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The Measurement of Creep Rates and Stress Relaxation for Micro Sized Lead-free Solder Joints

Milos Dusek & Chris Hunt

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The Measurement of Creep Rates and Stress Relaxation for Micro-sized Lead-free Solder Joints

Milos Dusek & Chris Hunt
Engineering & Process Control Division

ABSTRACT

With the arrival of legislative restriction on the use of lead solders there is a need to classify tests for obtaining material properties of lead-free solders. The main concern is that lead-free solder does not behave in the same way as lead-containing solder under accelerated thermocycling testing conditions, in particular that the joint is in shear whereas creep data have traditionally been obtained under tensile conditions. This is complicated by the ever decreasing volume of solder used in electronics interconnection, and testing should reflect the size of solder joints used in modern components in which solder joints are commonly found to be the weakest links. In this work a suitable new test method has been generated and validated, and FEA analysis has confirmed that the dominant mode of solder joint deformation in the test piece is the desired shear mode. The results have also highlighted the importance of primary creep, which must be included in any modelling of lead-free solder fatigue.

Stress relaxation is an alternative approach in generating relevant and credible material properties for low cycle fatigue, in which it is possible to estimate the actual stress in solder joints as a function of time. The method offers a number of advantages for obtaining data from micro-sized joints e.g. it takes account of primary creep, is relatively quick, and particularly useful when estimating stress in solder joints during thermal cycling temperature dwells. Using the new test method the performances of Sn3.5Ag, Sn3.8Ag0.7Cu and Sn37Pb solders were evaluated during creep and stress relaxation, as the basis for an efficient fatigue test and a source of data for FEA modelling purposes.

Although the differences between the secondary creep rates of SnAg and SnAgCu alloys are only marginal there is an interesting observation when compared to that of SnPb. When tested under constant stress and temperature the secondary creep rate of SnAgCu or SnAg can exceed that of SnPb at stresses above a shear stress of 20 MPa. Below this level the SnPb solder creeps faster than lead-free solders. This implies that the calculations of acceleration factors, as well as the temperature test profiles, have to be modified to match service conditions.

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National Physical Laboratory
Hampton Road, Teddington, Middlesex, TW11 0LW

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by Dr M G Cain, Knowledge Leader, Materials Processing Team
authorised by Director, Engineering and Process Control Division

CONTENTS

1 INTRODUCTION

With the arrival of legislative restriction on the use of lead solders there is a need to be able to predict the service life of solder joints made using lead-free solders – cf. solder joints are commonly found to be the weakest links in electronic assemblies. In turn this demands suitable test procedures for obtaining credible materials properties of the lead-free solders. The main concern is that lead-free solder does not behave in the same way as lead-containing solder under accelerated thermocycling test conditions. This is complicated by the ever-decreasing volume of solder used in electronics interconnection, and any test procedure should reflect the size of solder joints used in modern assemblies.

During service life solder joints experience thermo-mechanical loading, which causes re-crystallisation and fatigue. Hence test conditions for solder materials should reflect the loading conditions experienced under normal use. Testing conditions (strain rate, strain range, temperature) can be selected to permit empirical relationships (the constitutive equation) to be constructed. In this work simple geometries are tested so that the constitutive equation can be derived more straightforwardly. From this base more complex solder joint geometries can be modelled. For example a single thermocycle includes elastic deformation, primary and secondary creep as well as stress relaxation. All these mechanisms are temperature, stress, strain and strain rate dependent and can be described by tabulated values or combination of exponential, power and/or hyperbolic sine laws. To carry out calculations of stress-strain hysteresis loops and thus predict the reliability of lead-free solder joints a computer representation has to be constructed from finite elements, in the form of a 3D mesh. Solder joint calculations are then performed based on boundary conditions, i.e. the temperature cycling values. The important factor in the calculations is the time step used in the iteration algorithm, and using smaller time steps will improve the precision of the model, but more iterations and time are needed to calculate strains and stresses throughout the whole mesh and thermocycle [1]. The biggest factor in determining the model's accuracy is the quality and credibility of the materials data.

The main aim of this work, therefore, was to develop and validate a new method for generating high quality materials data from lead-free solder joints with geometries and dimensions mirroring those used in current assembly technology.

2 SPECIMEN MANUFACTURING

Traditionally, solder properties have been typically measured using samples manufactured by casting or machining into standard [2, 3] dumbbell ("dog bone") specimens, for both elastic and plastic material properties. However, such measurements give properties representative of bulk materials, which are not necessarily a good representation of the solder found in microelectronic joints [4]. Solder joints are usually formed between copper-coated electrodes and their volumes are in a range of 0.1-1 mm^3.

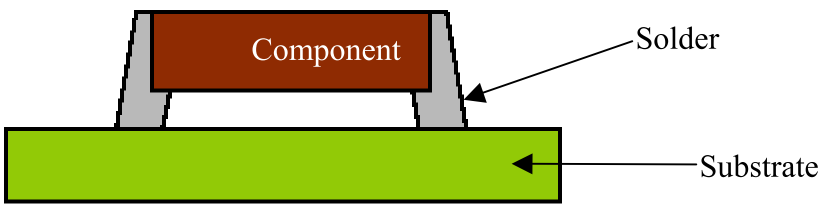

Figure 1. Typical geometry of a surface mount component on a base substrate

Figure 1 is a schematic of typical geometry for an electronic component mounted on a surface of a base substrate. The component body is usually manufactured from various layers of materials having either structural or electrical function. The component body materials are either metals, polymers, inorganic (glass) or ceramic, and the electrical materials are metals or inorganic semiconductors. The base substrate is either made from ceramic or polymers (thermoplastic or thermosetting such as resins), with glass fibres and sometimes metal reinforcement. The solder attachment joint is responsible for joining components to the base substrate with both a mechanical and an electrical bond. As a mechanical joining material solder has to resist strains developed between components and a base substrate. Indeed with the complete assembly manufactured with such materials, it is the solder that is the compliant point and relieves accumulated stresses.

The geometrical orientation of the component and substrate means that most of these strains are acting in shear, and accompanied by bending moments. Since a typical solder joint is about 100 μm in height, there are only a few microstructural grains from top to bottom of the joint. This of course is not typical of the situation in the bulk. Furthermore, we do not have a free surface, the solder is allowed at the interface with component and substrate by the formation of an intermetallic. Therefore any proposed test specimen should have a volume comparable to that of the solder joints used in electronics and should contain a metal interface with copper. In this experiment two lead-free alloys, Sn95.5Ag3.8Cu0.7 and Sn96.5Ag3.5, and one lead-containing alloy, Sn63Pb37, were used.

To form a solder joint the following procedure was followed. Solder joints were formed inside a copper bar, with dimensions of length 40 mm, height 7 mm, and thickness 1-3 mm. A finished specimen is shown in Figure 2. The bar was partly cut through the middle of the 6mm side. The gap was filled with a solder paste and reflowed with a gas torch, which supplied enough heat to reflow the solder paste. The gap width was determined by the thickness of the diamond blade cutting wheel (in this case 0.4 mm), and the solder joint size was defined by two additional trimming cuts as indicated in Figure 3. The created solder section could therefore be easily prepared between 1-2 mm long. Thinner joints are possible providing a thinner diamond blade is used, or alternatively thinner copper bars can be used (solder joint size down to 1 x 1 x 0.15 mm). If required during a test the specimen can be heated by passing an electrical current through it. Additionally, if the joint face is properly polished the developing microstructure of the joint can be observed during a test, and localised strains can be measured using a camera and image correlation system.

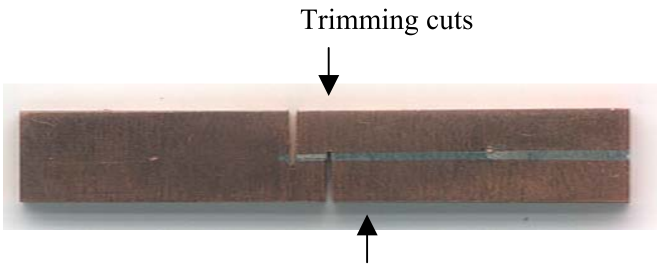

Figure 2. Specimen used for creep and stress relaxation testing

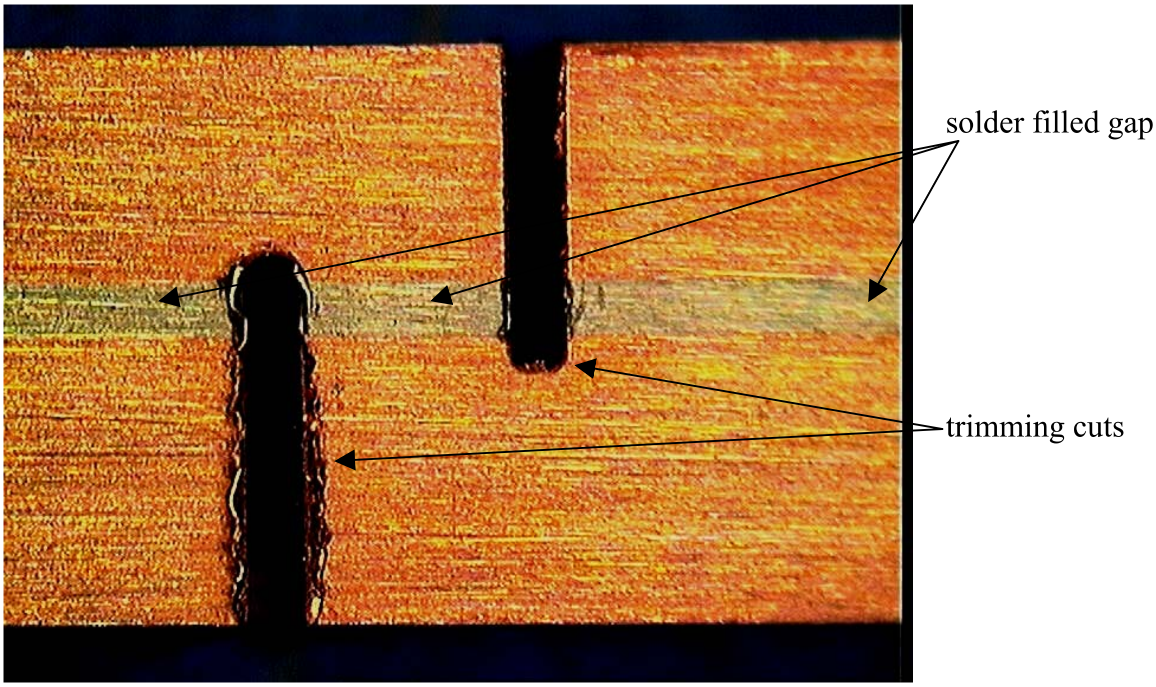

Figure 3. Detailed view of a solder joint for mechanical testing in shear

An issue with any new specimen design is how the is load dispersed. It is obviously desirable that the deformation is uniform throughout the entire solder joint volume, which is experiencing simple shear.

The deformation field inside the solder volume and copper bar were evaluated using FEA analysis. The results confirmed that during straining (tensile loading of the copper bar) the resultant shear strain appears to be uniformly distributed through the solder rather than the copper parts. Figure 4a illustrates a typical displacement field in the whole specimen, whilst Figure 4b provides a plot of the individual displacement at a cross-section whose location is indicated by an arrow.

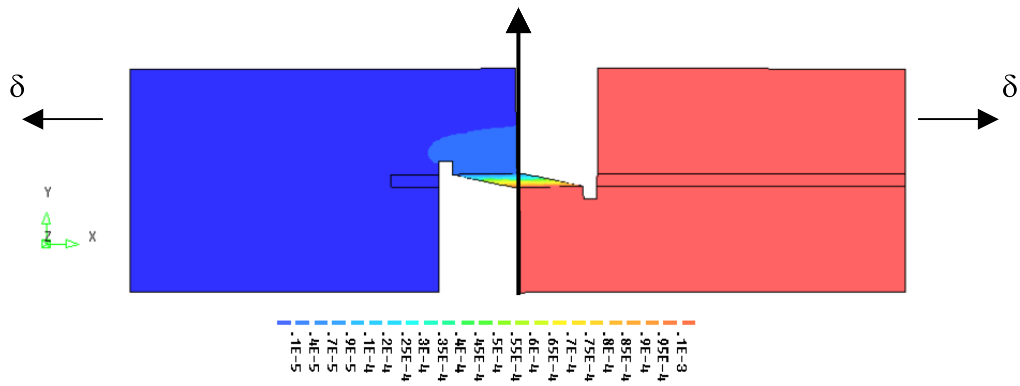

Figure 4a. FEA model of creep specimen showing direction and orientation of local vertical displacement

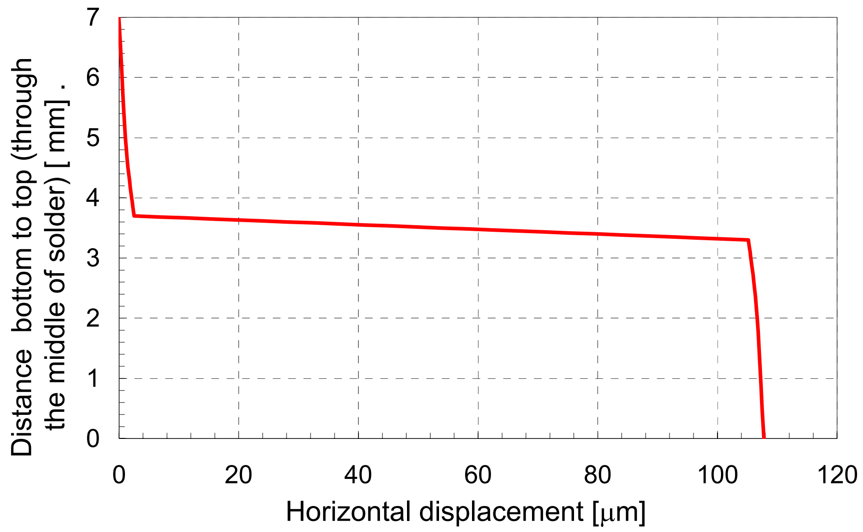

Figure 4 b. FEA model of creep specimen showing local vertical displacement in the sample along the arrow

Figure 4a,b highlights that virtually all the strain appears in the solder with only 5% of the total deflection in the copper. A similar analysis for the vertical component shows there is minimal deflection. Together these results confirm that the solder deformation is essentially in simple shear. It is pertinent to note that, in reality for components assembled onto substrates, both will tend to bend slightly i.e. the solder does not experience only simple shear, and there will be bending moments [5] as depicted in Figure 4b by the minimal, but real, change in the displacement.

3 CREEP MEASUREMENT

Creep is a time-dependent plastic deformation measured as a function of applied load and temperature. The load can be applied by simply hanging weights on a specimen or by a displacement arm with a load cell. Strain can be measured locally (camera + image correlation) or by displacement sensors [6]. The output variable of a creep test is a strain or strain rate (first time derivative) plotted as a function of time. Another way of plotting and analysing creep data is by using log strain rate vs. strain diagram [7]. Creep tests are usually long-term experiments that may include all three stages of creep - primary, steady (secondary) and tertiary (third) creep region (stage), as outlined in Figure 5. Lead-free solders reveal differences in primary creep to that of SnPb, which typically has negligible primary creep. The primary creep rate is unknown in lead-free solders and constitutes a significant gap in our knowledge of lead-free solder material properties. How primary creep affects reliability is not fully understood, and currently one of the challenges is to include this behaviour with the secondary creep behaviour in one constituency equation [7].

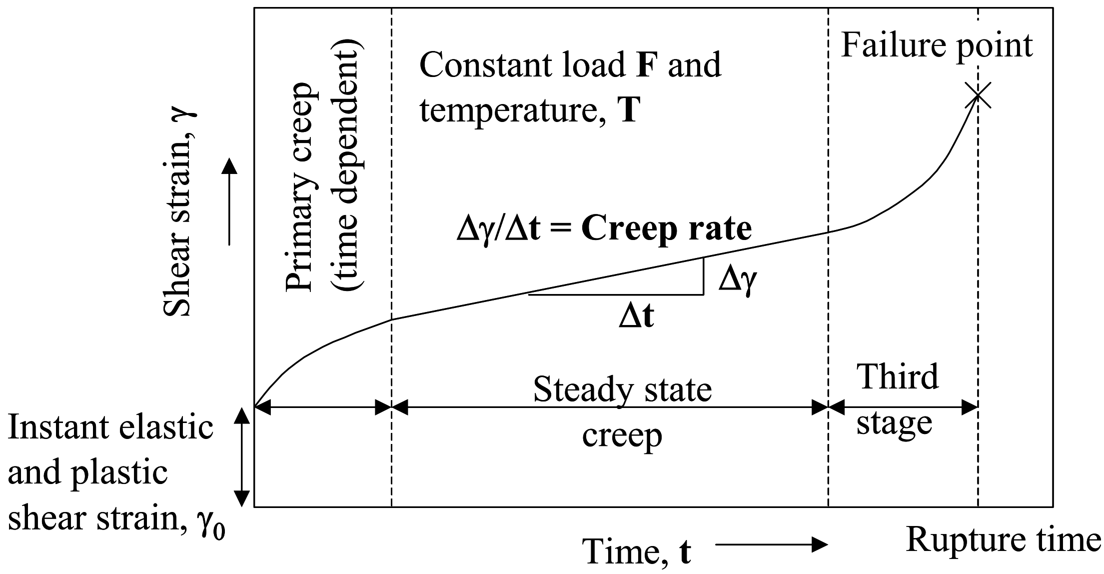

Figure 5. An idealistic creep curve

Figure 6 demonstrates a simple step test for assessing the yield stress of SnAgCu alloy. These measurements were taken using the NPL ETMT (Electro-Thermal-Mechanical Tester) now built under licence by Instron Corp., called ETMT Mark 2. A specimen is subjected to increasing stress (stepwise 1 MPa/min) and the strain is monitored at room temperature. For stresses up to 2 MPa there is a linear relationship (slope = shear modulus of elasticity), but the slope changes above 2.5 MPa. This slope change can be explained by time dependent plastic deformations hence creep tests at room temperature should be performed at stresses above 2.5 MPa.

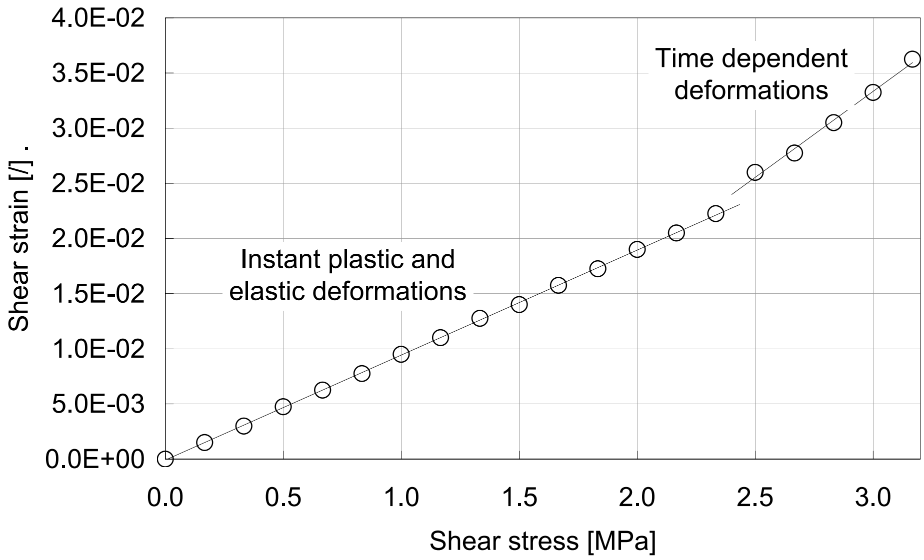

Figure 6. Estimate of SnAgCu elastic limit at 21°C

In Figure 7 there is an example of a creep test measured for SnAg solder. The specimen's solder joint volume was 2 x 0.4 x 3 = 2.4 mm^3, and the equivalent shear stress was 13.3MPa.

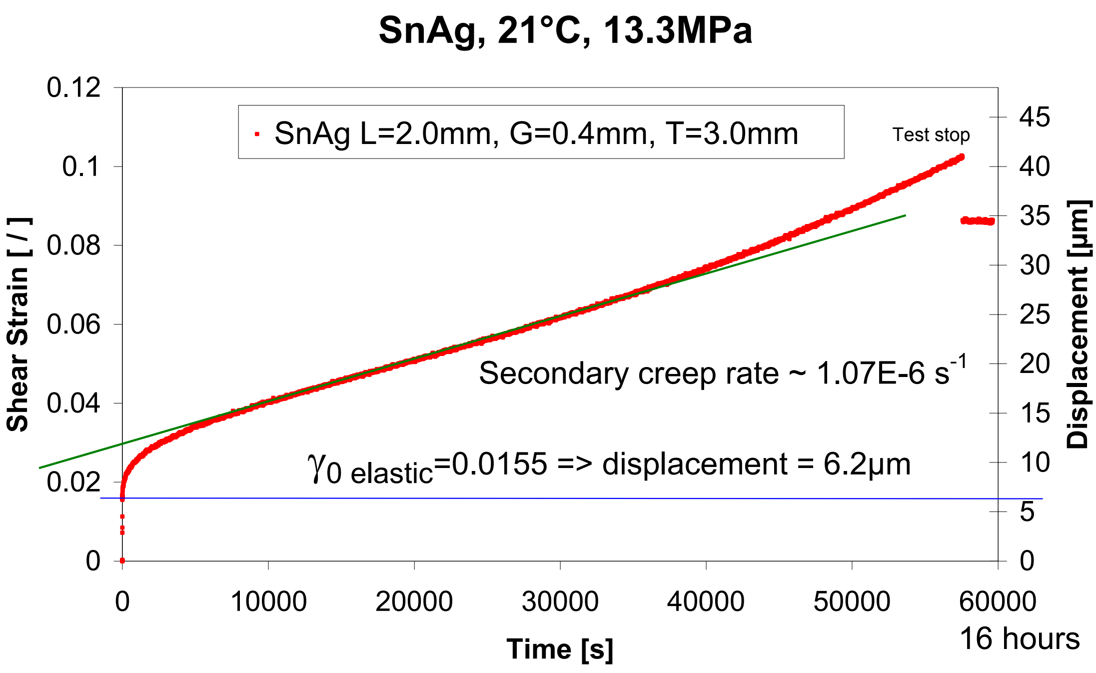

Figure 7. SnAg solder joint measured at constant load of 80N

The γ_0 in Figure 7 corresponds to an instantaneous elastic and plastic strain, which is followed by time dependent primary, secondary and tertiary creep. From the slope of the fitted line a minimum secondary creep rate can be derived. This region is a measure of steady plastic elongation under constant load. In Figure 8 a typical test specimen is shown after rupture in a creep test

Figure 8. Shear test specimen after ternary creep rupture, side view

Creep rate is a key material property used in FEA modelling and is needed to calculate the plastic deformation per thermal cycle. From the measurement of creep for this geometry an assessment of solder joints for more complicated shapes (i.e. BGA ball) is possible. To model a solder joint completely the creep rate must be known as a function of temperature and applied stress, so that the strain can be calculated in each finite element [8].

In Figures 9, 10 and 11 creep characteristics measured for SnAgCu, SnAg and SnPb solder for several nominal stresses (load / joint area) are presented. It is apparent that with SnPb and SnAg solder joints, the primary region is small, whereas with SnAgCu solder primary creep appears to extend for a greater time, and this difference is readily apparent for a shear stress of 25 MPa.

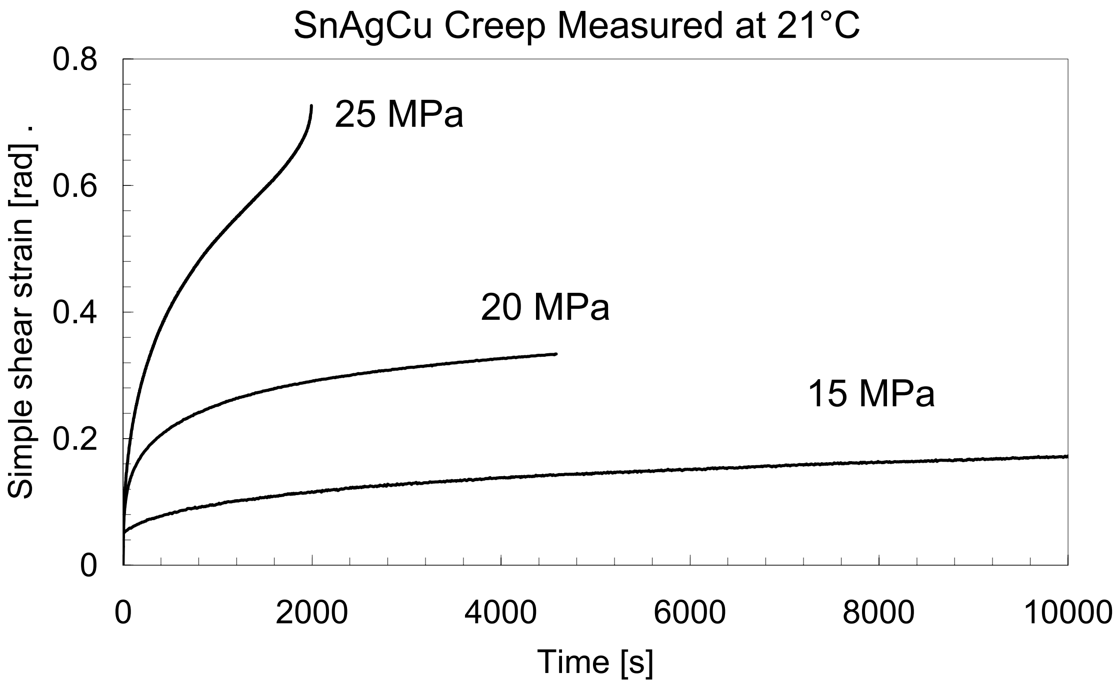

Figure 9. Creep strain for 3 shear stresses for SnAgCu measured at 21°C

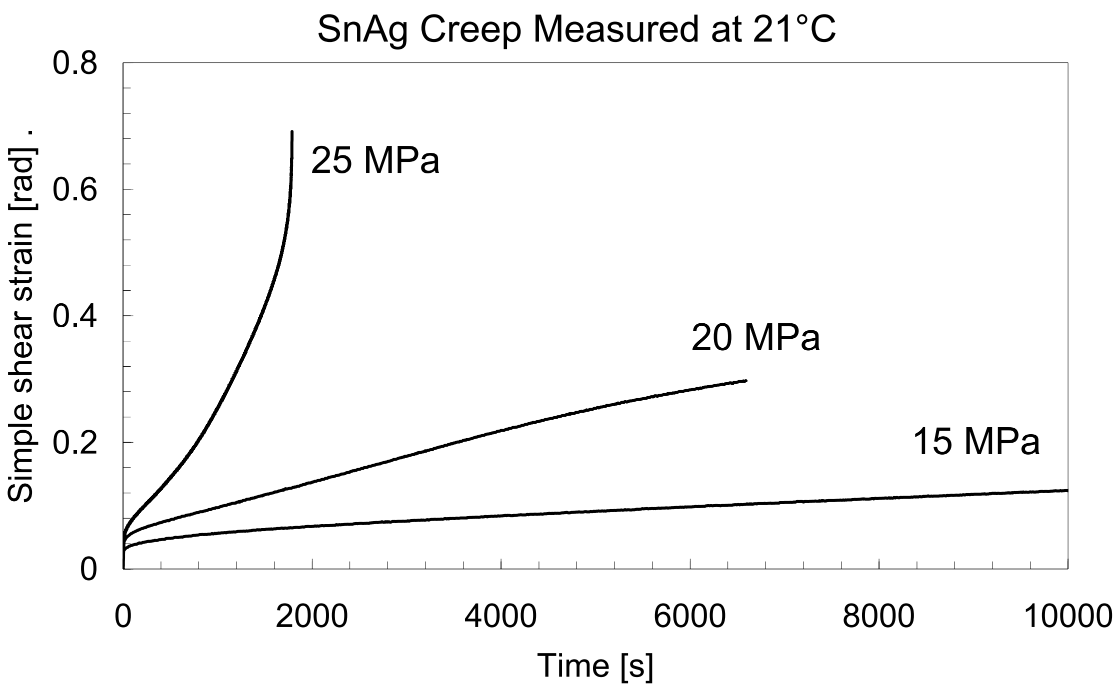

Figure 10. Creep strain for 3 shear stresses for SnAg measured at 21°C

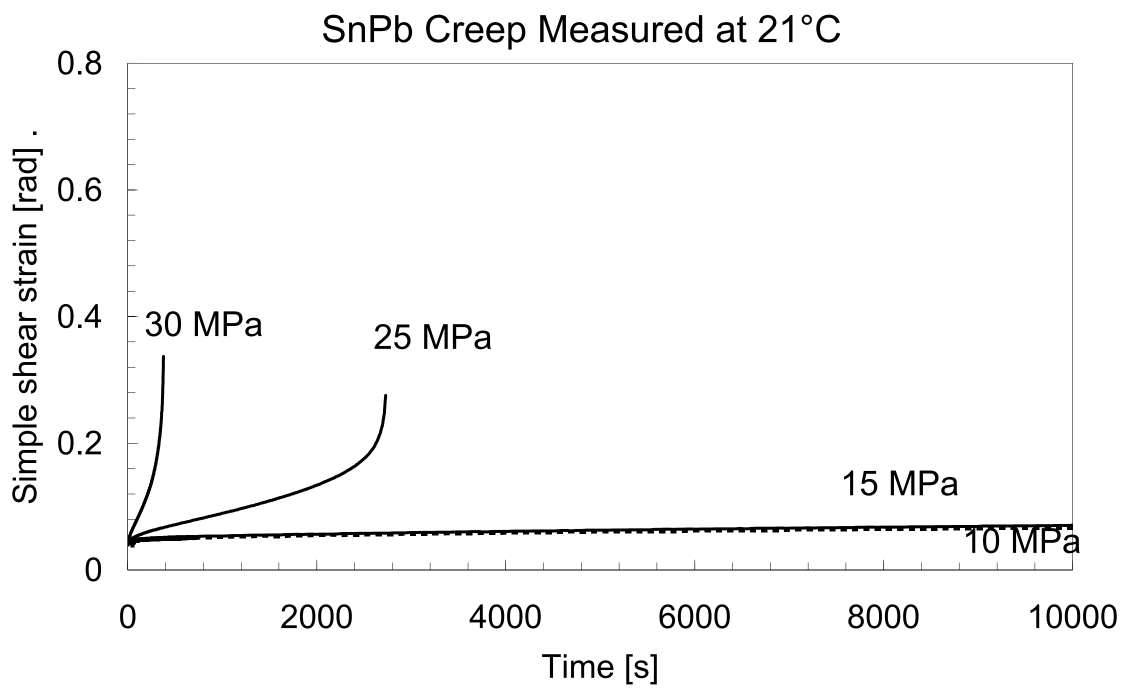

Figure 11. Creep strain for 4 shear stresses for SnPb measured at 21°C

In Figure 12 the minimum secondary creep strain rates for the three alloys are plotted as a function of applied stress at room temperature. The data show that at 20 MPa the secondary creep rates encountered by SnPb solder and both lead-free solders are very similar. However, Figure 12 shows an interesting difference between the slope of the line for SnPb and that for the two lead-free alloys. Below the cross-over point at 20 MPa, the SnPb solder creeps more quickly than the lead-free alloys, whereas above 20 MPa the opposite is true. This switch between which alloy creeps faster, depending on the stress, is indicative of different deformation processes that give rise to creep between lead-free and tin-lead solders.

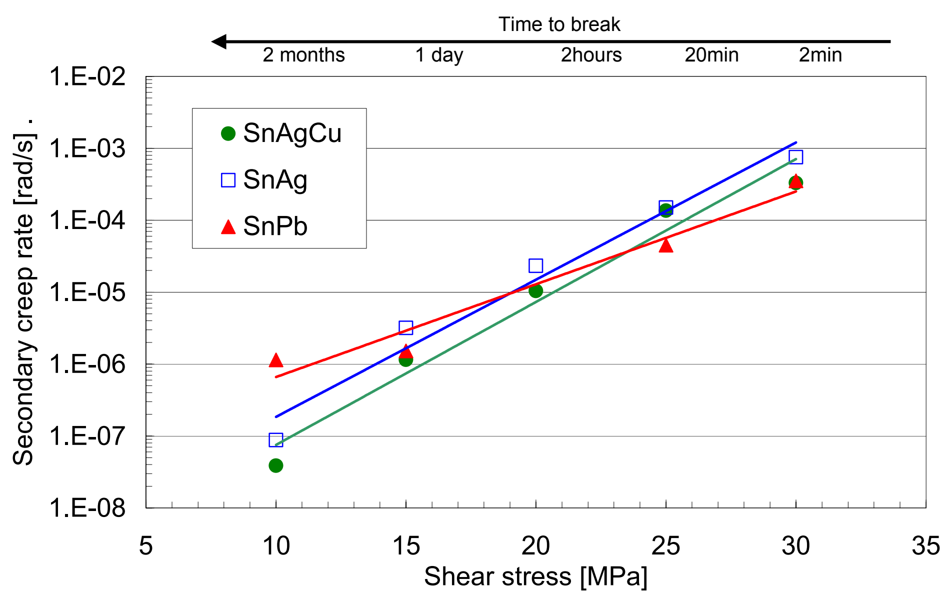

Figure 12. Secondary creep strain rate for SnPb, SnAg and SnAgCu at 21°C

In Figure 13 the secondary creep strain rates are illustrated for the three solders at two stress levels and three temperatures. It is clear that the creep rates change significantly with temperature between 20 and 80°C, by approximately a factor of 100. In the case of the SnPb alloy this change is even greater, reflecting its greater temperature sensitivity and lower melting point.

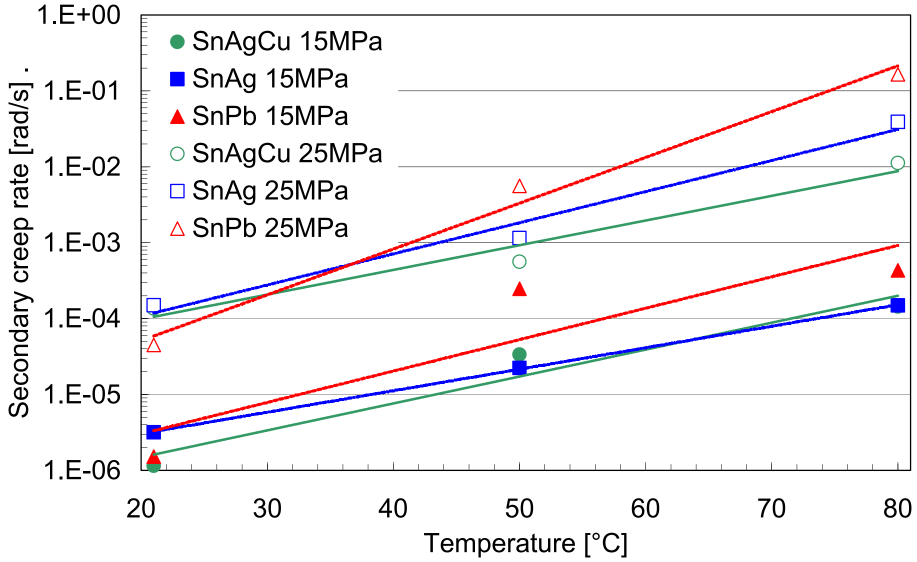

Figure 13. Secondary creep rates for SnPb, SnAg and SnAgCu at 21°C

A typical test specimen after the creep test is shown in Figure 14. The vertical grinding marks on the specimen's surface are clearly visible, and these are uniformly deformed in a diagonal direction, (except for the side edges and the solder interfaces). The results of fine polishing of this surface are presented in Figures 15 and 16, which reveal tin dendrites arranged in parallel bands (colonies) with clearly delineated boundaries. These boundaries are weaker than the matrix and are often the location for cracking when the final tertiary creep region is reached.

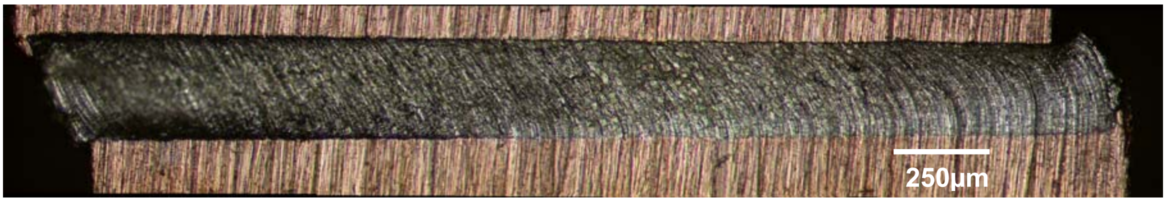

Figure 14. Microstructure of SnAgCu after a creep test (15 MPa at room temperature) coarse grinding marks show localised strain

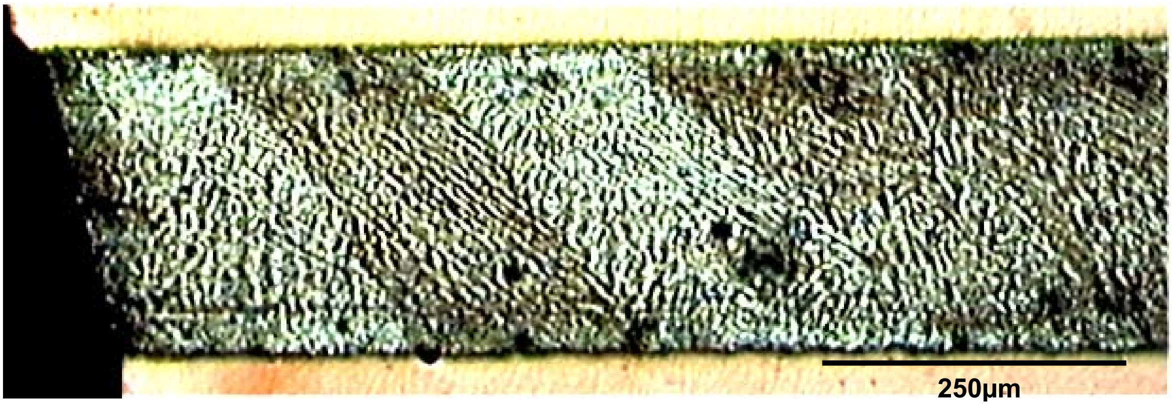

Figure 15. Tin dendrite colonies arranged into bands after a creep test (SnAgCu at 15 MPa and room temperature)

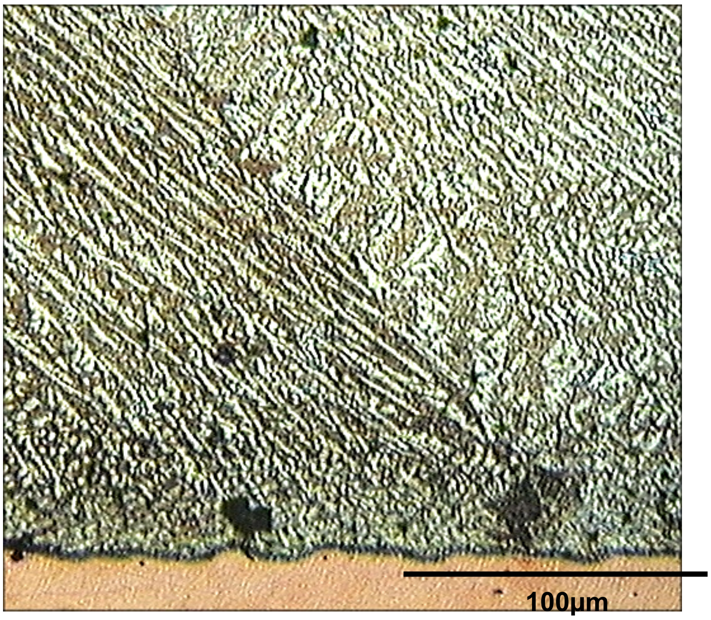

Figure 16. Detail of deformation tin dendrites forming a colony after a creep test (SnAgCu at 15 MPa and room temperature)

4 STRESS RELAXATION MEASUREMENT

During accelerated testing low cycle fatigue of solder takes place. An accelerated testing regime is typically thermocycling [9] or power cycling, during which stress is accumulated due to localised CTE material mismatches. The relatively weak solder joints are the most compliant materials in the assembly (Figure 1), and hence any stress due to localised CTE mismatches (i.e. between components and substrates) is relieved by the solder. This scenario is different to that posed in the previous section where a constant stress was applied. In the case of stress relaxation an instantaneous and fixed strain is applied. This is more representative of thermal cycling in which the CTE mismatch applies a fixed elongation.

To measure the stress relaxation rate, a nominal stress is applied by displacing specimens a certain distance. This displacement is then maintained while monitoring the load. In Figure 17 an example of this load relaxation following the application of 25 MPa is shown for SnPb and SnAgCu solders. For SnPb two initial stress settings were used, 20 and 25 MPa, for SnAgCu the initials conditions were 15 and 25 MPa. The results for SnAg at 25 MPa have also been included. The relaxation rate depends on the initial stress and is different for each alloy type. The results show that SnPb solder relaxes much more slowly than do the SnAg and SnAgCu solders. In addition, while initially the stress remains high, after about 2000 s it declines faster.

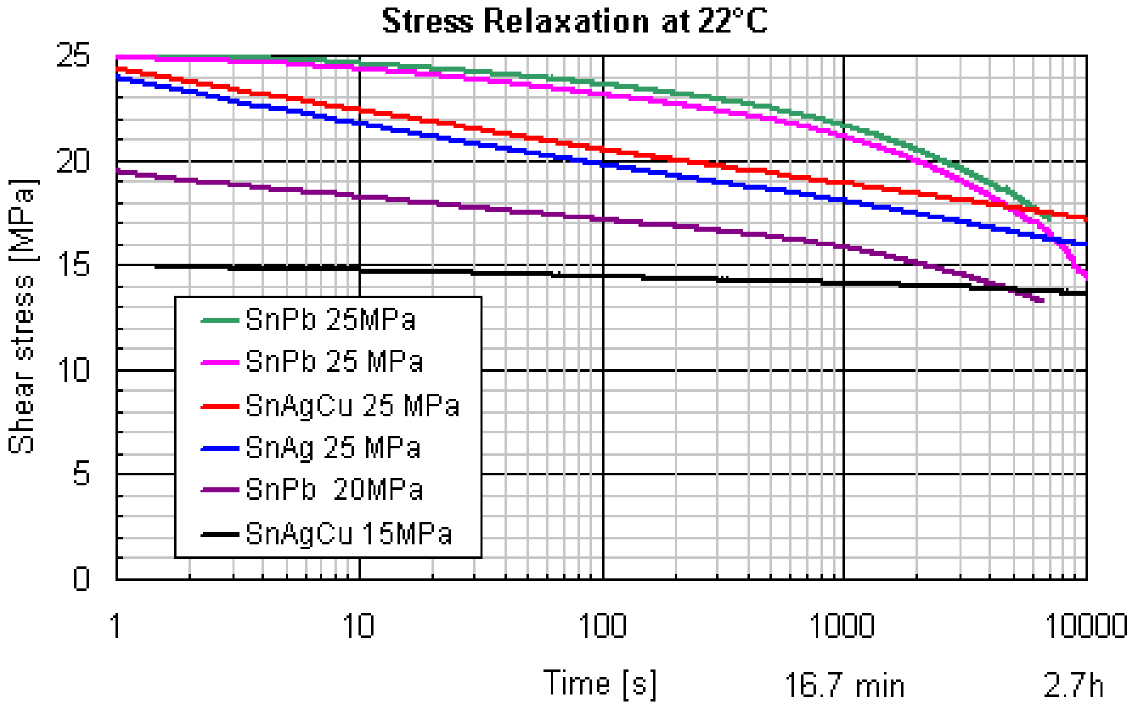

Figure 17. Stress relaxation measurements (15, 20 and 25 MPa)

The largest relative displacements (shear strains) are usually found between a **FR4 substrate** and assembled **component**, but the overall strain range between the substrate and a component is smaller than the difference of expansion between the two different materials. This reduction of the theoretically achievable strain is caused by the solder reacting and restricting the expansion of the joined materials. This restriction predominately occurs at temperatures under 0°C. At higher temperatures the solder is more compliant, and expansion driven by the CTE mismatch occurs more easily. It has been shown [10] from comparing hysteresis loops that the **SnPb** solder restricts the movement of joined parts slightly **less** than do the lead-free solder counterparts. To measure a solder's capability to withstand stress generated at the same level of shear strain, stress must be monitored after deforming specimens by the same amount of shear strain. In Figures 18 and 19 comparisons are presented of stress relaxation curves of three solder materials after displacing to 0.03 and 0.06 of shear strain. The stress relaxation is expressed as normalised stress (%) = actual stress / nominal stress. The nominal stress is the instantaneous value of stress reached when strains of 0.03 or 0.06 are applied. The nominal stresses, and actual stresses after 8 hours, are given in Table 1. The shear strains of 0.03 and 0.06 were chosen to be similar to the maximum available total strains for 1206 and 2512-type resistor components when thermally cycled between –55 and +125°C.

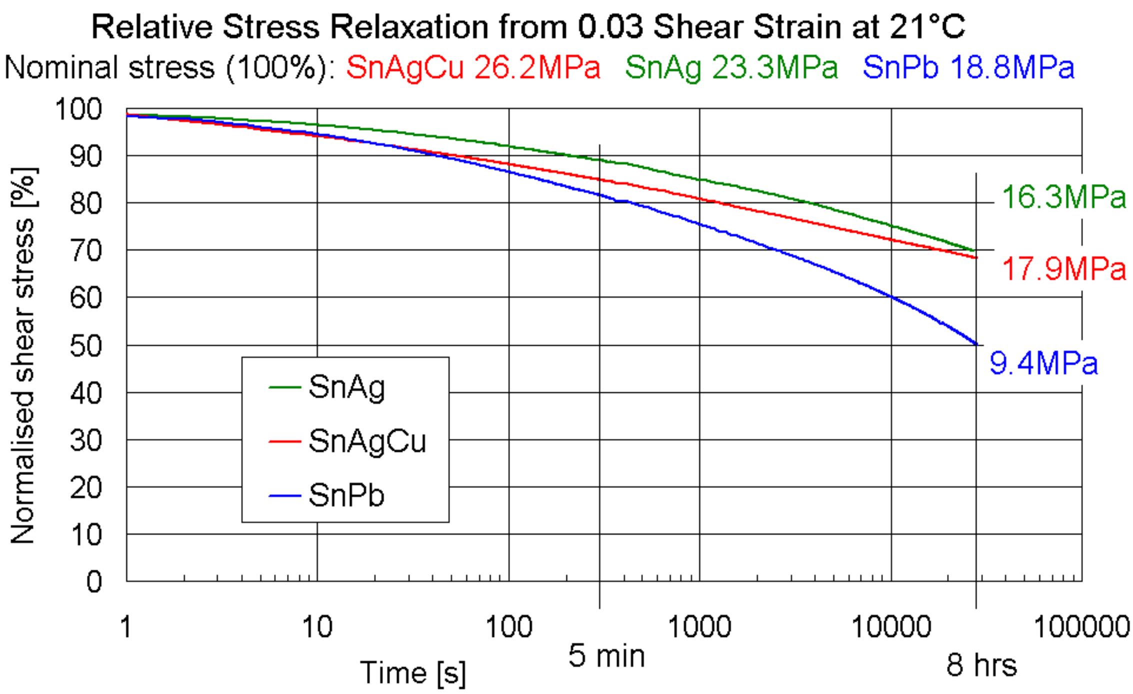

Figure 18. Stress relaxation from 0.03 shear strain for 3 alloys

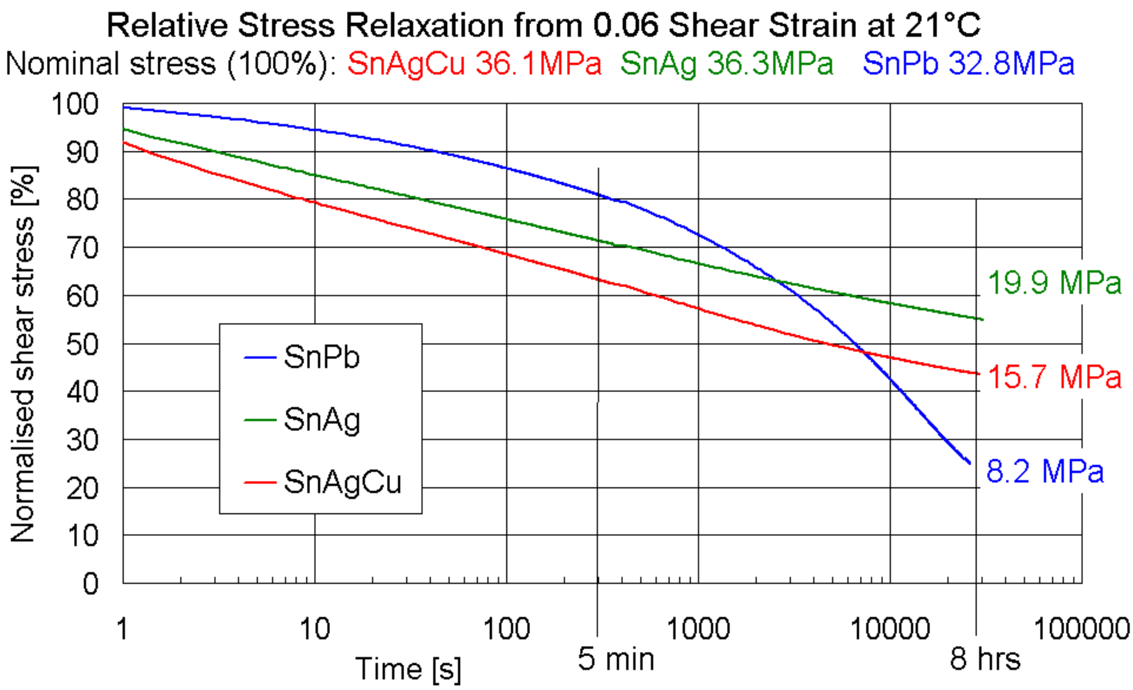

Figure 19. Stress relaxation from 0.06 shear strain for 3 alloys

Table 1. Shear stress relaxation

Shear Strain	SnAgCu [MPa]		SnAg [MPa]		SnPb [MPa]	
	Nominal	After 8 hours	Nominal	After 8 hours	Nominal	After 8 hours
0.03	26.2	17.9	23.3	16.3	18.8	9.4
0.06	36.1	15.7	36.6	19.9	32.8	8.2

5 DISCUSSION

It is clear that, if the behaviour of solder is to be understood and measured, then a sound knowledge of the material properties such as creep is essential. Solder joints in electronic assemblies experience mainly shear forces, and tensile forces are rarely encountered. However, historically, creep measurements have been made under tensile conditions and then, using the von Misses criteria, the shear properties have been calculated. Clearly it would be better to measure the shear properties directly, and this has been recognised for some time. In order to do this, however, it requires a test piece that can be loaded in tension on the axis on a force machine, such that the solder joint within the sample is in shear. This requirement is challenging and must be achieved carefully if the solder joint is not to experience any bending moments, or complex stress forces.

The main aim of this work, therefore, was to develop and validate a new method for generating high quality credible materials data from lead-free solder joints with geometries and dimensions mirroring those used in current assembly technology.

In this work a suitable test piece has been successfully developed. FEA analysis has been used to confirm that only simple shear is being applied to the solder joint. Moreover, by cutting the copper specimen with a diamond saw, both the alignment of the solder joint and the dimensions are assured in one simple step. For example, if two separate pieces of copper were to be used then parallelism of the two pieces becomes a critical issue. Furthermore, the method of manufacture also allows the solder joint dimensions to be readily changed, and the copper can be plated using conventional PCB fabrication processes leading to other possible avenues of investigation. Hence for the rest of the work this design has been fully exploited.

Using this new test specimen, creep tests were undertaken to obtain comparative data for joints made from the three alloys, SnPb, SnAg, and SnAgCu. The results at room temperature reveal a very interesting difference between the behaviours of SnPb and the lead-free alloys. At low stress SnPb creeps faster, but above 20 MPa the creep rate of SnPb is less than those of the lead-free alloys. This response reflects a similar cross-over observed in reliability measurements during low cycle thermal fatigue experiments [11]. In that work SnPb solder joints under high strain (e.g. with 2512-type resistors) were more reliable than their lead-free counterparts, whereas the converse was true at low and medium strains (e.g. with BGA and 0603-type resistors), where the SnAgCu alloy was more reliable. These creep data are therefore consistent with the observed differences in reliability results and can be fed into the FEA models to help improve the reliability prediction.

Temperature is a difficult parameter to be included in mechanical testing, especially when the target temperature is below ambient. But temperature is clearly going to be important when operating at such high homologous temperatures. The data in Figure 13 clearly show a difference between the behaviours of SnPb and the lead-free alloys, with creep rates increasing faster at higher temperatures for SnPb, reflecting the lower melting point. A typical thermal cycle is –55 to +125ºC, and if at 125ºC a constant stress is applied, then the creep rate of SnPb solder will be faster than for the SnAgCu alloy from room temperature values. The data reported here show the magnitude of this effect.

The data obtained from the NPL creep measurements fit well with data observed at other laboratories. In reference [12] Clech compares shear data from NPL with that from Wiese, Pang, Morris and Zhang in Figure 2a at room temperature for SnAgCu, and shows that the two sets of data are similar. All the data give an approximate shear strain rate of $1x10^{-6}$ at 15 MPa. However, NPL and Weise et al used slightly different arrangements, so it is encouraging that there is broad agreement.

The creep data generated in this work can be fitted to a sinh creep law for secondary steady creep shear rate. However, these data highlight that primary creep is dominant in a range from 0 to 1000s for lead-free solders, specifically SnAgCu. The explicit equations capturing this behaviour have yet to be developed [7], but these data confirm the need to develop these measurements further and explore the primary creep region with more vigour.

Traditionally for SnPb solder joints, creep data have been the corner stone of FEA modelling. However, the creep data specifically referred to secondary creep, in which the creep rate is constant at fixed temperature and stress. Clearly with the lead-free alloys, and particularly SnAgCu, primary creep is far more significant than it is for SnPb solder. That primary creep is important was further made by Plumbridge [13] who studied the ratios of primary, secondary and tertiary creep for rupture to occur in SnAgCu solder. It was found that primary creep deformation mechanisms represent 40-60% of solder joint life-time (rupture time). Hence deriving and using secondary creep data only is overlooking an important aspect of the material properties. This is very important when calculating the strain-stress hysteresis cycle, and hence ***primary creep must be included in any modelling of lead-free solder fatigue***.

The stress relaxation technique offers a potential solution to the problem of acquiring relevant materials data that are sensitive to primary creep. Measuring the stress after the instant application, and maintenance, of a constant strain does provide data relevant to the scenario of thermal cycling. The relaxation test has the added advantage that the test time is relatively short when compared to creep testing, and hence mimics more closely the excursions occurring in a thermal cycle. Since stress relaxation is the major phenomenon taking place during thermal cycling, there is a requirement to measure the properties in the relevant temperature range. Future developments of equipment will be necessary to address this need. ***Stress relaxation data will be key to future FEA modelling of lead-free solders.***

6 CONCLUSIONS

- A new method has been generated for generating high quality materials data from lead-free solder joints under shear with geometries and dimensions mirroring those used in current assembly technology. Such data are key to future FEA modelling.

- The new test piece geometry and preparation procedure for the lead-free solder joints have been detailed, and FEA modelling has confirmed that the dominant mode of solder joint deformation in the test piece is the desired shear mode.

- Stress relaxation is an alternative approach in generating relevant and credible material properties for low cycle fatigue. With the stress relaxation method, by following the curves monitored after certain shear strains, it is possible to estimate the actual stress in solder joint as a function of time.

- The stress relaxation method offers a number of advantages for generating materials data from micro-sized lead-free solder joints, e.g. it takes account of primary creep, is relatively quick, and particularly useful when estimating stress in solder joints during thermal cycling temperature dwells.

- Creep measurements taken at room temperature (21°C) have demonstrated (Figure 12) a cross-over point between the behaviours of SnPb and lead-free alloys, at around 20 MPa of shear stress. Below this cross-over point SnPb solder creeps faster than lead-free solders, and above this stress SnPb creeps slower than lead-free solders (SnAg and SnAgCu).

- Creep measurements taken at 50 and 80°C have highlighted (Figure 13) faster creep rates for SnPb rather than for lead-free solders (SnAg, SnAgCu). This is valid for stress levels of 15 and 25 MPa.

7 ACKNOWLEDGMENTS

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