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**Test Approach to Isothermal
Fatigue Measurements for
Lead-free Solders**

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Test Approach to Isothermal Fatigue Measurements for Lead-free Solders

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ABSTRACT

Driven by European legislation, which comes into force in July 2006 and effectively bans the use of lead in solders, the electronics manufacturing industry is studying a range of potential lead-free solder replacements. A major concern is the reliability of the solder joints which has traditionally been predicted using modelling techniques and established materials data. Although the mechanical behaviour of lead-free solders is known to be different from that of their traditional counterparts, there is a dearth of credible materials data, and hence there is an urgent need to generate such data in order to evaluate the likely lead-free solder performance. There is also a realisation that any new materials data should be obtained from solder samples that have volumes similar to those of solder joints, and that the joints should be loaded in shear, mirroring the practical situation in the field. However, currently available test instruments do not readily meet these constraints. This paper describes a new approach developed at NPL to overcome these constraints, resulting in the design of the new instrument with a sample geometry that permits small solder volumes to be studied in pure shear. Example data are presented and illustrate how the fatigue resistance of solders can be characterised. Advantages of the new approach include (i) it can accommodate various solder alloys and surface coatings, (ii) the solder joint volumes mirror those in modern assemblies, (iii) the solder is under shear, (iv) the samples are relatively easy to manufacture, (v) the construction of the specimen allows direct microscopic examination during the test at room temperature. A 4-point measurement system for resistance monitoring has also been evaluated and found to correlate well with load drop during fatigue testing of solders.

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by Dr M G Cain, Knowledge Leader, Materials Processing Team
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1 INTRODUCTION

Although the principal aim of a solder joint is to achieve both an electrical connection and a mechanical attachment, it is the latter that generally gives cause for concern. In terms of the bond strength, or the force needed to break a solder joint by push off or mechanical shock, the solder joint is considerably over-engineered. However, fatigue behaviour poses a very different situation, and the ability of solder to withstand considerable damage, while retaining the component connection, is critical. Stronger materials that could resist the fatigue damage, would result in an unacceptable change in failure mode, with failures occurring in the component body or in the substrate rather than in the solder.

Materials broadly fall into two types depending on their response to the application of a cyclic load. The application of a load can be either force (stress) controlled or displacement (strain) controlled. For the purpose of fatigue measurements, solid materials can be separated into two groups. The first group, mainly designed to function within the elastic deformation region (in reversible elastic deformation mode), includes ceramics, steels, nickel, aluminium alloys etc. These materials are called **high cyclic fatigue (HCF)** materials, since it takes a high number of cycles to cause failure. For this failure mode the control variable is **stress (force)**, which typically induces small variations in strain. The induced small strain amplitude prevents the material failing via a brittle fracture. In Figure 1 typical stress-strain relationships are illustrated for two materials, one a high cycle, and the other a low cycle fatigue material.

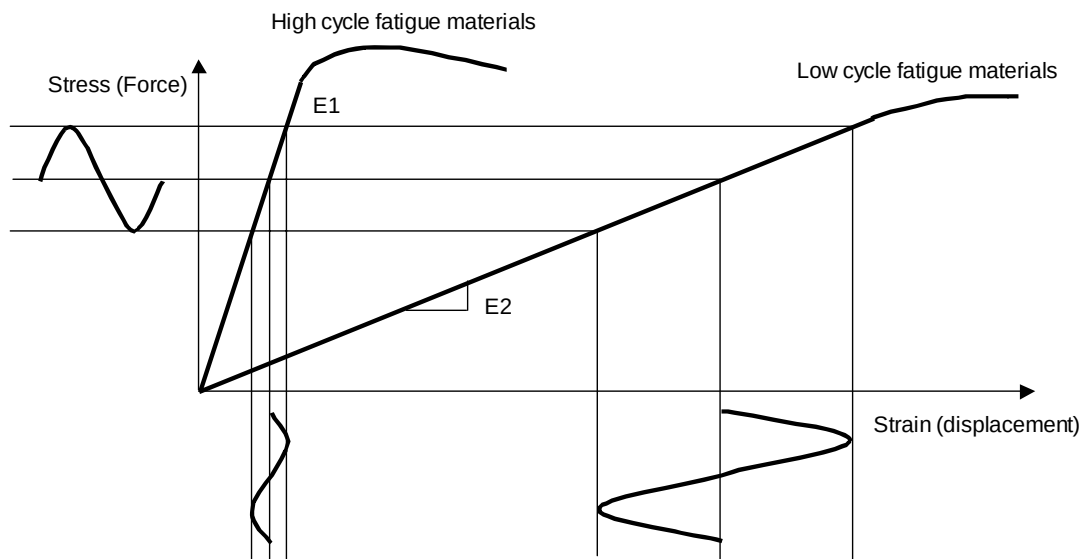


Figure 1. Difference in behaviour for high and low cycle materials

The high cycle fatigue materials have a high Young's modulus ($E1$) and can withstand tens of thousands to millions of stress cycles before the structural integrity degrades. It is also evident from Figure 1 that the strain amplitude is relatively low, and this makes it difficult to control the test instrument in a strain mode. Additionally, any noise in a

dynamic system makes the situation more difficult. Hence the test machine is controlled in a force, or stress mode. The HCF materials are normally stress cycle tested at high frequencies (1 Hz – 1 kHz range) to achieve fatigue failures in reasonable timeframes, and at low homologous temperatures ($T_h < 0.5$).

The second group i.e. the **low cyclic fatigue (LCF)** materials, have a low Young's modulus (E_2 in Figure 1) and include solder alloys (SnPb, SnAgCu, SnAg, etc.) used in electronics. They will deform inelastically at low stresses, are designed for use outside their elastic region, and are prone to fail in a ductile mode at high strain levels. For mechanical testing of these materials a **strain (displacement)** controlled mode is used. The number of strain cycles to failure is usually in the range of hundreds to a few thousands. These materials are tested at a low frequency of strain cycles (100 μ Hz – 10 mHz) and at high homologous temperatures, $T_h > 0.6$, (expressing the temperature as a fraction of the melting point in Kelvin).

A comprehensive understanding of the mechanical behaviour of SnPb solder has been built up over more than 50 years. However, with the implementation of the European legislation, lead-containing solders will be banned after July 2006, and there is a dearth of information on the mechanical behaviour of their likely lead-free replacements. Hence there is a critical requirement to acquire materials data for these new lead-free solders in order to use them for reliability modelling. But there is a realisation that any new materials data should be obtained from solder samples that have volumes similar to those of solder joints, and that the joints should be loaded in shear, mirroring the practical situation in the field. Hence there is a requirement to generate new data on the new materials, and to acquire this in a shear mode. Historically the majority of the SnPb materials data were measured using appropriate methods at the time and produced data that were useful to the industry then, and typically that would have been using tensile specimens with a 10 mm gauge diameter. Therefore new measurement techniques are required, however, currently available commercial test instruments do not readily meet these constraints. This report details a new approach developed at NPL to overcome these constraints for measuring the basic lead-free solder properties that are key to future modelling.

Creep, relaxation and fatigue are the key parameters that need to be measured. These mechanical measurements must be made at various temperatures, and ideally test instruments need to be able to accommodate measurements under dynamic conditions. Since small samples are to be studied the displacement measurement accuracy required needs to be better than 0.1 μ m. These mechanical and thermal requirements are quite demanding and have generated a number of novel solutions [Ref 2, pp. 67].

A solder sample undergoing repetitive cyclic strain fatigue will fail gradually. The resistive force to the applied strain will decrease as a crack grows and microstructural changes occur. In each repeating strain cycle the maximum and minimum force will reduce as the crack grows. The rate of degradation (of the difference between the maximum and minimum force per cycle) is a measure of the solder performance. The point used to define the number of cycles to failure does not necessarily have to coincide with a 100% crack length. Hence a load drop parameter is defined as the reduction in the ratio of the difference between the maximum and minimum load at N cycles, compared to the difference between the maximum and minimum load at zero cycles. Whilst a proposed Japanese standard for tensile solder specimens recommends a

25% drop of load to define life-time [Ref 2, pp 57], a similar US standard [Ref 2, pp 57] recommends a 50% load decrease. Alternatively, another definition of life-time can be derived from the crack length in the test piece or an electrical resistance increase of tested specimen, as a direct cause of fatigue cracking.

2 MODEL SOLDER TEST SPECIMEN

Solder used in electronics is a relatively ductile material and is used predominantly at very high homologous temperatures $T > 0.9T_m$. Creep rates in materials at these temperatures are high, and hence testing has traditionally been performed in the controlled strain mode. But as mentioned above there is a requirement to obtain the new materials data from small solder joints in shear. Since testing in shear using a traditional test instrument is challenging, it is better to use an instrument that operates along a single axis, and have this axial loading converted into a shear action within the sample. In **Figure 2** a sample format is proposed that allows the central solder section to be loaded in plain shear, while applying an axial load overall to the sample.

The sample is fabricated from a copper bar of dimensions length 43 mm, height 6 mm and thickness 2 mm. The bar is wire (spark) eroded down the middle of the 6 mm side to within the final 3 mm and then finally cut using a diamond saw for the final 3 mm. **The gap** width is determined by the thickness of the diamond blade (~ 0.32 mm). This final cut is made at a slow speed to avoid impregnating any carbonaceous material that occurs with wire erosion. The gap is filled with a solder paste, which may be either lead-free or lead-containing, and reflowed using a gas torch capable of fully reflowing a solder paste. Care should be exercised to avoid exhausting the flux and causing any voiding. Preparing the sample in this way ensures not only alignment of the solder joint, but also parallelism of the two copper halves of the joint. Finally, after soldering, the two vertical cuts are made 2 mm apart to define the solder joint.

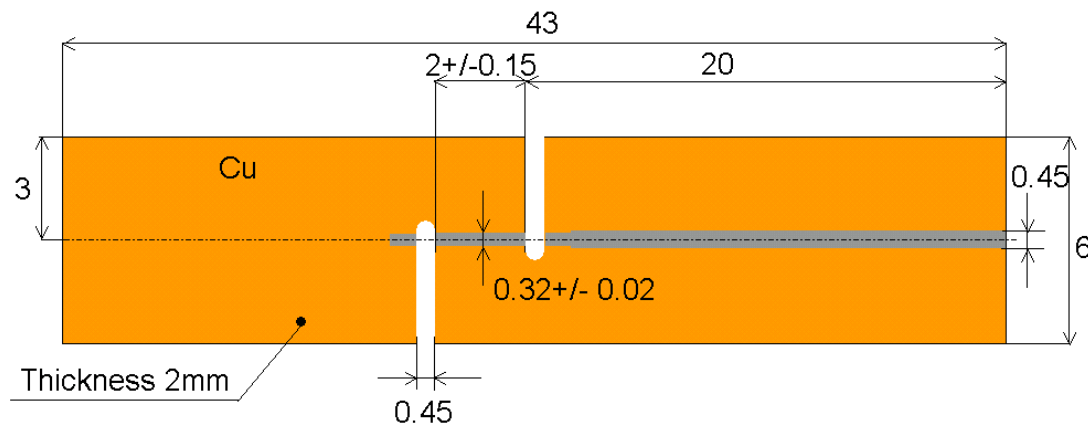


Figure 2. Drawing of the test piece (all dimensions are in mm)

This design has the advantages that it can accommodate any solder, and that the copper bar can be plated using conventional PCB fabrication finishes (e.g. ENIG, immersion tin, immersion silver) prior to soldering. A typical section through the joint is illustrated in Figure 3.

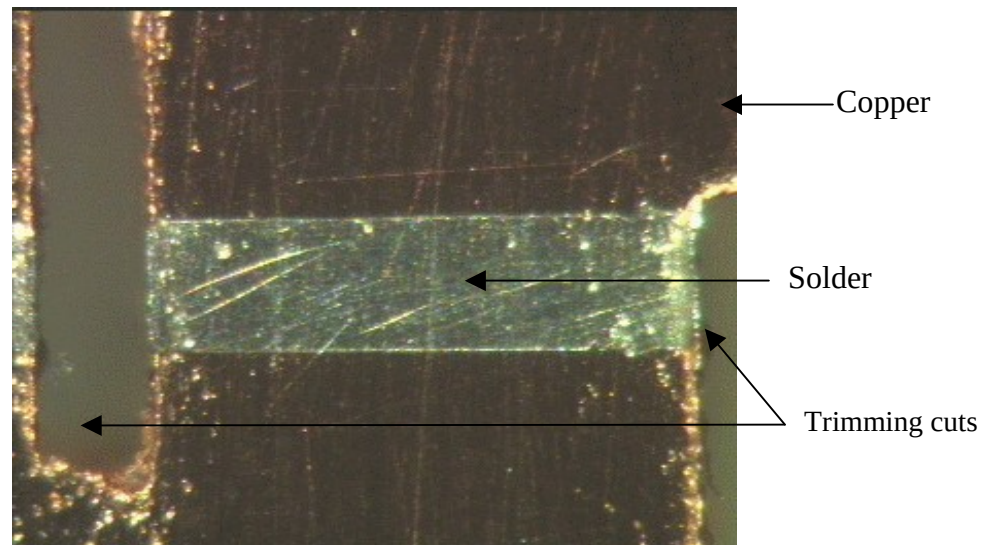


Figure 3. Solder joint formed between the copper arms of a test piece

3 INSTRUMENT DESIGN

The construction of the new test instrument suitable for strain-controlled experiments [1] is based on the controlled thermal expansion of a stainless steel tube (displacement tube) supporting one side of the copper sample (see schematic in Figure 4). The other side of the sample is held by a load beam, which monitors axial forces in a sample. The stainless steel tube is heated by a resistive heating element (constantan wire wound around the tube), and the displacement is measured using two Linear Differential Variable Transformers (LDVT), mounted above and below the sample, as is shown in Figure 5.

The single axis of the design minimises any off-axis force being exerted on the sample, and indeed FEA analyses confirmed that only pure shear was exerted on the sample. Another advantage of the design is that of using the thermal expansion of the tube with compliant beam. With the current instrument a CTE of $6.5 \mu\text{m}/^\circ\text{C}$ can be achieved without any load. The temperature range of the tube is 200°C , and by heating the tube to 110°C and then locking the sample in position, it is straight forward to apply compression or tension.

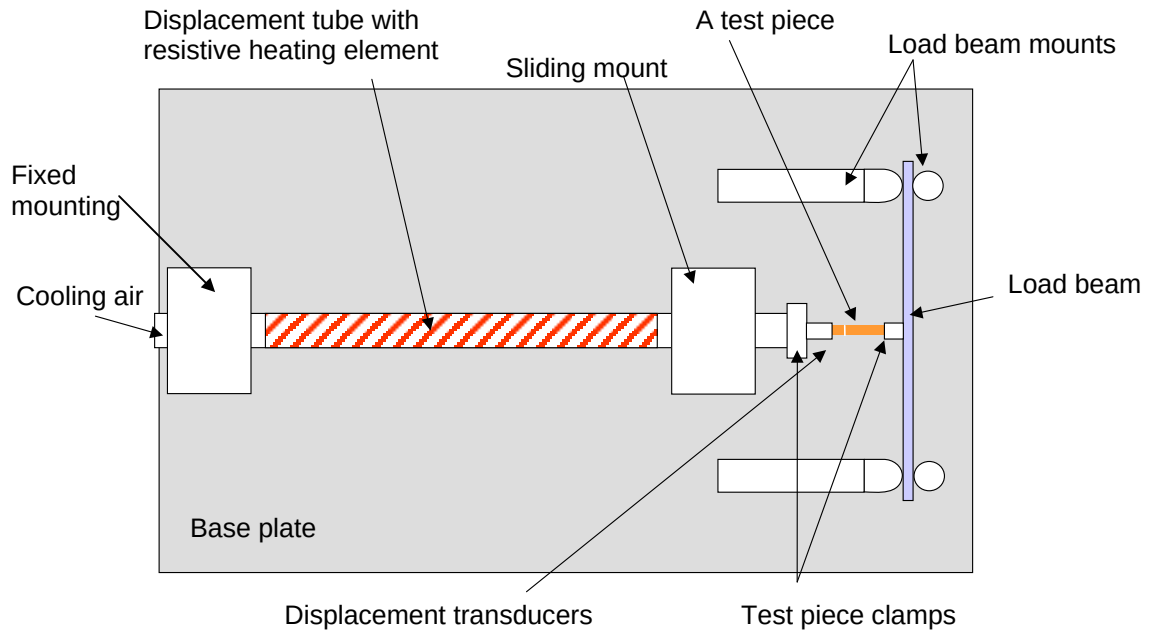


Figure 4. Schematic of strain control test machine (top view)

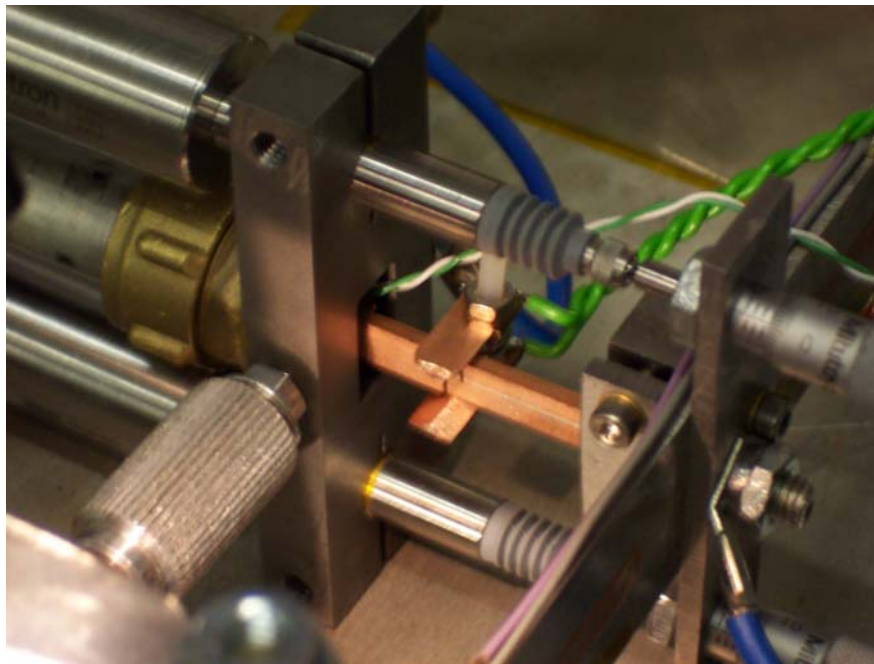


Figure 5. Detail of test specimen, showing the two LVDTs above and below the sample. The picture also shows the 4-point resistance test connections (current lines blue, potential lines green) that are discussed later.

The control of the machine is achieved using a PC, which collects displacement, temperature and force readings from 18-bit A/D data acquisition device, and controls a power source (resistive heating element) via standard communication ports (RS-232C, GPIB, USB). Although in the design shown here the sample is tested at room

temperature, a heater inserted around the sample provides an elevated temperature facility. The instrument is therefore capable of performing an isothermal fatigue test under controlled strain conditions, where the displacement follows a defined profile.

4 TEST MEASUREMENT METHOD

In order to determine the displacement profiles to be applied to the copper samples, typical strains experienced in surface mount components were calculated. In Table 1 and Table 2 typical parameters are given for ceramic chip resistors and relevant materials. To calculate the strain range experienced by a chip resistor the following assumptions were made: the alumina in a chip resistor has a CTE = 4.5 ppm/°C, and is mounted on a FR4 substrate with a CTE_{xy} = 18 ppm/°C; the assembly is subjected to thermal cycling between –55 and +125 °C, i.e. a temperature span (ΔT) of 180 °C. In Table 2, column 2, the resistor body lengths (L) are listed. In column 3, ΔL is the difference in expansion between the resistor body and the substrate when measured from the centre point over a temperature change of 180 °C. For a chip resistor the average stand-off height is 80 μm , and calculated approximate average shear strain ranges (γ) are given in the fourth column. The displacement applied to the model joint to simulate the same shear strain as experienced by a single resistor joint, is given in column 5. The value is 4 times that of column 3 as the joint height is four times greater, i.e. 320 μm as opposed to 80 μm .

Table 1. Experimental variables used to calculate equivalent strain range

ΔT	180	°C
SoH	80	μm
CTE pcb	18	ppm/°C
CTE Al ₂ O ₃	4.5	ppm/°C
Gap	320	μm

Table 2. Calculation of experimental total strain range

Resistor type	L [mm]	ΔL [μm]	γ	$\pm \Delta l$ (μm)
2512	6.2	7.5	0.094	15.1
1206	3.2	3.9	0.049	7.8
0805	2.0	2.4	0.030	4.8
0603	1.5	1.8	0.023	3.7

A typical displacement profile used to achieve an equivalent deformation to that experienced by a type 2512-resistor in a –55 to +125 °C thermal cycle, is presented in Figure 6. There is a significant difference between the thermal cycling sample and the copper sample in the instrument. The isothermal strain cycling in the instrument is a first approximation (worst case) against which various solders can be assessed. In a full thermo-mechanical fatigue test the displacement profile is synchronised with a

temperature profile, which then simulates a thermal cycling experiment. Hence the application of an identical strain range in the machine at room temperature, where the creep rates are lower, is a more severe test on the solder than the typical thermal cycling regime.

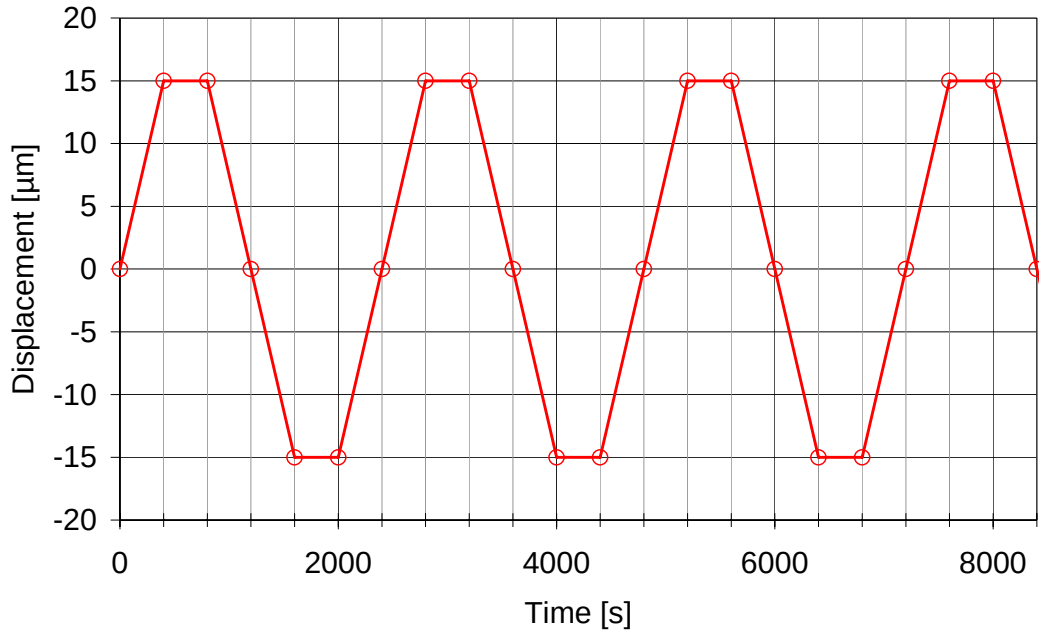


Figure 6. Displacement profile (equivalent to 2512-type resistor)

To detect any degradation of a solder joint the maximum and minimum loads are monitored during each cycle. A load drop parameter is defined as the percentage of maximal load range achieved during the strain cycling. Reductions to between 50%-70% of the initial value are usually taken as performance criteria for a number of life-cycles. In addition, the resistance across the solder joint can be monitored using a 4-point measurement method. It is assumed that there is no change in resistance due to microstructural changes, and hence the resistance increase (in $\mu\Omega$) can be correlated with crack growth. This method can be used to augment monitoring of the degradation of the solder joint and of the variation in the load drop parameter.

In Figure 5 the test specimen connections to the 4-point electrode system are shown. Blue (thick) cables temporarily supply DC current (10A) through the whole of the copper sample, and electrodes connected to the green cables are sensing a potential drop across the solder joint in the vertical direction. As the crack area increases the bulk resistance through the solder increases. Since the method is very sensitive and can detect $0.1 \mu\Omega$ increases in resistance, it is important to monitor the temperature of a specimen and correct for any thermal fluctuations.

One disadvantage of this sample design is the compliance in the copper. The sample displacement measured is a combination of the deformation in the solder and the extension of the copper. This elastic extension in the copper can be added to the measured deformation for solder (displacement) as expressed in Equation 1.

$$L_{\text{total}} = L_{\text{compl}} + L_{\text{solder}} \quad \text{Equation 1}$$

Where:

- L_{total} – is total displacement (deformation) necessary
- L_{compl} – is the displacement correcting for elastic deformation in the copper arms
- L_{solder} – is the required displacement following the displacement (strain) profile

5 RESULTS OF MEASUREMENTS

As discussed above the instrument can be operated in either controlled stress or controlled strain modes. Hence, for creep measurements it is operated in the controlled stress mode, and for fatigue measurements in the controlled strain mode. An example of strain-controlled deformation of solder is shown in Figure 7 at the start of the 25th cycle, in which the resultant stress is shown in red.

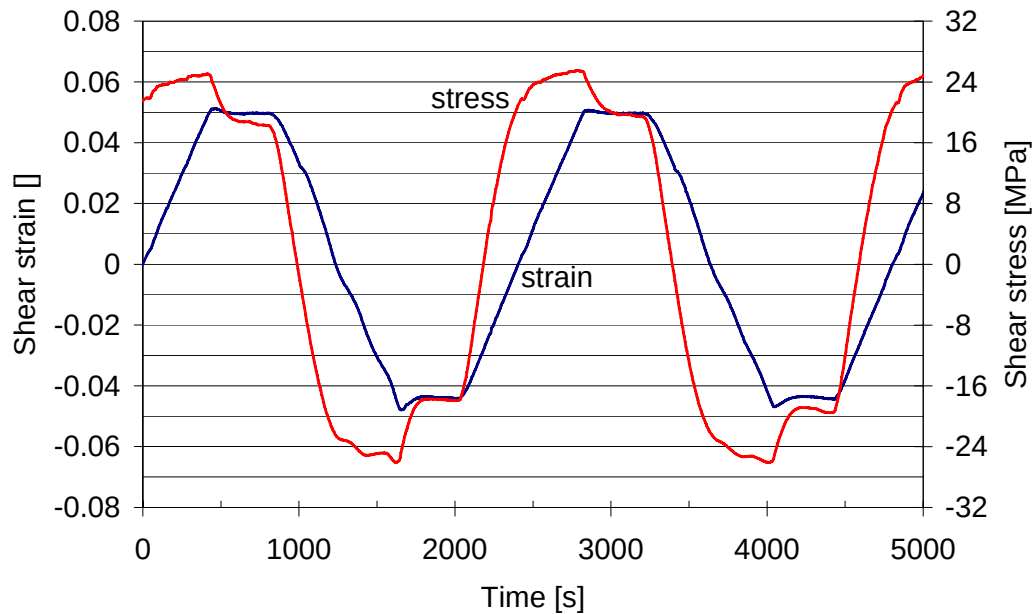


Figure 7. The wave form of shear strain (start of the 25th cycle) and shear stress as a function of time at 25 °C

It is apparent that after an initial start from zero strain and zero stress, the solder reacts to the displacement with a phase shift of about 30°. The material is exhibiting clear yielding behaviour above 16 MPa of shear stress and 0.045 of strain. The results also show that the control system is operating well, imposing the desired strain profile.

In Figure 8 the shear strain and shear stress are plotted for the 25th cycle. For an elastic material this plot would be a straight line, but for a material with plastic properties a hysteresis loop is observed, indicating the work done in the cycle. In an isothermal cyclic test this loop should be a symmetric, and any asymmetry can be used to estimate the amount of plastic and elastic strain contributing to total strain. In this case the

plastic strain is about ± 0.030 and the elastic strain about ± 0.017 . The plastic range is defined as that between the points where the loop intercepts the x-axis.

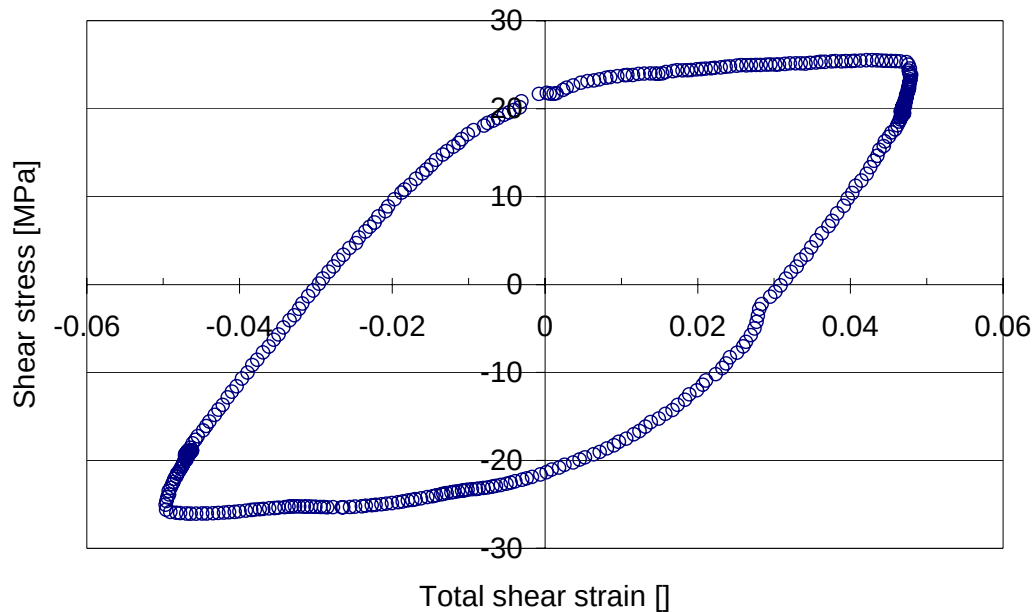


Figure 8. Hysteresis loop for the 25th cycle of SAC solder joint at 25 C

Repeated shear strain cycles will fatigue the solder, and the solder will start to fail as a crack develops. Hence the measured load decreases until the sample completely fails. Plotting the hysteresis loop for each cycle highlights the stress gradually decreasing as the crack propagates. Strictly, the stress does not decrease; it is the load that decreases as the crack propagates. However, the new area of the joint is unknown, and therefore by convention the stress is plotted assuming the original area is still intact, which results in a plotted decrease in stress. In Figure 9 the maximum and minimum nominal stresses (assuming the cross-sectional area is constant) are plotted for each strain cycle (SnAgCu – SAC - solder). There is an initial strain hardening as the solder joint reaches the maximum shear stress range of 54 MPa (-27 MPa to + 27 MPa), which is reduced to 27 MPa (-13.5 MPa to +13.5 MPa; ~50%) after 80 cycles. The lifetime of the solder joint is defined as the point of 50% stress (load) reduction.

In Figure 9 the resistance across the solder joint, monitored in every cycle (green symbol), is also shown. The initial resistance of about $18.5 \mu\Omega$ increases steadily and slowly up to 70 cycles. Assuming the resistivity of the solder joint and the solder joint gap remain constant, the only variable is the area of the solder joint perpendicular to the measurement current ($\sim 10A$). Hence the resistance measurement is directly related to the development of a crack. This correlation is demonstrated by replotting the data from Figure 9 in Figure 10, where values have been normalised at zero cycles. It can be seen that the more rapid increase in resistance, and the 50% increase in resistance value correspond with the point of the 50% load drop. Therefore the resistance is a complimentary technique to the load drop measurements, but the resistance values are purely a geometric effect, whereas the load drop maybe influenced by other materials changes. Hence the resistance data can be used to predict crack growth rates.

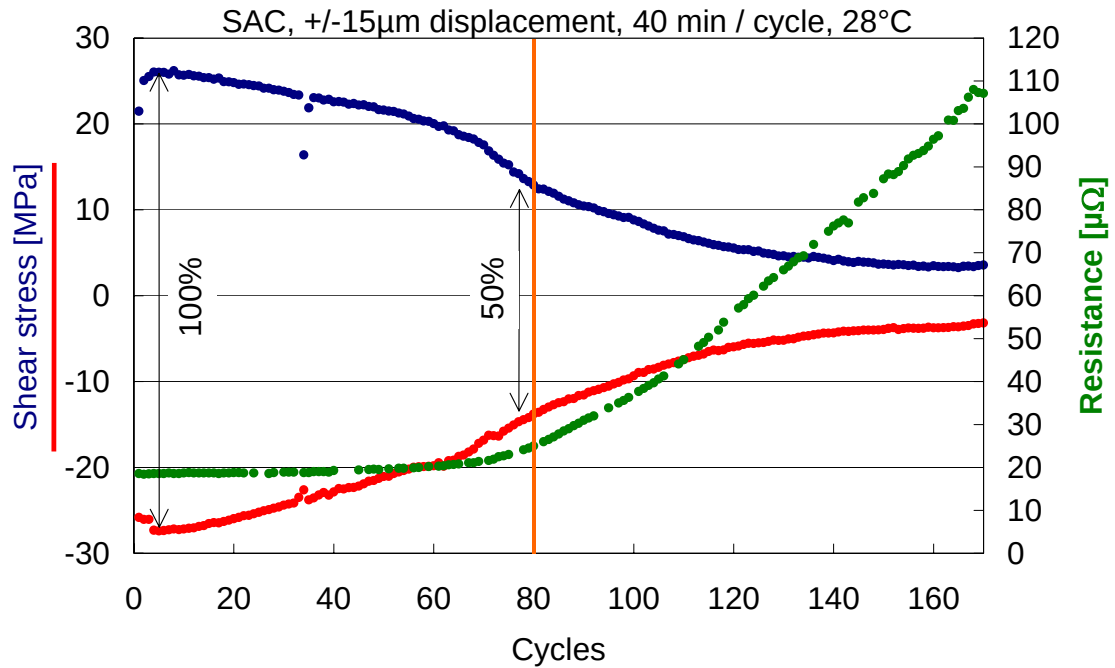


Figure 9. Maximum (blue) and minimum (red) stress, and resistance (green) across a solder joint during strain cycling

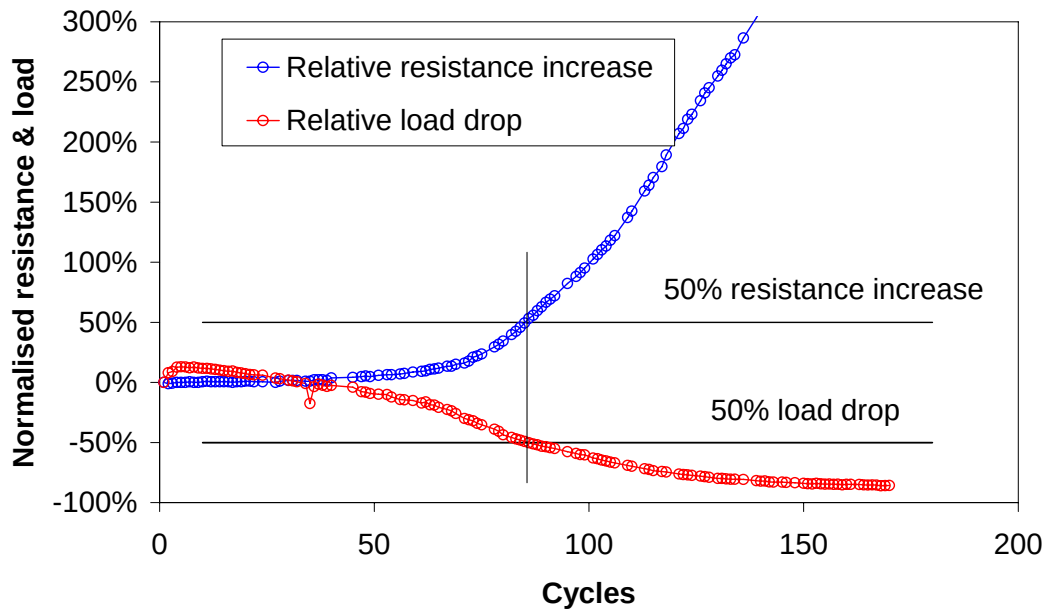


Figure 10: Normalised plot of load drop (red) and resistance increase (blue)

From the above it is evident that credible materials properties of very small amounts of solders can be determined, and importantly, the plastic strain range and the hysteresis loop can be measured. These are important parameters for lifetime prediction, as they

are used in the Coffin-Manson and Morrow equations respectively. Measuring these parameters directly, for different solders and conditions, and relating them to real assembly performance, will greatly advance lifetime prediction for lead-free alloys.

6 CONCLUSIONS

A new approach for measuring solder fatigue is described. This is based on the construction of an instrument to apply defined loading under precision (displacement or force) control to measure the materials properties. The experimental design includes a new sample geometry that permits small solder volumes to be studied in pure shear. These two elements permit the necessary solder properties to be collected for new solder alloys under geometric conditions that reflect common usage. Preliminary data are presented, which will be applied to FEA modelling of solder performance.

Advantages of the new test specimen design are:

- (i) It can easily accommodate various solder alloys and surface coatings.
- (ii) The solder joint volume mirrors that used in modern electronics assembly
- (iii) The solder is under shear, mirroring the practical situation
- (iv) The samples are relatively easy to manufacture.
- (v) The construction of the specimen is designed such that the polished surface of the solder joint can be observed with an optical microscope during the test at room temperature.

A 4-point measurement system for resistance monitoring was evaluated and found to correlate well with load drop during fatigue testing of solders.

7 ACKNOWLEDGEMENTS

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