. The method is based on the assumption that the degree of crack propagation will influence the strength of the joint, and hence a correlation will exist with the strength of the joint as tested in shear.

3.2.1 Specimen Preparation

Boards can be cut into sections containing two or three components for testing, using a conventional water-cooled diamond saw. This produces a clean edge with the minimum stress to board. The smaller sections of board can be cleaned to remove any contaminants/residues from the cutting process, and then dried using compressed air.

3.2.2 Sample Testing Arrangement

Figure 4 shows a typical experimental arrangement of the board placed within a jig ready for testing. This particular machine has a movable X-Y table and the sample can be positioned with the shear-test tool directly behind the component (as shown). For each test the push-off tool can be at the same pre-set height and centred on the component. A typical height is 80 µm and a tool speed of 200 µm/s. The end of a typical test is shown in Figure 5.

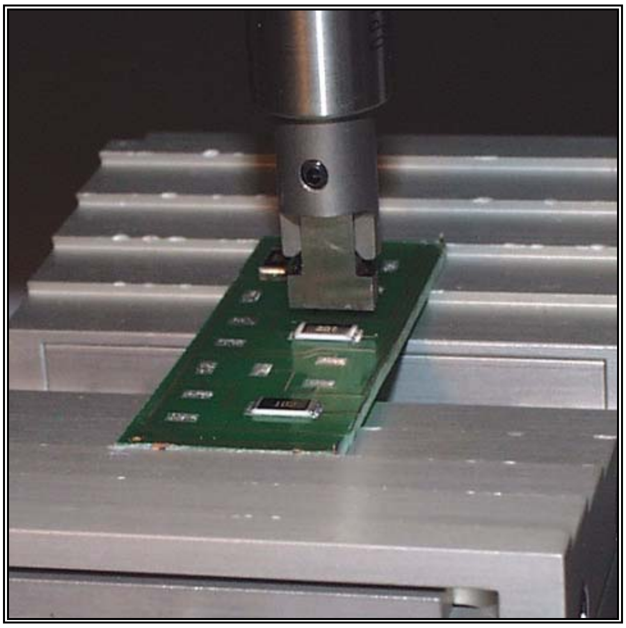

Figure 4. Shear test jig and push-off tool.

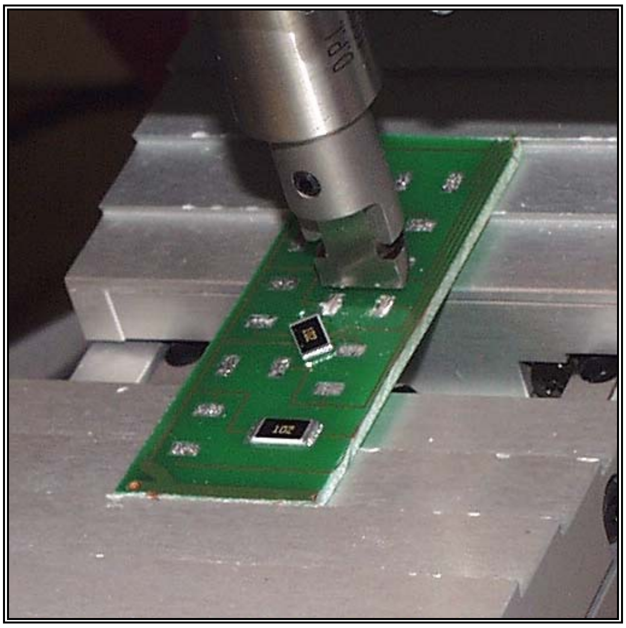

Figure 5. Typical joint break after failure

For each thermally cycled board at least 10 resistors should be tested in order to produce a meaningful statistical average of joint strength.

3.3 CONTINUITY MEASUREMENT

Following manufacture of the pcbs, it is recommended that all the components connected in circuits for continuity measurements should be electrically tested before thermal cycling. All the components should exhibit an electrical resistance within the manufacturers' tolerance of ± 5%. All component resistances should be recorded, and filed for future use.

The resistance of each continuity loop can be measured using the Voltage Method, in which a constant voltage of 1 V is applied across a device and the current through the device measured.

There are three possible strategies for measuring the resistance of components, and these are described in NPL report [6].

The first occurrence of a resistance value of more than 10 % above the nominal value should be counted as the failure of that component. From an analysis of the failure data a Weibull distribution can be constructed to obtain the failure rate, and the N_f median numbers of cycles for 50 % failure rate can therefore be estimated [5]. The error of this measurement depends on the probability of a failure detection [3] and the sampling rate [6] of continuity measurements.

4 REFERENCES

[1] Vincent J. Improved Design Life and Environmentally Aware Manufacturing of Electronics Assemblies by Lead-Free Soldering: “IDEALS”, Synthesis report BE95-1994

[2] Dušek M. Hunt C. The Impact of Solderability on Reliability and Yield of Surface Mount Assembly, NPL Report CMMT(A)214, Teddington, September 1999

[3] Dušek M. Hunt C. Optimum Pad Design and Solder Joint Shape for Reliability, NPL Report CMMT(A)215, Teddington, August 1999

[4] Mills K. Metals Handbook Ninth Edition Volume 9, Metallography and Microstructure, American Society for Metals, 1985, ISBN 0-87170-007-7

[5] Dušek M. Nottay J. Hunt C. The Use of Shear Testing and Thermal Cycling for Assessment of Solder Joint Reliability, NPL Report CMMT(A)268, Teddington, June 2000

[6] Dušek M. Nottay J. Hunt C. A Test Method for Assessing Pb-free Solder Joint Reliability, NPL Report CMMT(A)273, Teddington, July 2000

ACKNOWLEDGEMENTS

The authors are grateful for the support of the DTI as part of their Measurement for the Processability of Materials (MPM) programme, and to Altera UK Limited, DEK Printing Machines, Alpha Metals and Multicore Solders for their support. The authors are also grateful to Martin Wickham for many useful discussions through out the work.