Oral reference: ICF 100135OR

Fatigue-Creep Interactions in Solder Alloys.

J E Moffatt and W J Plumbridge.

Department of Materials Engineering, The Open University
Milton Keynes, MK7 6AA, UK

Abstract

Isothermal, low cycle, fatigue testing is a popular method of evaluating behaviour under thermomechanical fatigue conditions in many applications, such as power generation and, more recently, performance of interconnections in electronic equipment. In this latter context, strain-controlled fatigue tests, involving dwells at maximum strain limits, have been performed on bulk specimens of a eutectic lead-tin solder alloy and two lead-free solders (Sn-3.5 weight percent Ag and Sn-0.5 Cu) at room temperature and 75˚C. During continuous cycling, softening occurs at each temperature. The fatigue endurance is reduced by up to one third at the higher temperature in all alloys, with Pb-Sn showing the greatest reduction. The incorporation of a dwell of 10 or 100s into the cycle generally causes a reduction in fatigue life in comparison to that observed during continuous cycling, although for the Sn-0.5 Cu alloy, a 10s hold produces an increase in life at room temperature. Cycles containing balanced dwells at maximum and minimum strain limits are the most deleterious when lifetime debits of up to fivefold are observed at both temperatures. Generally, unbalanced compression-only cycle profiles tend to be the least damaging. The stress relaxation characteristics are similar in all dwells and at both temperatures, with the eutectic Pb-Sn exhibiting 80 percent relaxation and the lead-free solders up to 50 percent after 100s dwell. Metallographic observation of sectioned specimens reveals surface and intergranular cracking which is accentuated at higher-strain ranges and temperature but not dramatically affected by the cycle shape. These findings are considered in terms of the behaviour of other engineering alloys, and their significance for life prediction is discussed.

Keywords: solders, life prediction, electronics, lead-free alloys.

1 Introduction

The most common cause of failure in electronics equipment is thermomechanical fatigue (TMF) of soldered interconnections. This arises due to temperature fluctuations, either from power switching or from the external environment, and to the fact that the materials which constitute the joint (solder, substrate, board) have substantially different coefficients of thermal expansion, α. For example, α for common solder (Sn-37Pb) is 22×10^{-6} K^{-1} and for alumina (a common substrate) it is 6.5×10^{-6} K^{-1}. Cycling between temperature limits leads eventually to crack initiation, growth and failure, usually within the solder itself since this is the softest element of the joint. In practice, temperature excursions usually occur at different rates, and the overall cycle often contains a dwell during which the temperature is essentially constant. Continuous cycling data is of limited use for life prediction. Controlled thermomechanical fatigue testing is complex and expensive to perform, and the more common approach is to evaluate relevant mechanical properties isothermally.

Continued miniaturisation of devices has placed greater pressure on structural integrity, especially for surface mount configurations. Reliable design requires more sophisticated approaches, and this challenge is compounded by the emergence of a new generation of solder alloys that, for environmental reasons, do not contain lead. The present paper examines the performance of Sn-37 Pb solder and two lead-free alloys during high strain cycling with and without dwell periods.

2 Experimental Details

The materials used were commercial grade eutectic 63Sn-37Pb alloy, supplied in the form of rectangular ingots; the tin-3.5 silver and tin-0.5 copper were supplied as rods or bars. The alloys were heated to match the optimum reflow profile, to about 40˚C above their melting point, and cast into cylindrical aluminium moulds, preheated to the same temperature. The moulds were then rapidly quenched in water. The resultant surface finish on the specimen obtained after casting required no further treatment. Specimens were stored at -18˚C in order to minimise natural ageing. Prior to testing they were warmed to ambient for 2 hours. Their final dimensions were; gauge diameter of 11.28mm (cross sectional area 100mm^2) and a gauge length of 25mm.

Fatigue and fatigue plus dwell tests were carried out using an Instron 1342 servo hydraulic testing machine under total strain control. Dwell cycles were timed and controlled using a computer generated wave form. The test machine was fitted with an environmental chamber operating at 75˚C. Strain was measured using a contacting extensometer attached to the gauge length with coil springs. Tests were performed at a constant strain rate of $3.33 \times 10^{-3} s^{-1}$. The cyclic frequency therefore varied for each test depending on the strain amplitude. A triangular waveform was used with a strain ratio, R, of -1 (where R = ε_{min}: ε_{max}). The strain ranges employed in continuous cycling varied between 0.5 and 3.0 percent, and during cycling with dwells the strain range was 1.0 percent. Load and total displacement were continuously recorded. A tensile load reduction of 20 percent with respect to the first cycle was employed as the criterion of failure and then tests were terminated.

After testing, specimens were examined using both optical and scanning electron microscopy. Samples from the gauge length of the test pieces were sectioned longitudinally using electrical discharge machining to minimise surface damage, and subsequently polished to a 1μm surface finish.

3 Results

3.1 Cyclic Response

All hysteresis loops show a progressive drop in the load range necessary to maintain the constant strain limits, indicating cyclic softening. Saturation of the load range occurs at strain ranges of 1 percent and above, whereas, below this level, the plastic strain range continues to increase and saturation is not reached. A cyclic stress-strain curve, derived from the stress range during the first cycle and the total strain range may be described by the relationship,

$$\Delta\sigma = A\Delta\varepsilon^{\beta}$$

The values for the constants A and ß are presented in Table 1.

TABLE 1

VALUES OF CONSTANTS IN THE CYCLIC STRESS-STRAIN EQUATION

	Pb/Sn		Sn/Ag		Sn/Cu	
	RT	75	RT	75	RT	75
A	129	64	88.9	56	55.5	43.08
ß	25.2	22.1	30.85	20.3	4.5	8.7

A convenient means of depicting strength changes during high strain cycling is via the load drop parameter, Ø, (which is defined as Ø = 1 – (ΔP/ΔPm) where ΔP is the load range at any cycle and ΔPm is the load range during the first cycle). The variation in the load drop as a function of the fraction of fatigue life is shown in figure 1 for a strain range of 1 percent, with a dwell of 10 seconds incorporated at maximum tensile strain, at room temperature and 75˚C. The load falls (indicated by an increase in load drop parameter) continuously from the first cycle, and the rate of cyclic softening with respect to total cyclic life is broadly similar in all three materials, at both temperatures and for all cycle profiles examined.

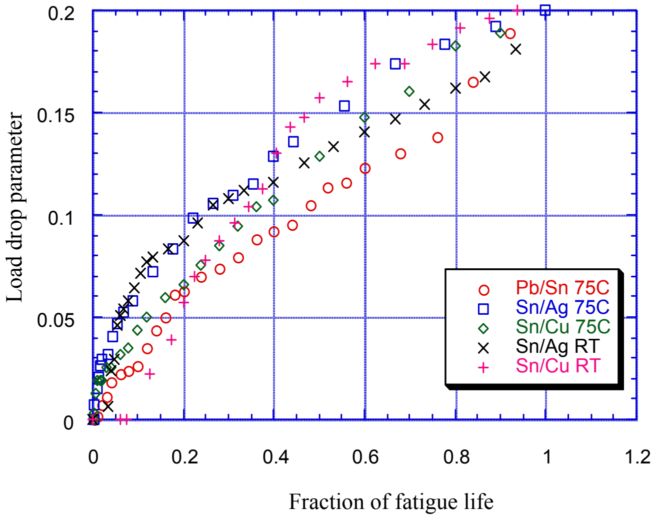


Figure 1. Load drop parameter v fraction of fatigue life during cycling with dwells of 10s at room temperature and 75ūC.

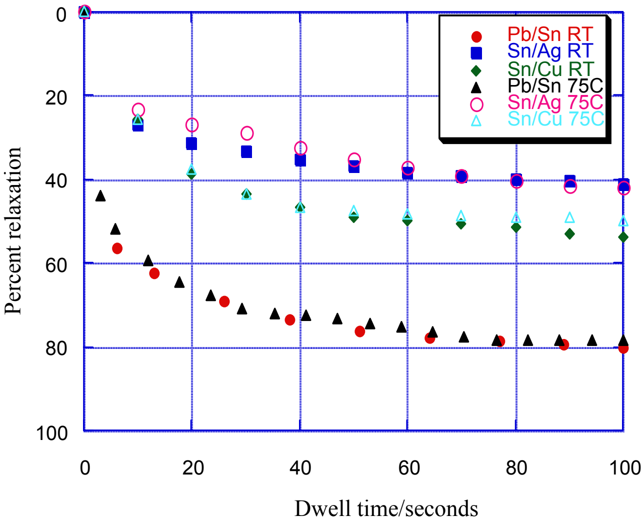


Figure 2. Stress relaxation during tensile dwell periods room temperature and 75ūC.

3.2 Stress Relaxation During Dwells

Stress relaxation ranges during dwells is substantial, ranging from 80 percent in Sn-37Pb to 40 percent in Sn-3.5Ag after 100s. It is independent of the temperature and cycle type. Figure 2 shows stress relaxation at room temperature and 75˚C during a tensile dwell cycle (designated t/0) of 100s. During other cycle profiles (compression-only, 0/t, and balanced dwells, t/t) the extent of stress relaxation varies by no more than 8 percent for any of the profiles, and at either temperature. The amount of stress relaxation is also independent of the cycle number. The equation

$$\sigma = A\, t^{m}$$

provides a good description of the relaxation process. The values of A and m are presented in Table 2.

TABLE 2

VALUES OF CONSTANTS IN THE STRESS RELAXATION EXPRESSION

	A	m
Pb/Sn	26.8	27.9
Sn/Ag	9.1	15.6
Sn/Cu	12.3	20.7

3.3 Fatigue Endurance - continuous cycling

In general, during continuous cycling the fatigue life at room temperature exceeds that at 75˚C, although the effect of temperature is not substantial. Figure 3 shows Coffin-Manson plots for the three alloys at both temperatures during continuous cycling. In all alloys at strain ranges equal to or below 1percent, continuous cycling at 75˚C exhibits up to 50 percent fatigue life reduction when compared to room temperature. At higher strain ranges the lives are reduced and the difference is less marked.

3.4 Cycles with dwells

Dwells produce a reduction in fatigue life when compared to the continuous cycling case. Figure 4 shows the load drop as a function of number of cycles for a dwell of 100s at the maximum tensile strain. Cycles containing balanced dwells are the most deleterious. Table 3 shows the number of cycles to failure for continuous cycling and for cycles containing dwell periods at 1percent strain range. These results follow a similar trend although at the lower temperature a dwell during the tensile cycle is the most damaging. The sensitivity to dwells, as defined by the Influence Ratio, which is the ratio of fatigue lives with and without dwells, is shown in figure 5. The Sn-0.5 Cu alloy is more resistant to short (10s) hold periods in the cycle but this superiority disappears when the dwell is extended to 100s. Apart from the short dwells for the Sn-0.5Cu, all other cycle profiles produced a deleterious effect on life.

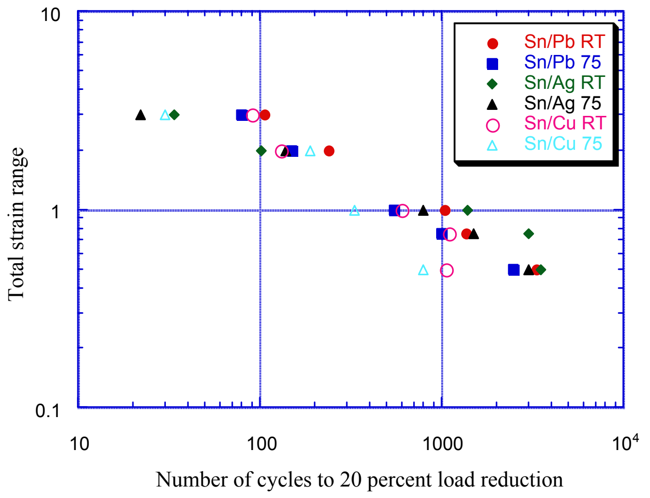


Figure 3. Cofin-Manson plot of total strain v number of cycles to 20 percent load reduction.

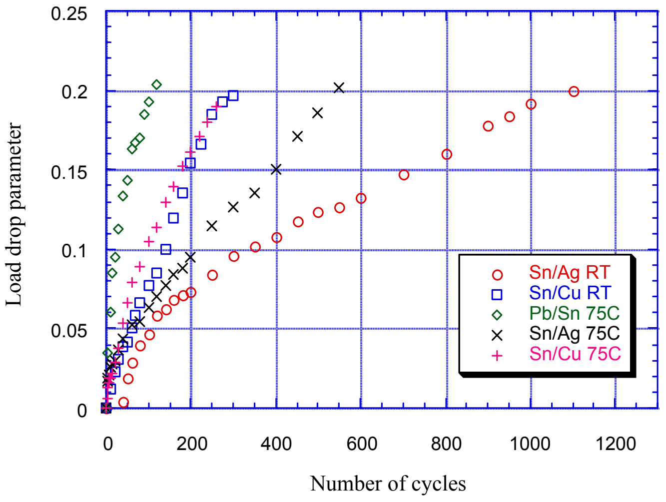


Figure 4. Load drop parameter v number of cycles with a 100s tensile dwell, 1 percent strain range.

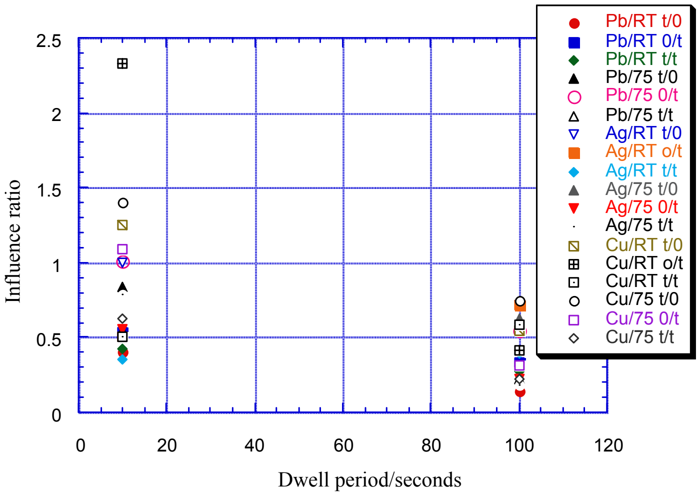
TABLE 3

EFFECT OF DWELLS ON FATIGUE LIFE AT 75˚C AND ROOM TEMPERATURE (IN ITALICS) DURING DWELLS OF 10 AND 100 SECONDS.

Cyclic shape	zero dwell 0/0	10s dwell	100s dwell
Pb/Sn	550 / *1030*		
t/0		460 / *415*	125 / *150*
0/t		560 / *550*	300 / *340*
t/t		300 / *435*	120 / *282*
Sn/Ag	800 / *1400*		
t/0		400 /*1400*	500 / *1000*
0/t		450 / *700*	180 / *1000*
t/t		700 / *500*	145 / *550*
Sn/Cu	320 / *600*		
t/0		450 / *750*	240 / *325*
0/t		350 / *1400*	100 / *250*
t/t		200 / *300*	70 / *350*

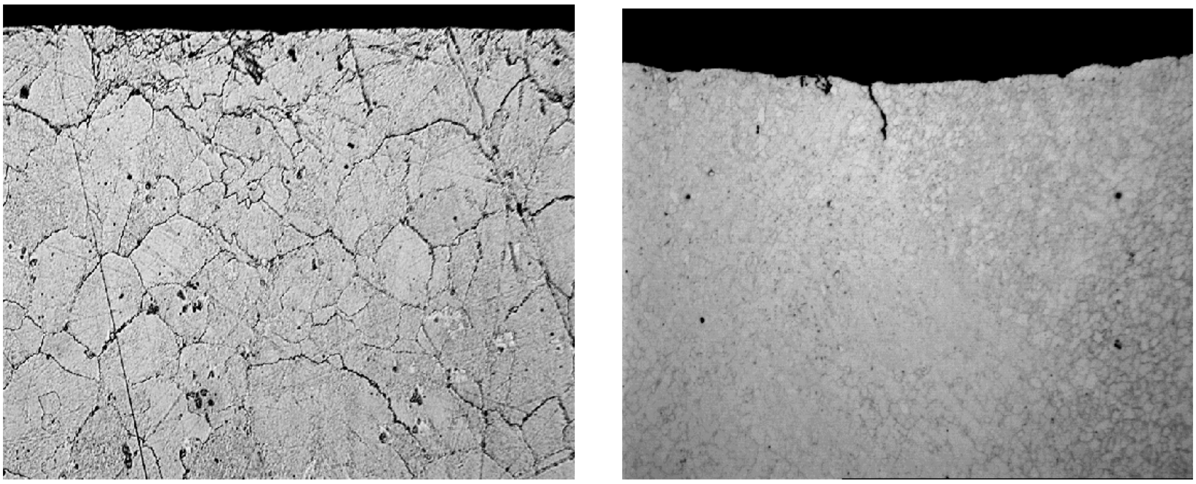
3.5 Microstructure

In Sn-Pb, cracking around colony boundaries became more extensive at higher strain ranges and cycles with incorporated dwell periods. Figures 6(a) and 6(b) compares this cracking in Sn-Pb and Sn-Cu



(Influence ratio is Nf(dwell):Nf(no dwell))

specimens tested at 75˚C, after being subjected to a 100s dwell at maximum tensile strain. Both Sn-Ag and Sn-Cu showed virtually no macroscopic cracking under the same conditions.



(a) Sn-Pb 75˚C (b) Sn-Cu 75°C

Figure 6. Comparison of Sn/Pb and Sn/Cu alloys after testing at 75˚C with a 100s dwell at the maximum tensile strain (magnification 200x).

Further investigation is planned. In Sn-Pb, intergranular cracking occurs throughout the bulk of the specimen. At low strain ranges (0.5 and 0.75 percent) cracking is confined to the surface layer, while at higher strain ranges, cracking is apparent throughout the bulk of the specimen although the majority of damage was found near to the surface. Specimens experiencing dwell cycles exhibited a higher crack density and the number of surface cracks was reduced. Cycle profile appeared to have little effect.

4 Discussion

This study has demonstrated that both lead-containing and lead-free solder alloys exhibit cyclic softening when subjected to high strain fatigue. The extent of softening is largely unaffected by temperature, strain range and the presence of dwell periods in the strain-time cycle. It is similar to that measured in a 1Cr-Mo-V steel at both room temperature and 565˚C [1]. Fatigue endurance is generally slightly lower at 75˚C than at room temperature. Insertion of hold periods in the fatigue usually causes a reduction in life by up to a factor of six for dwells of 100s duration. Post test metallographic examination reveals that fatigue produces macroscopic cracking in lead based alloys but not in lead free alloys. These findings are now considered in more detail.

A decrease in the load level can be caused by microstructural changes, fatigue crack nucleation or cavity formation. Some microstructural changes, for example those involving dislocation multiplication and sub grain formation, result in cyclic hardening. Since crack or void nucleation is associated with a reduction in load-bearing section, an immediate and continuous fall in load is observed unless the defects cease to grow. In the classic model of cyclic softening, microstructural changes produce a drop in load followed by a saturation level until fatigue cracking begins and results in a further load drop [2]. However, in a ductile material such as solder, it is likely that both processes, deformation and cracking, will occur simultaneously to some extent with the former predominant in the early stages. The balance between them will be influenced by the strain range and the ductility of the alloy. It is unlikely that in these alloys, crack initiation will occur immediately. Kariya and Otsuka [3] define three distinct stages in the load drop curve, in the first stage Ø increases rapidly, and crack initiation and propagation occur; the second stage is linear reflecting steady state growth, and the third state shows accelerating growth leading to failure. Most of the fatigue life is spent in the second steady state and the fatigue life is dominated by this steady load drop rate dØ/dN. In this study, since testing was terminated at 20 percent load drop the third state was not usually reached. Jiang et al [4] attributed similar load changes in a Sn-37 Pb alloy at room temperature to the predominance of cracking. Microstructural examination indicates progressive fatigue cracking taking place throughout all strain ranges but as yet observation of the very early stages is incomplete.

Stress relaxation in the Sn-37Pb alloy is significantly greater than that in the lead-free alloys. This cannot be explained on strength or melting point considerations. Temperature itself has negligible effect on the extent of relaxation in any of the alloys, and the strength of the Sn-0.5 Cu alloy over a range of strain rates is similar to that of the Sn-37Pb and significantly lower than that of the Sn-3.5Ag [5].

The fatigue endurance during continuous cycling is broadly similar for all the alloys examined. Since strength is not a good indicator of high strain fatigue resistance, this is not surprising. Indeed, it has been shown that this similarity extends to many engineering alloys [6]. Under total, as opposed to plastic, strain control some advantage might be expected to accrue to the stronger silver-containing alloy but this is offset by its lower ductility[5]. Endurance in the presence of dwells is reflected by the extent of stress relaxation with the Sn-3.5 Ag alloys exhibiting the longest life. However, the relative insensitivity of the Sn-0.5 Cu alloy to short dwells is difficult to explain. The alloy is ductile but not significantly more so than the Sn-37Pb, and a ductility argument would not account for the loss of relative resistance at longer dwells. It is possible that partitioning of the relaxed strain to different locations or into different mechanisms may be required to account for this apparent anomaly.

5 Conclusions

When the solder alloys, Sn-37Pb, Sn-3.5Ag and Sn-0.5Cu, are subjected high strain fatigue at 75˚C and room temperature, it has been found that:

- they exhibit cyclic softening to a similar degree which is independent of the strain range, temperature and cycle shape;
- their fatigue endurance is broadly similar, with fatigue at 75˚C being slightly more deleterious than at room temperature;
- during a dwell period in the cycle, stress relaxation occurs to an extent that is independent of temperature and location of the dwell, although it is significantly higher in the Sn-37Pb alloy;
- the endurance of all alloys is usually susceptible to the inclusion of dwells, and lifetimes may fall by up to six times after dwells of 100s duration.

6 References

1. Plumbridge, W. J. and. Bartlett, R. A. (1982) Int. J. Fatigue, 4, p 209.
2. Solomon H. D. (1986). Electronic Packaging - Materials and Processes, ASM p.29.
3. Kariya Y. and Otsuka M. (1998). J. of Electronic Materials, 27, 1229-1237.
4. Jiang, H, Hermann R, and Plumbridge W. J. (1996). J. of Materials Science, 31 p6455-6461.
5. Plumbridge W. J. and Gagg C. R. (1999). J Electronic Materials, 10, 461-468.
6. Plumbridge W. J. (2000) Materials at High Temperatures, ,17, 381-387.