

Report

NPL REPORT
DEPC-MPR058

**Low Cycle Isothermal Fatigue
Properties of Lead-free
Solders**

M Dusek and C P Hunt

NOT RESTRICTED

JANUARY 2007



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Low Cycle Isothermal Fatigue Properties of Lead-free Solders

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ABSTRACT

Driven by European legislation, that came into force in July 2006 banning the use of lead in solders in a number of consumer applications, the high reliability sector of the electronics manufacturing industry is urgently studying the 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 with established SnPb solder 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 report describes a new approach developed at NPL to overcome these constraints, resulting in the design of a new instrument IPTM (Interconnect Properties Test Machine), 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 decreases recorded during fatigue testing of solders. The results of this study reveal that lead-free solders at high temperatures have increased lifetimes. A route to predict a fundamental reliability variable of solder has been identified.

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Approved on behalf of the Managing Director, NPL,
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authorised by Director, Engineering and Process Control Division

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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 resistance 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.

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 have now been banned in certain applications from 1 July 2006, and there is a dearth of information on the mechanical behaviour of their lead-free replacements. Hence there is a critical requirement to acquire materials data for these new lead-free solders, both to gain confidence in their performance and to supply the performance information for reliability modelling. At the same time there is a realisation that acquiring data in tension from typical materials laboratory instruments is not appropriate and that any new materials data should be obtained from solder samples having volumes similar to those of solder joints. Moreover the joints should be loaded in shear (not tension), mirroring the practical situation in the field. Consequently, there is a requirement to generate new data on the new materials, and to acquire them in a shear mode. This report describes a new approach developed at NPL to overcome these constraints, resulting in a new instrument [Ref 1 pp.468] with a sample geometry that permits small solder volumes to be studied in shear.

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 μm . These requirements are quite demanding and as a consequence a number of novel solutions have been generated [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 (the difference between the maximum and minimum forces 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 20% drop of load to define life-time [Ref 3], a similar US standard [Ref 4, 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 $0.6T_m - 0.8T_m$ (T_m is melting temperature in K). Creep rates in any materials at these temperatures are high, and hence testing has traditionally been performed in the controlled tensile 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 specimen. In Figure 1 a specimen format is proposed that allows the central solder section to be loaded in plain shear, while applying an axial load overall to the sample [Ref 5].

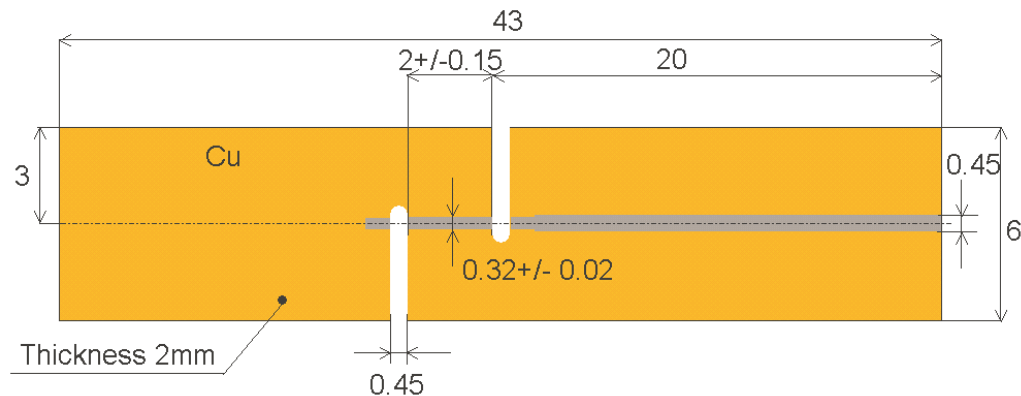


Figure 1. Drawing of the test piece (all dimensions are in mm)

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, silver) prior to soldering. A typical joint specimen is illustrated in Figure 2.

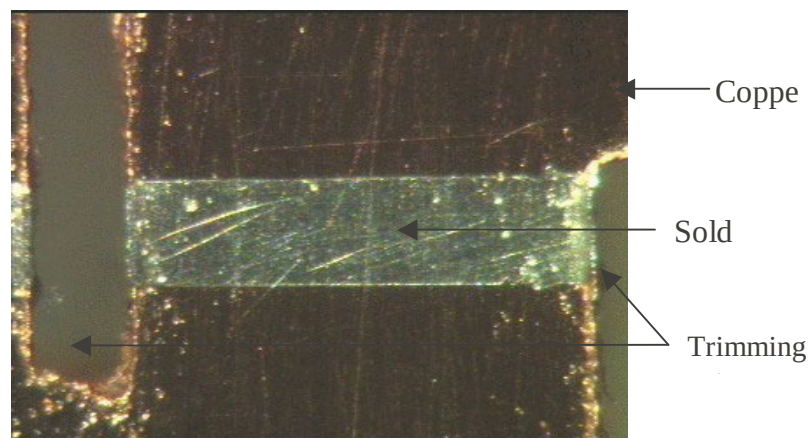


Figure 2. Solder joint formed between the copper arms of a test piece

3 INSTRUMENT DESIGN

The construction of the new test instrument IPTM (Interconnect Properties Test Machine) suitable for strain-controlled experiments [Ref 1 pp. 468] is based on the controlled thermal expansion of a stainless steel tube (displacement tube) attached to one side of the copper sample (see schematic in Figure 1) using a linear bearing. The other side of a specimen is held by fixed jaw clamp. The stainless steel tube is heated by a resistive heating element and the displacement is measured using two linear differential variable transformers (LDVT), mounted alongside the test specimen, as is shown in Figures 3 and 4.

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 is exerted on the sample [Ref 6]. Another advantage of the design is that by using the thermal expansion of the tube with compliant beam connected to a load cell, a displacement rate of $6.5 \mu\text{m}/^\circ\text{C}$ can be achieved without any load, with a precision of $0.1 \mu\text{m}$ limited by the measurement of LVDT signal. The temperature range of the tube is $25\text{--}200^\circ\text{C}$, and by heating the tube to 160°C and then securing the specimen at zero load, it is a straightforward matter to apply compression or tension. In order to give faster response when cooling, the zero point load is offset to higher temperature than the mid point between 25 and 200°C .

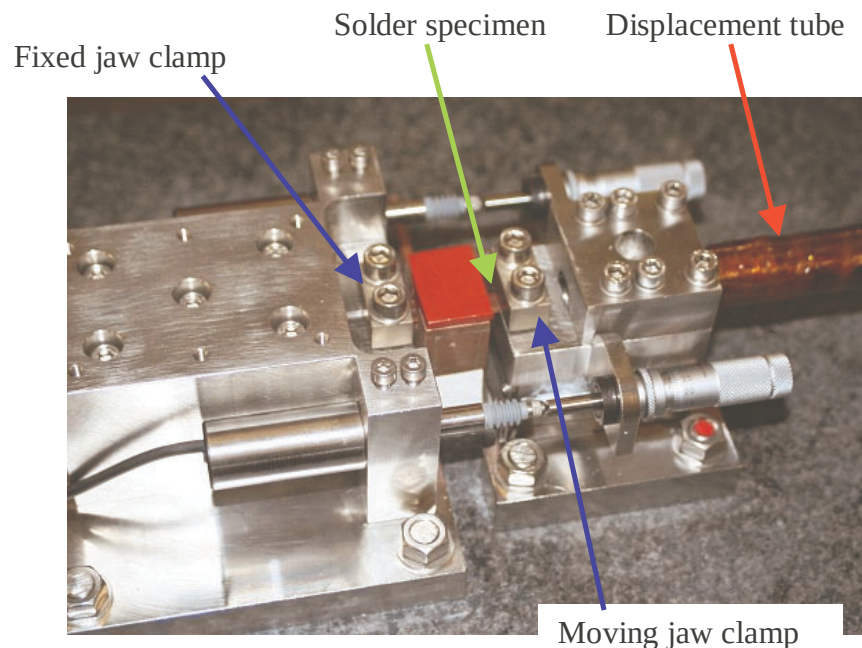


Figure 3. Detail of test specimen, showing the two LVDTs to the left and right of the sample

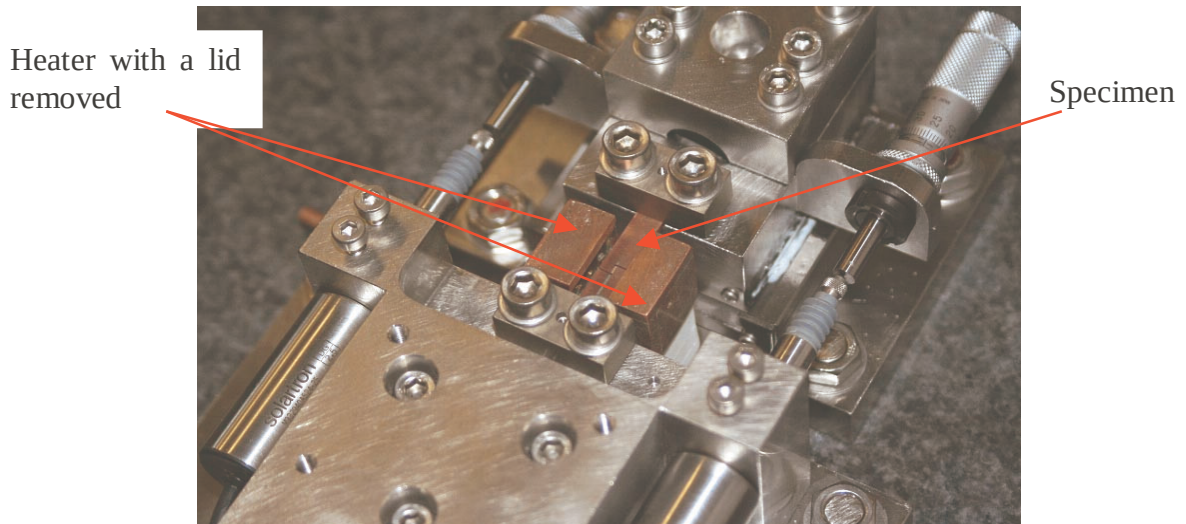


Figure 4. Detail of test specimen with open temperature cell

The control of the machine is achieved using a PC, which collects displacement, temperatures and force data. Although in the design shown here the sample is tested at room temperature, a heater inserted around the sample provides a temperature control facility. ***The instrument is therefore capable of performing an isothermal fatigue test under controlled strain conditions, where the displacement follows a defined profile.***

In Figure 5 example results are presented of 10 tensile tests to verify machine capability. In this test a copper specimen was elastically tensioned to assess Young's modulus. Up to 0.1 % strain the error is within 16 % of tabulated values. Young's modulus measurements are strain rate dependent and a consistently lower Young's modulus was recorded at a slow displacement rate of 0.11 $\mu\text{m/s}$ (strain rate 5.8E-6 /s).

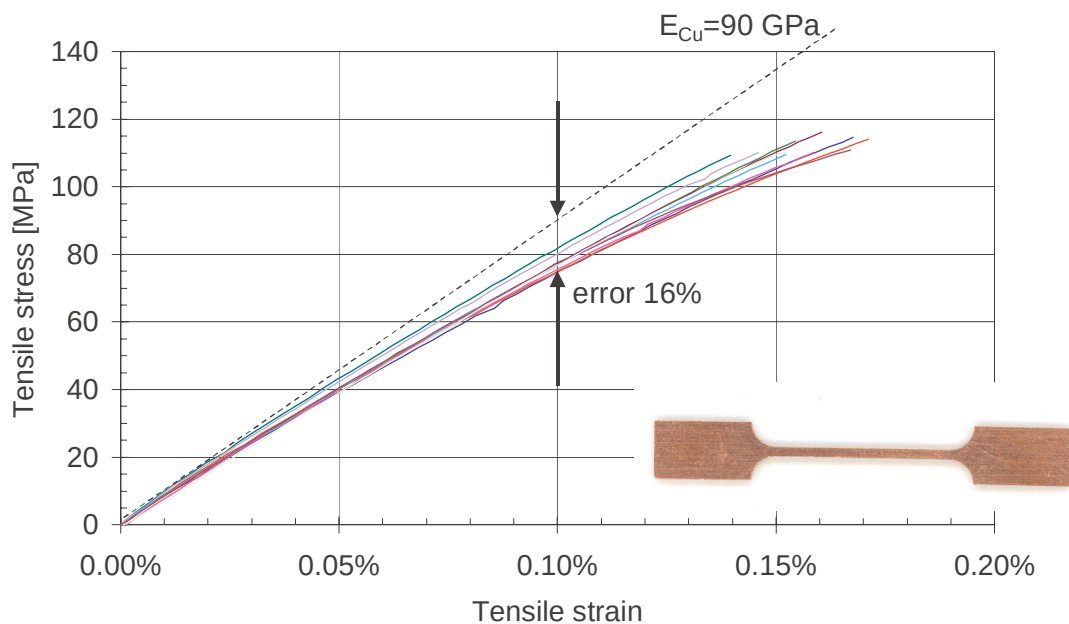


Figure 5. Tensile test specimens for verification of the measurements machine

4 TEST MEASUREMENT METHOD

In order to determine the displacement profiles to be applied to the copper samples, strains experienced in surface mount components have to be estimated. In Table 1 and Table 2 typical parameters are given for ceramic chip resistor and relevant materials. To calculate the strain range experienced by a chip resistor the following assumptions were made: the alumina in a 2512-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 length (L) is 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 the calculated approximate average shear strain range (γ) is recorded 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 (stand-off height).

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. Experimental total strain range

Resistor type	L [mm]	ΔL [μm]	γ	Δl (μm)
2512	6.2	7.5	0.094	30

A 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 shown in Figure 6. There is a difference between thermal cycling the PCB assembly and the copper-solder test specimen tested by the instrument. However the isothermal strain cycling in the instrument is a first approximation against which various solders can be assessed. In a full thermo-mechanical fatigue test the displacement profile would be synchronised with a temperature profile, simulating a thermal cycling experiment. The isothermal experiment may actually be a more severe test on a material. This is because the strain range is constant here, irrespective of temperature, but the creep rates will differ.

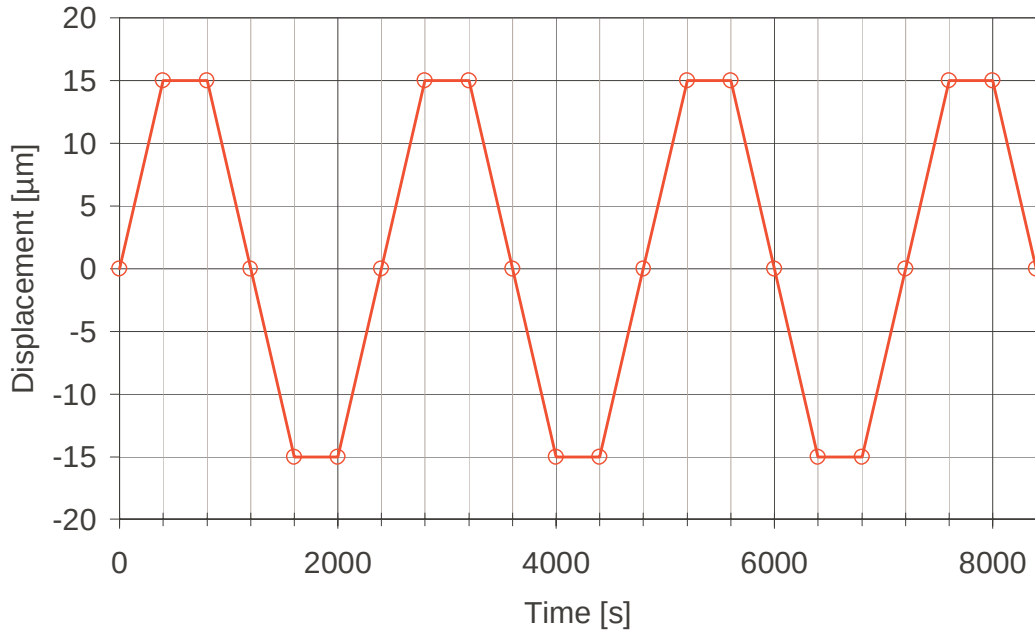


Figure 6. Displacement profile (equivalent to 2512-type resistor)

Failure can be defined by a load drop or by an increase in joint resistance during the strain cycling. Changes from 80%-50% 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; as the crack area increases the resistance through the solder joint increases. 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. Since the method is very sensitive and 0.1 $\mu\Omega$ increases in resistance can be detected, it is important to monitor specimen temperature and correct for thermal fluctuations.

A disadvantage of the specimen design is the elastic compliance in the copper body of the specimen. The specimen 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} - total measured displacement (deformation)
- L_{compl} - the displacement correcting for elastic deformation in the copper body
- L_{solder} - the displacement of the solder following the applied displacement profile

The maximum and minimum nominal stresses from each cycle are plotted in Figure 7. One failure criterion in measuring the life time of solder joints can be a relative load (or nominal stress) decrease by 50%. Other criteria can be defined as a resistance increase

(Figure 7, green line), which can be correlated with crack length. In Figure 7 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 then defined as the point of 50% load (nominal stress) reduction.

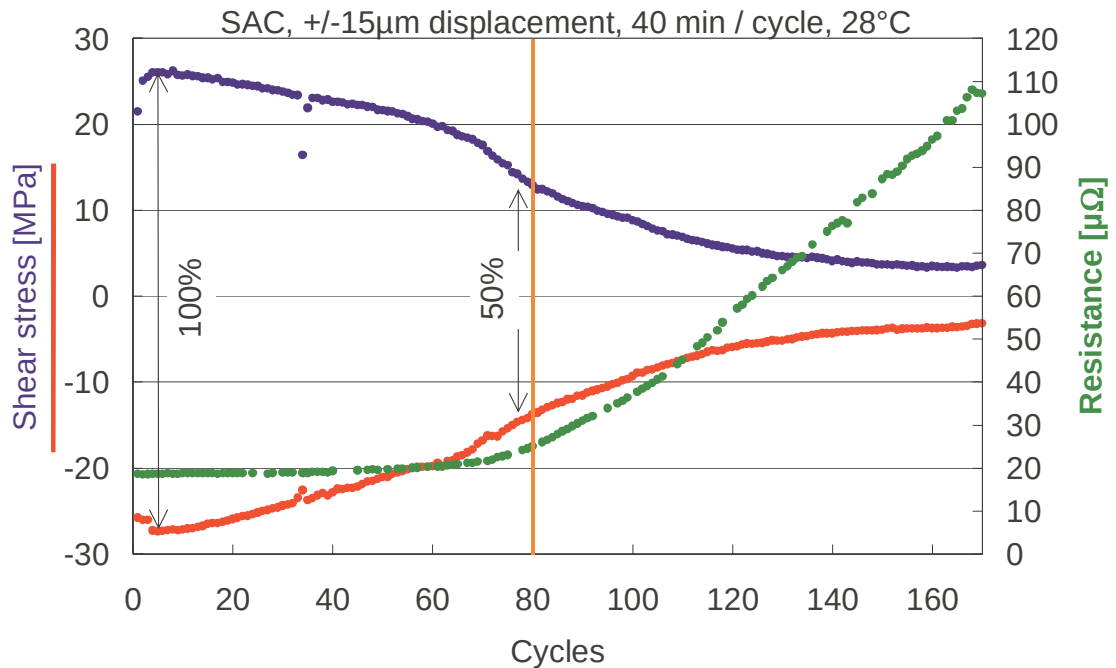


Figure 7. Maximum (blue) and minimum (red) nominal stresses, and resistance (green) across a solder joint during strain cycling

In Figure 7 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 ($\sim 10\text{A}$), which is related directly to the presence of a crack.. Hence ***the resistance measurement is directly related to the development of a crack.***

This correlation is demonstrated by re-plotting the data in Figure 8, in which 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 measurement of resistance can be used as a complementary technique to the measurements of load decrease. It is assumed the resistance value changes are purely a geometric effect, whereas the load drop may be influenced by other materials changes, such as strain hardening, and property changes due to the presence of any intermetallics. ***Hence the resistance data can be used to predict crack growth rates.***

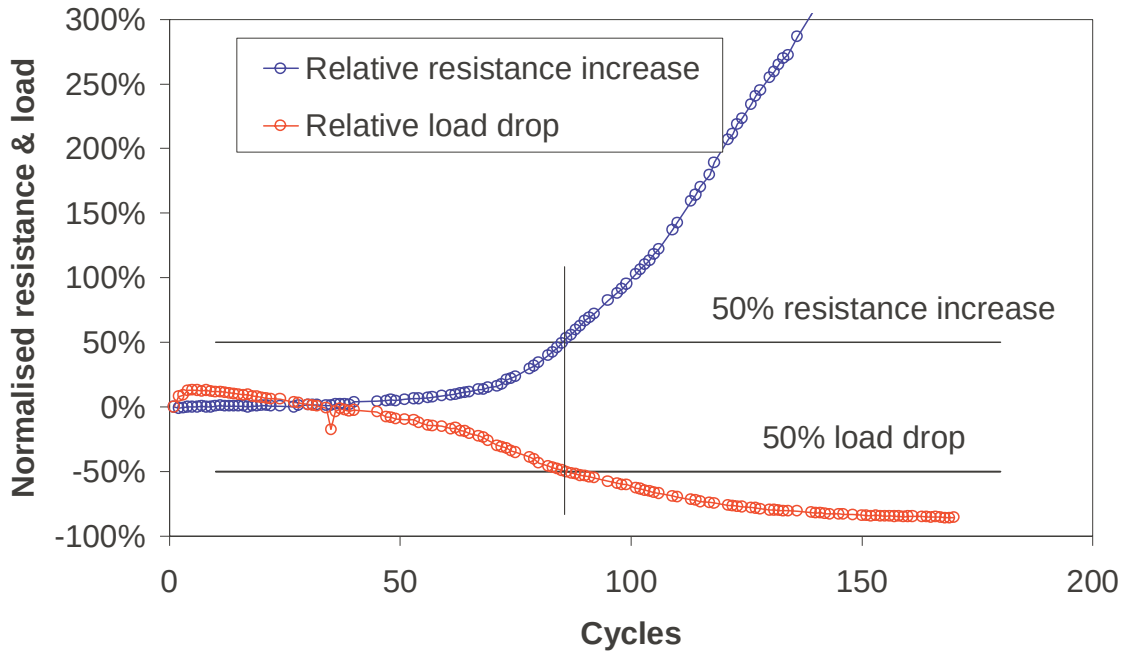


Figure 8. Normalised plot of load drop (red) and resistance increase (blue)

In Figure 9 absolute resistance is plotted for various solder joints at various temperatures, the resistance being measured at the end of each cycle. The initial resistance should be, for identical geometries, only a function of material and temperature. It can be seen that there is a variation in the solder joint size (length) since highest initial resistance (at 0 cycles) was recorded at 100°C and not 125°C. By normalising the relative resistance, the geometry and temperature variations can be eliminated as demonstrated in Equation 2. The relative resistance increases are plotted in Figure 10.

$$R_r = \frac{R_i - R_0}{R_0} \cdot 100\% \quad \text{Equation 2}$$

Where:

R_r – Relative resistance increase

R_i – resistance measured at the end of each cycle

R_0 – nominal resistance (before 1st cycle)

Crack growth can be estimated using the relative resistance of a solder joint. An electrical resistance model of solder joint is shown in Figure 11, and comprises a number of equally thick layers. In this analysis one of the layers contains the crack, and is being shorted, with a resultant resistance increase (number of cycles). The resistance measured across the solder joint does include a resistance in the copper body (R_c) and the solder joint (R_s) as expressed in Equation 3. A single crack model is used due to equivalence in electronic resistance circuitry i.e. two opposite cracks behave like one of double thickness.

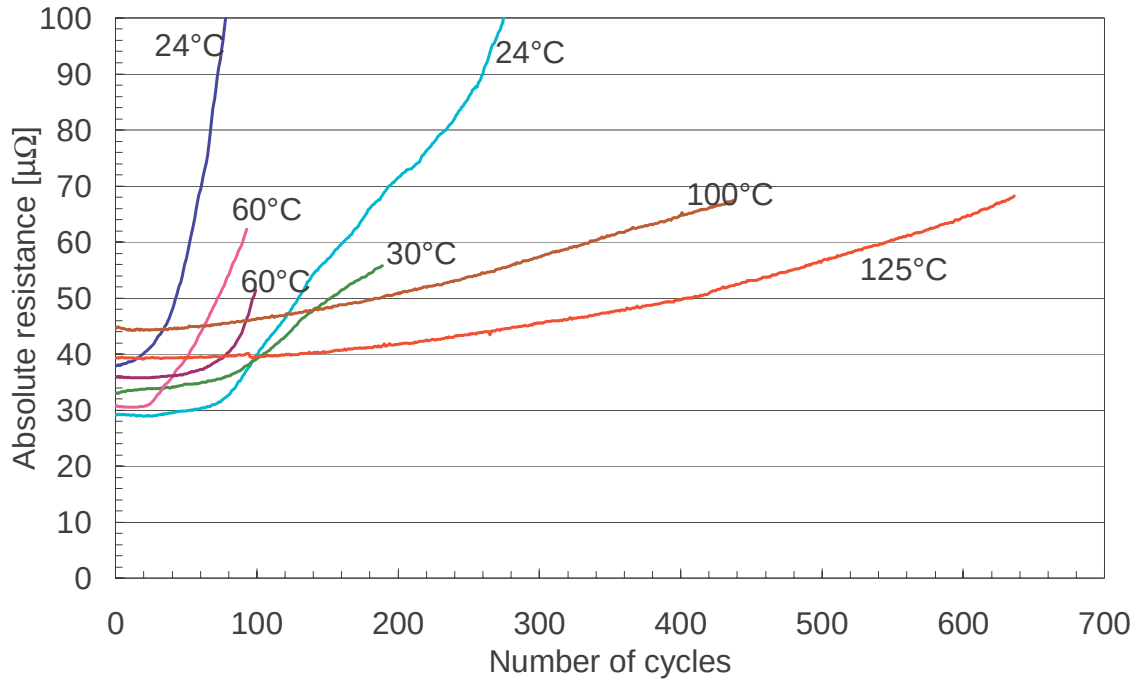


Figure 9. Absolute resistance as a function of number of cycles

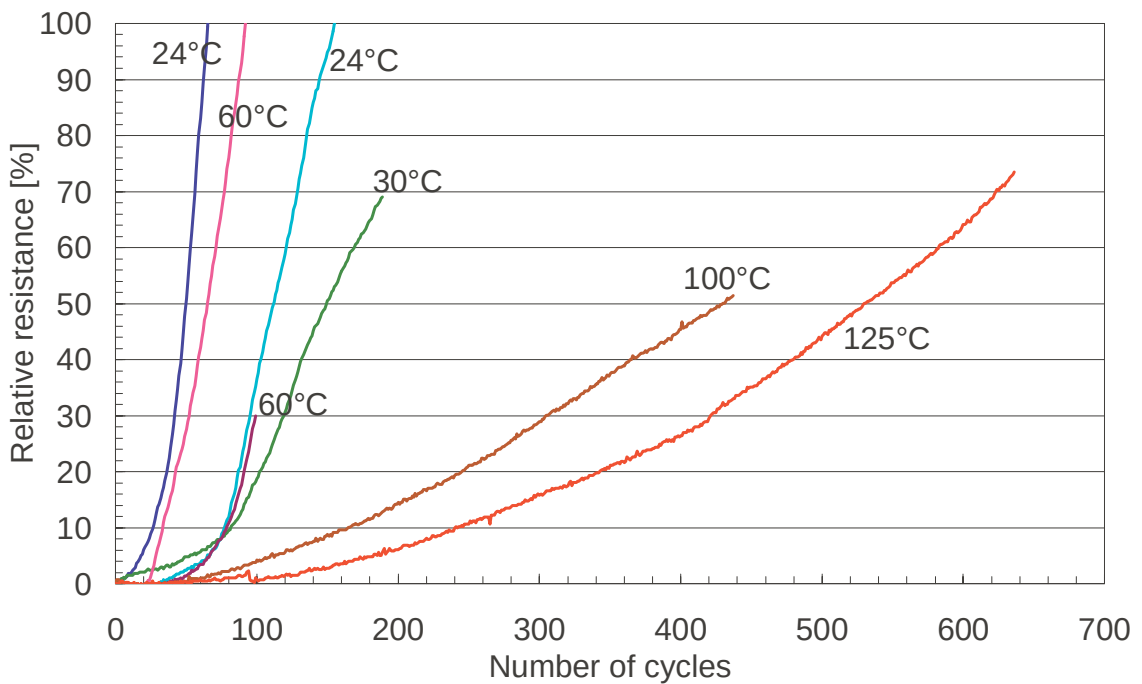


Figure 10. Relative resistance as a function of number of cycles

The resistance across the copper part is very low ($1.2 \mu\Omega$), due to larger geometry, and is in fact much lower than the resistance through the solder layers. For simplicity the crack length is assumed to progress along one interface only - see in Equation 4.

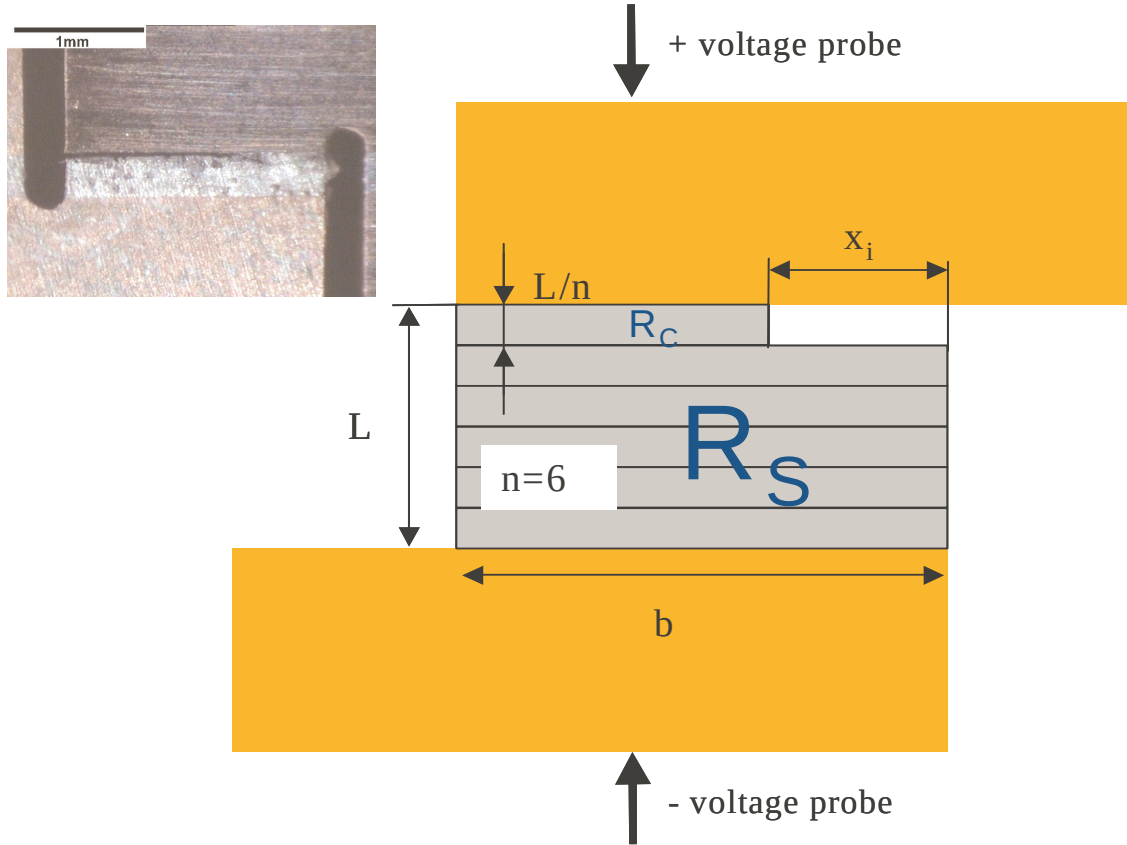


Figure 11. Model of solder joint for calculation of a crack length

$$R_0 = R_s + R_c \quad \text{Equation 3}$$

where: $R_c \ll R_s$

$$x_i = \frac{b \cdot n}{n + \frac{R_0}{\Delta R_i}} \quad \text{Equation 4}$$

where:

- x_i - crack length
- b - solder joint length (in direction of crack propagation)
- n - number of model layers (n is set to 6 in this experiment)
- R_0 - nominal resistance of solder joint
- ΔR_i - absolute increase of resistance after i -th cycle ($\Delta R_i = R_i - R_0$)

The only unknown variable in Equation 4 is n the number of layers in the model of the solder joint. The thickness of a crack is hence the gap (L) divided by number of layers (n). To estimate n , simulations was undertaken on one measurement in which n was varied from 5 to 100. Results of this simulation are shown in Figure 12. It can be seen that a small noise at the beginning of experiment contributed largely to a scattering of results of crack length for large values of n (small crack height). After the analysis of

noise the value of n was arbitrary set to 6. According to the model larger values of n would significantly open and close the crack, which does not accord with observations using a microscope.

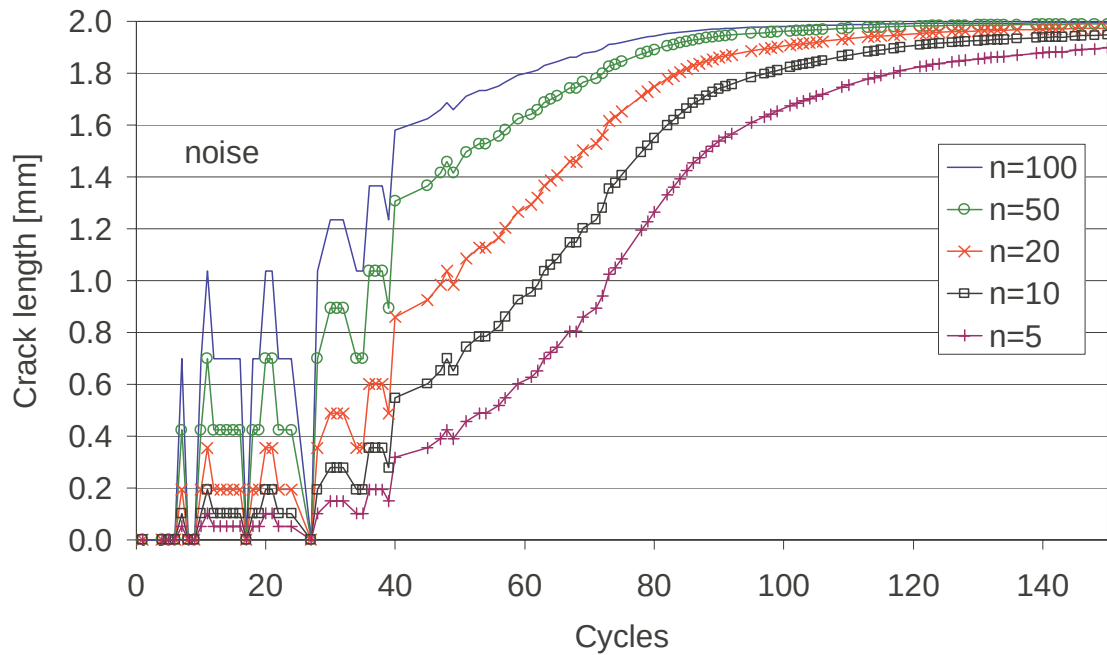


Figure 12. Simulation of crack length as a function of the number of layers n

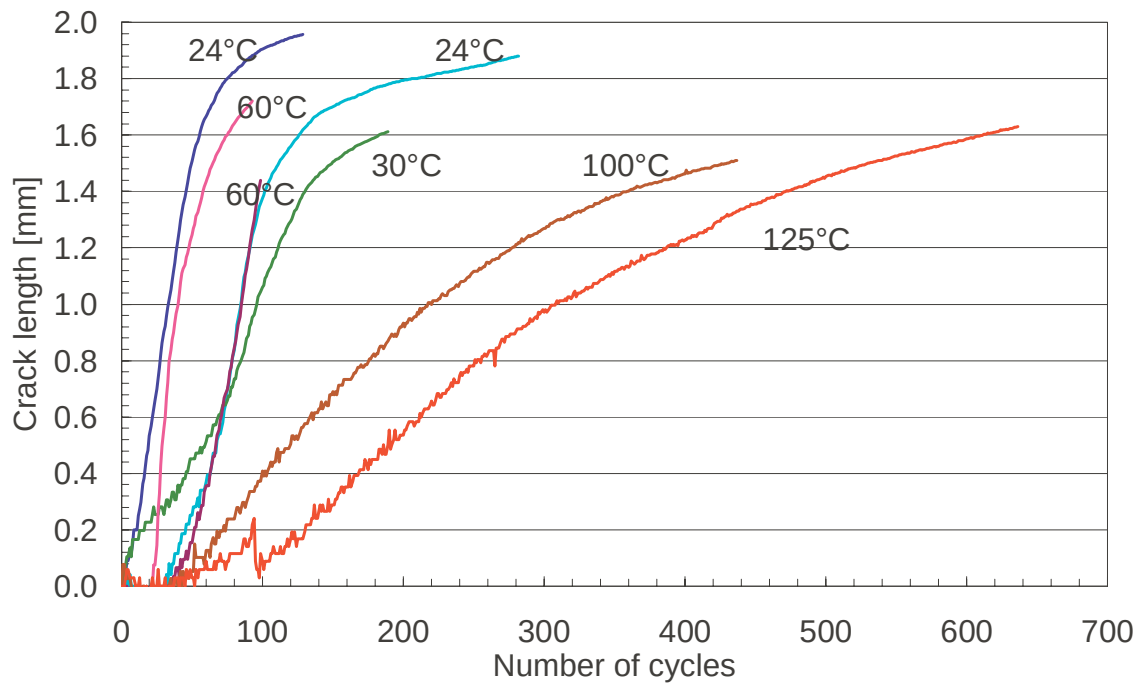


Figure 13. Crack length as a function of the number of cycles for $n=6$ and various solder joint temperatures

In Figure 13 the relative resistance measurements have been converted to crack length according to the model with $n=6$ (Equation 4). In general, ***crack growth is slower at higher temperatures with slow mechanical cycling where creep and stress relaxation dominate the deformation mode.***

Figure 14 presents a comparison of the engineering and true shear stresses present for measurement taken at 24°C. Usually, the true stress cannot be calculated, since the area over which the load is acting is unknown, but in this case the crack area can be predicted from the relative change in resistance. The calculation indicates that, unlike the engineering stress, the true stress increases as the crack grows. These results show that the final true stress achieves values close to the yield point [Ref 7]. These higher stresses are more consistent with failure of the joint than are the engineering values. Comparisons with literature values are limited by the low strain rates and relaxation that were present in these experiments.

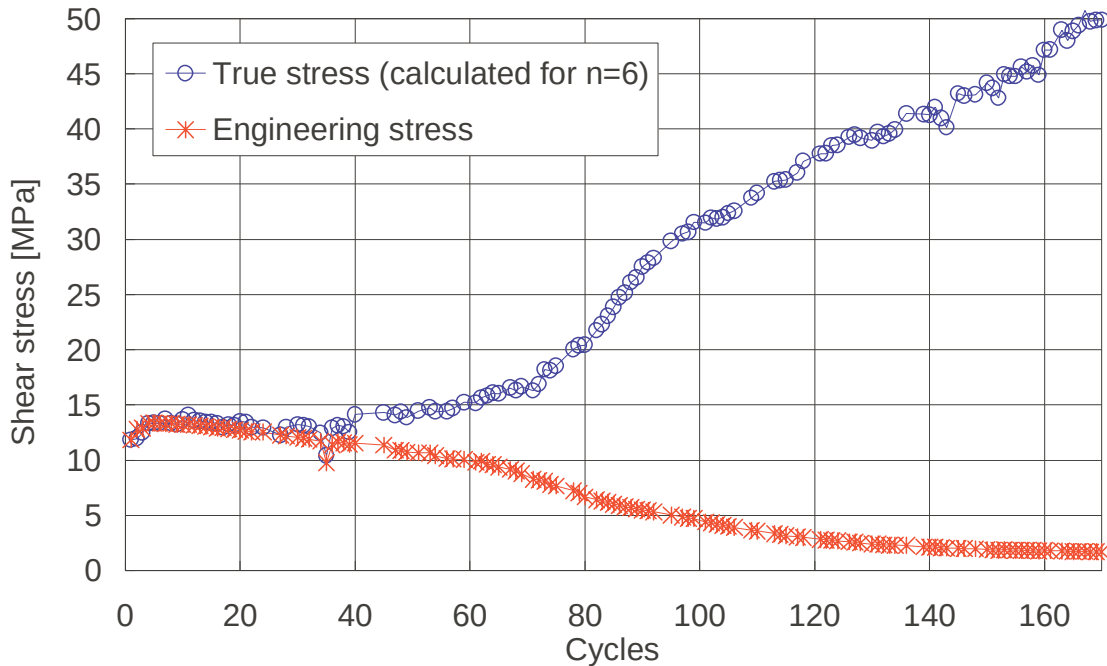


Figure 14. Comparison of true (calculated) and nominal (measured) stresses at 24°C

It is useful to be able to relate crack length and joint resistance – see Figure 15. For example, a 50% increase in resistance corresponds to a crack growth of 75% relative to the solder joint size, for $n=6$ (Equation 4).

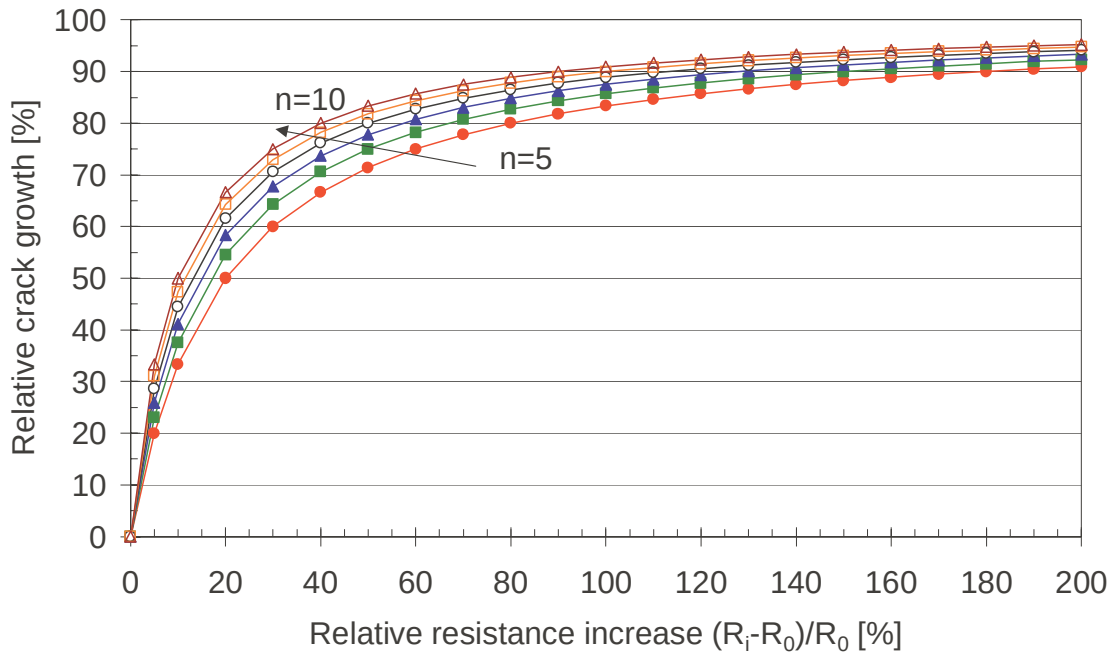


Figure 15. A model relation between relative resistance increase and crack growth for number of layers $n=5$ to 10

5 RESULTS OF MEASUREMENTS

Tests were performed to evaluate lifetime and the development of true stress during isothermal fatigue. The SnAg3.5Cu0.5 test specimens were measured at 24, 30, 60, 100 and 125°C. The most significant difference from the engineering stress hysteresis loops was that as the crack developed, the hysteresis loop did not collapse, but increased in area. Hence the creep energy density, proportional to hysteresis loop area, was increasing and eventually reached a critical value causing the solder joint to break down. During the fatigue test it is assumed that strain is controlled according to the set-point profile, which is, in practice, very difficult since the dynamic properties of solder change as the material fatigues. The design of a controller (PID, or PI^2) has to accommodate changes and correct for dynamic behaviour of the material under test [Ref 8].

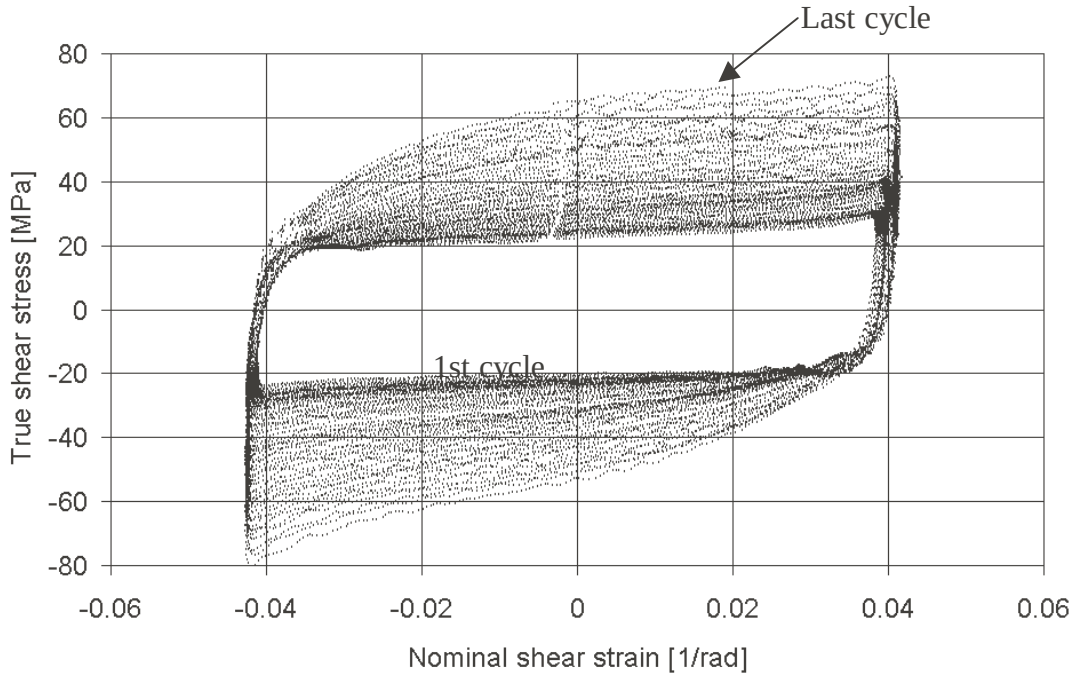


Figure 16. True stress hysteresis loops at 24°C

Figures 16 to 22 present the result of fatigue and development of the hysteresis loops under isothermal conditions at various temperatures. The first cycle is always on the inside of the envelope of loops and the last cycle is the outer envelope. It is clear that at higher temperatures the solder material does not resist to the same level of stress as it does at lower temperatures for the same level of strain deformation. With a slow cycle in which creep and stress relaxation play dominant roles, the number of cycles to failure increases with higher test temperatures. This is in agreement with the damage collected (or the strain energy density) in one cycle at low or high temperature.

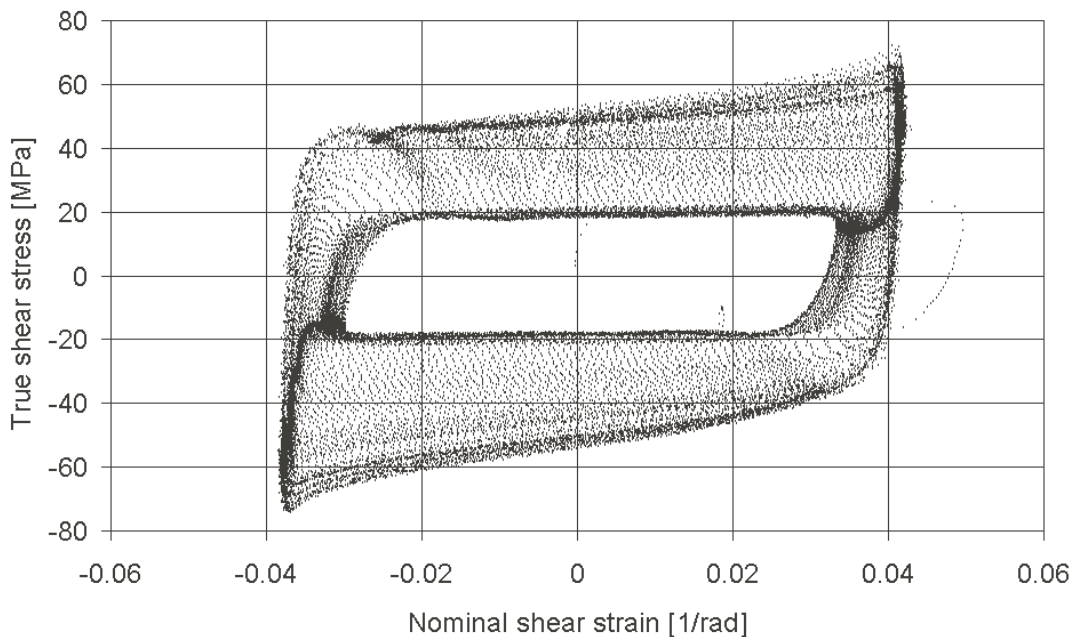


Figure 17. True stress hysteresis loops at 24°C

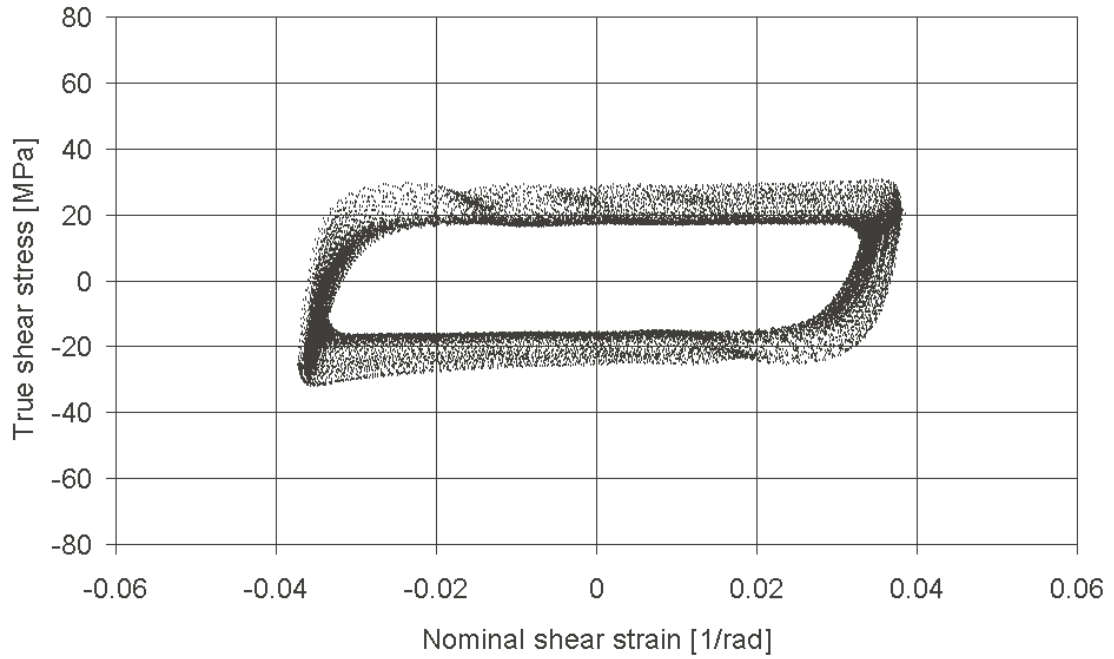


Figure 18. True stress hysteresis loops at 30°C

Figures 16 and 17 represent repeat measurements. It should be noted that the 30°C test was terminated after 70% increase in resistance, whereas at 24°C the test was terminated at 100% increase. Hence the loop is larger for the 24°C test.

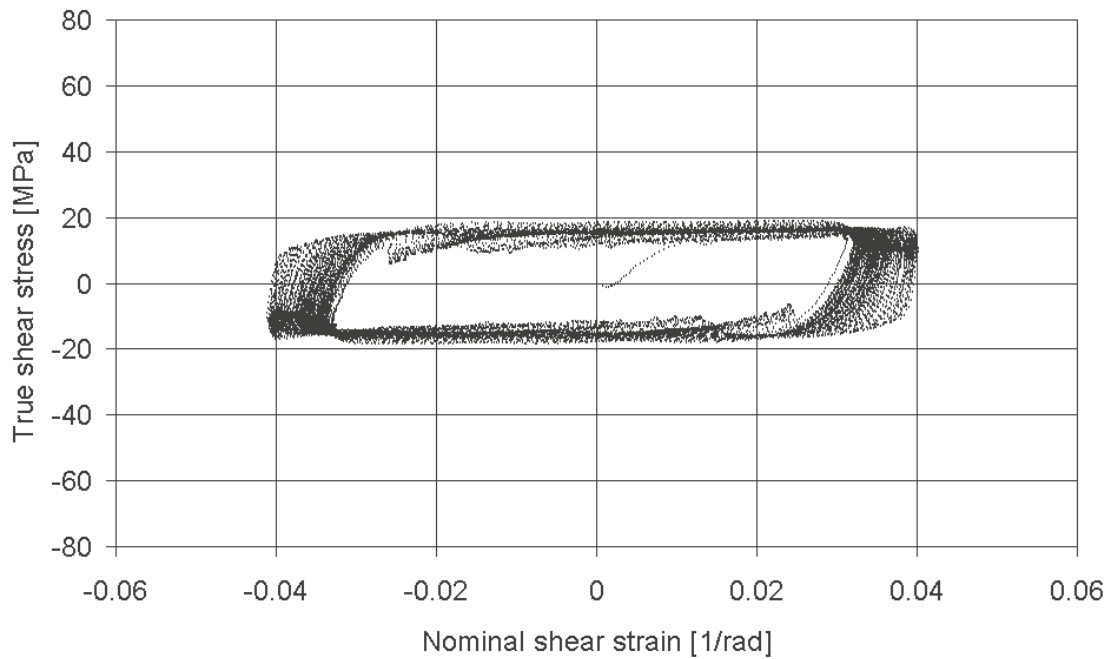


Figure 19. True stress hysteresis loops at 60°C

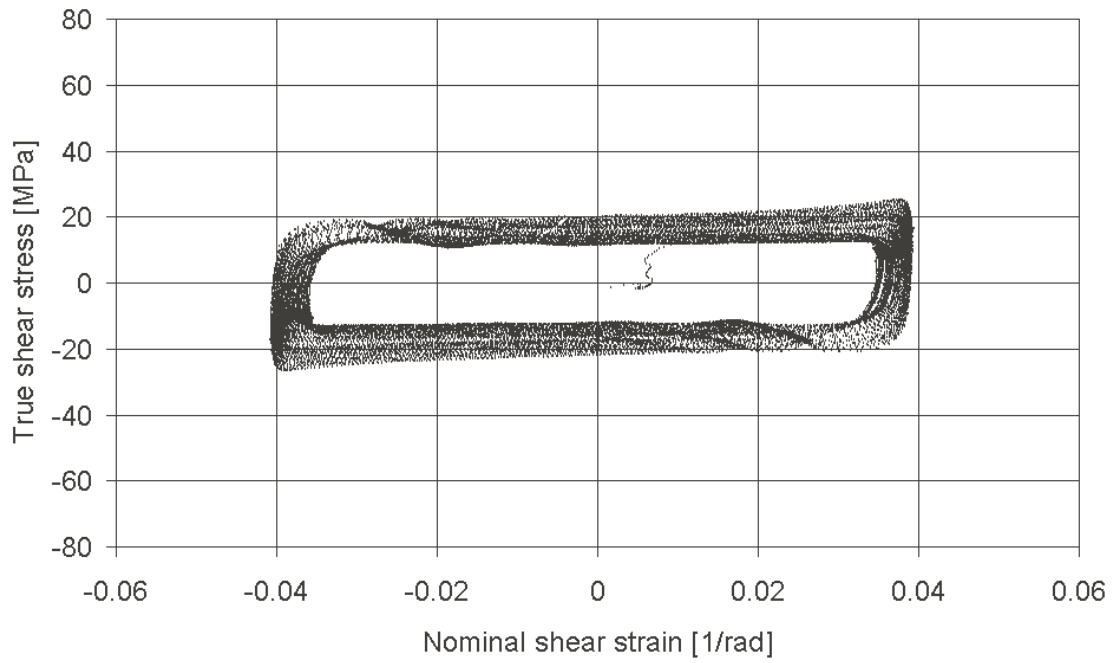


Figure 20. True stress hysteresis loops at 60°C

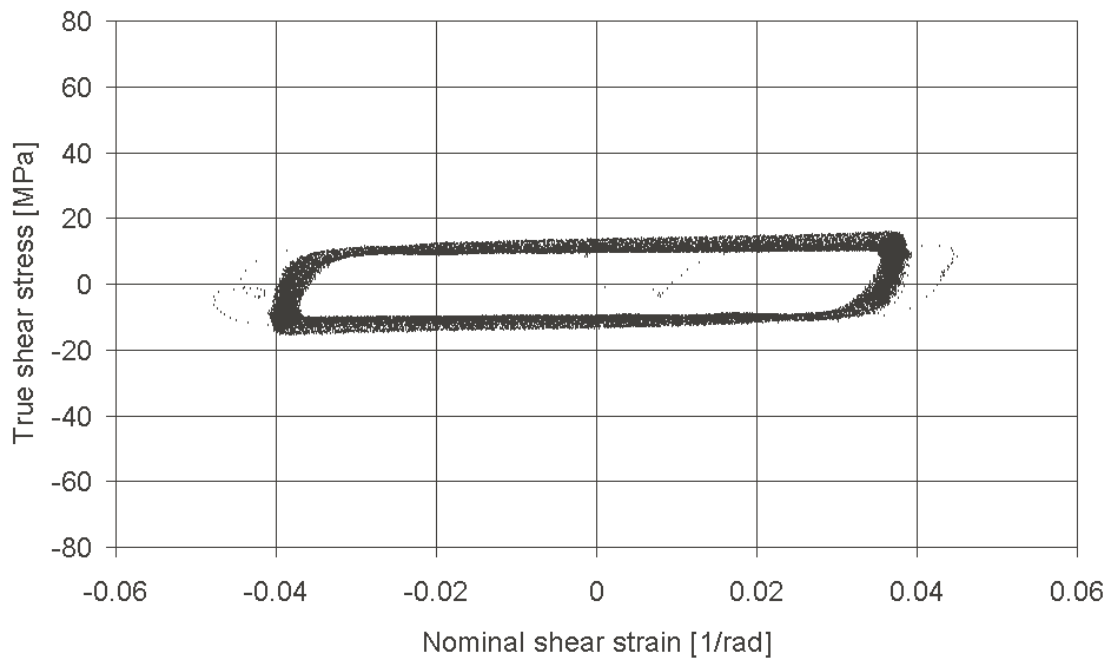


Figure 21. True stress hysteresis loops at 100°C

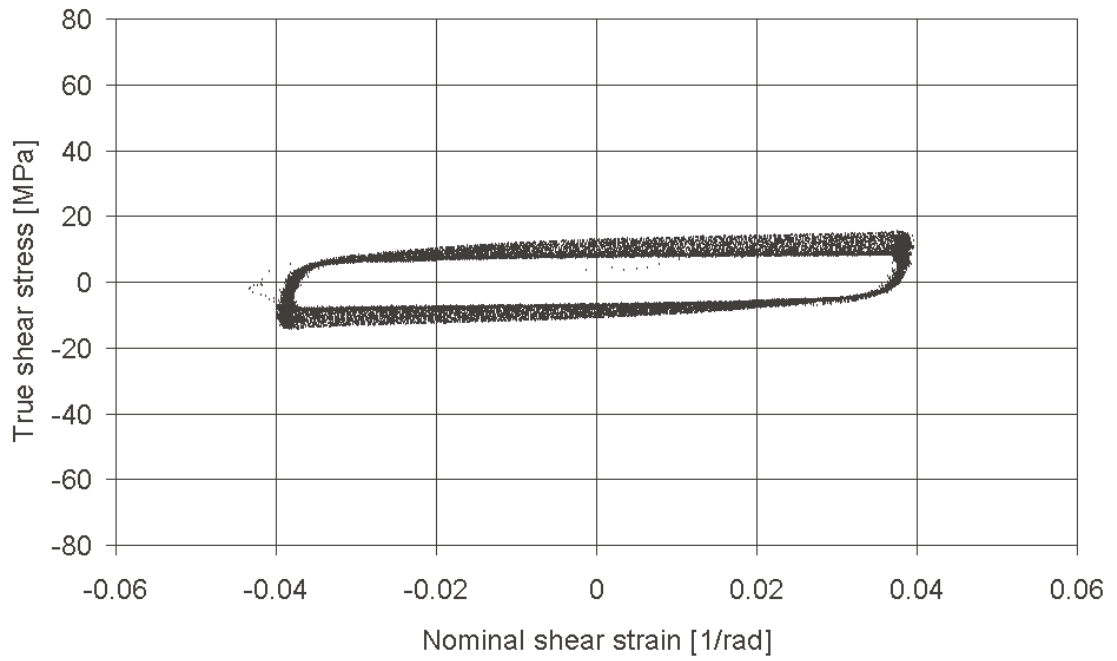


Figure 22. True stress hysteresis loops at 125°C

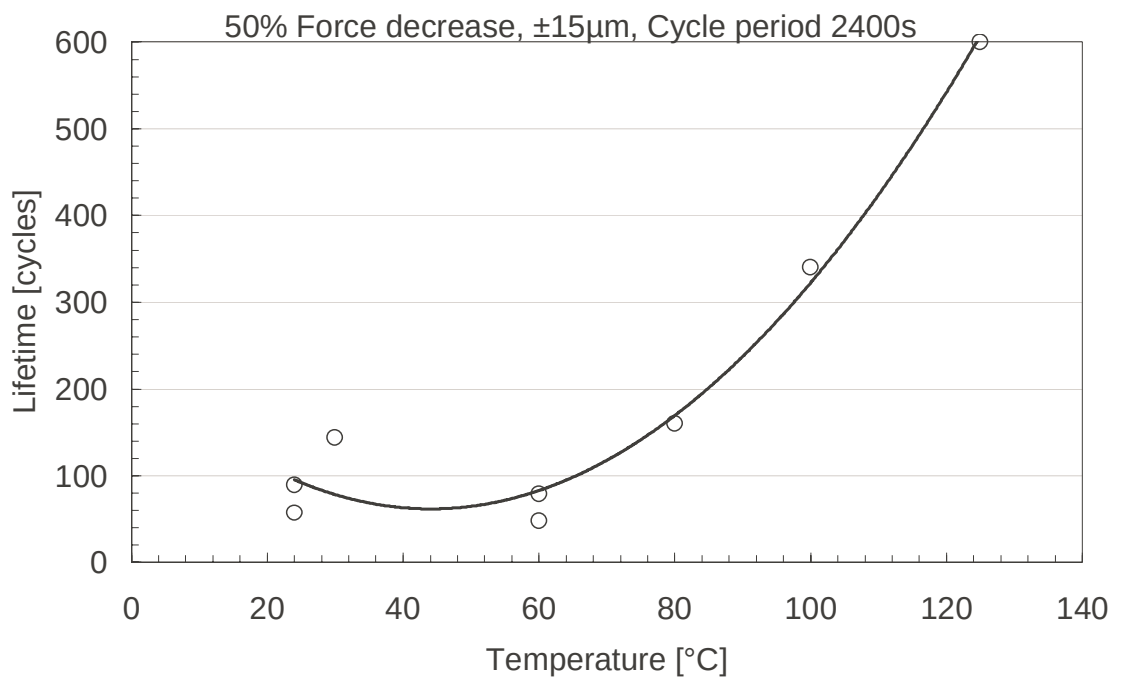


Figure 23. Lifetime of solder joints at various temperatures based on 50% load decrease

The isothermal fatigue measurements of Sn3.5Ag0.5Cu solder are summarised in Figure 23. The lifetime is assessed as the number of cycles necessary for a 50% reduction of load amplitude

Alternatively, the increase in resistance can be used to assess lifetime as shown in Figure 24, and outlined in Section 4. The criterion is a 50% increase in resistance, corresponding to a similar crack area.

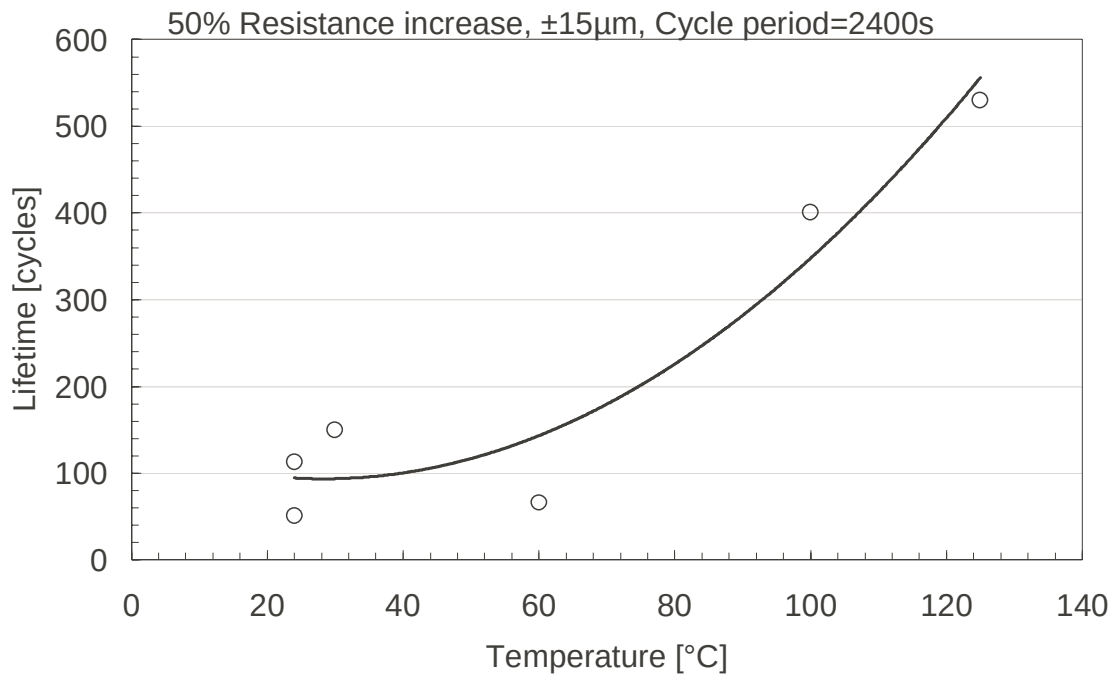


Figure 24. Lifetime of solder joints at various temperatures based on 50% resistance increase

The linear relationship between the two failure criteria (load decrease and resistance increase) is highlighted in Figure 25. The correlation coefficient is 98.2% for the 50% failure criteria. When compared for 20% criteria, shown in Figure 26, the correlation coefficient is 92%. For a linear fit, 96% of the data fit with the 50% failure criteria, and 84% of data fit the linear function for 20% failure criteria.

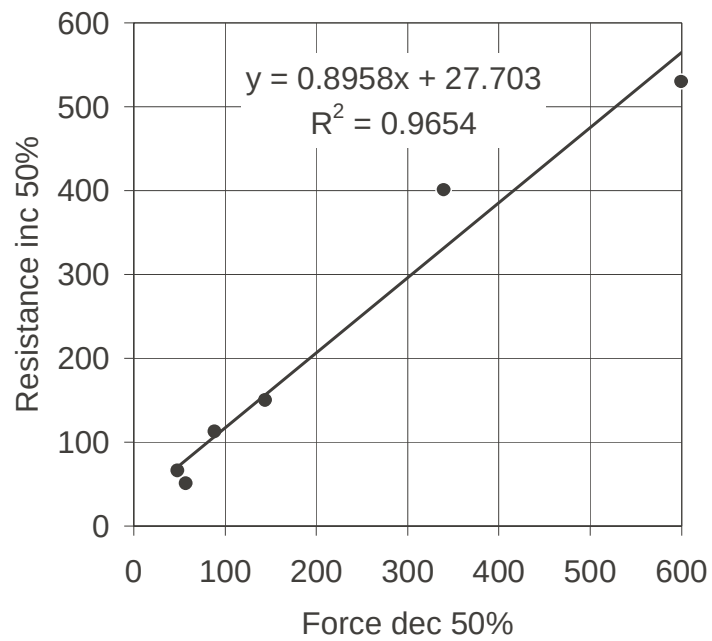


Figure 25. A linear fit between resistance increase and load decrease (50% criteria)

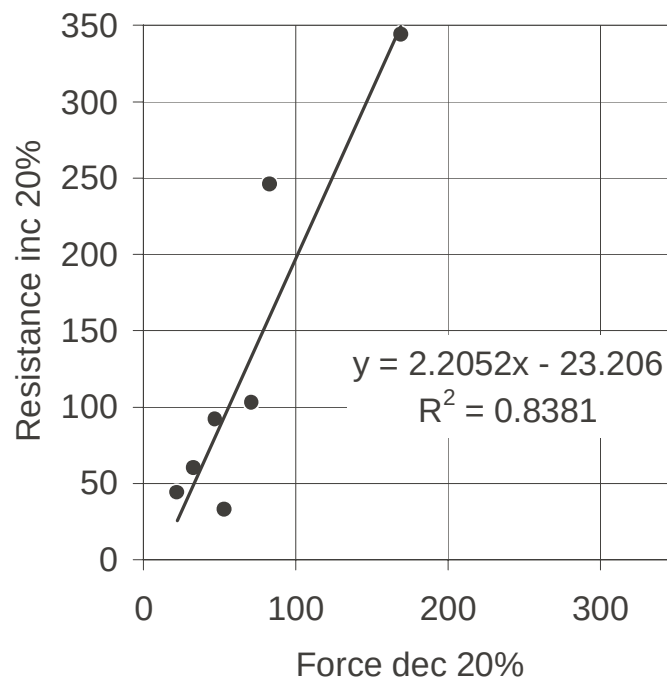


Figure 26. A linear fit between resistance increase and load decrease (20% criteria)

From this approach it is clear that ***lifetime*** (Figures 23 & 24) ***can be measured using the load decrease and/or the resistance increase***. Example lifetimes derived from these measurements have been demonstrated for 50% load drop and 50% resistance increase (75% crack length). These are important parameters for lifetime predictions, and the applicability can be broadened by measurements using different size joints and strain ranges. By integrating the strain energy density, as measured by the true hysteresis loop area, it is possible to determine the strain energy density to rupture (strain energy density capacity) of a solder material. This will be a fundamental parameter of any particular solder performance, with great significance in predicting joint reliability. ***Measuring these parameters directly, for different solders and conditions, and relating them to real assembly performance, will greatly advance modelling of 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 and 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 and temperature that reflect common usage. Preliminary data thus acquired are presented, which can be utilised by FEA modelling of solder performance.
- A 4-point measurement system for resistance monitoring has been evaluated and the results found to correlate well with load decrease during isothermal fatigue testing of solders.
- A route to predict a fundamental reliability variable of solder has been identified

7 ACKNOWLEDGEMENTS

The work was carried out as part of a project in the Materials Processing Metrology Programme of the UK Department of Trade and Industry.

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