PART I

Metals
ISOTHERMAL FATIGUE OF 62Sn-36Pb-2Ag SOLDER

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ABSTRACT

This paper discusses the effects of the most important variables during isothermal fatigue such as strain range, ramp time, tensile and compressive hold times, and temperature on fatigue life of near-eutectic 62Sn-36Pb-2Ag solder at strain ranges below 3.0%. The Coffin-Manson relation does not hold for 62Sn-36Pb-2Ag solder below 1% strain range. Decreasing frequency below $10^2$ in no-hold tests reduces the number of cycles to failure. Tensile hold time or compressive hold time alone in the cycle dramatically reduce the number of cycles to failure. Increase of hold time over a few minutes leads to saturation of $N_f$. Combined tensile and compressive hold times affect the fatigue life of this solder less than either tensile or compressive hold alone. The effect of hold times on fatigue life is much stronger than the effect of ramp time. Practically no ramp time effect was observed in tests with tensile hold times. Very little effect of temperature over the range 25 to 80°C on fatigue life of 62Sn-36Pb-2Ag solder was observed when tested at total strain range of 1%.

INTRODUCTION

Failure of solder joints due to thermal fatigue is a topic of serious concern to the electronics and power industries [1,2]. Recent advances in electronic design have lead to a significant reduction of the strain on the solder joint. However, fatigue life data did not previously exist for most solders in this low strain range (less than 1%). Therefore, existing high-strain data were extrapolated to low strains by use of the Coffin-Manson relation [3,4]:

$$N_f = B (\epsilon_p - C)^P$$

where

- $N_f$ - number of cycles to failure;
- $\epsilon_p$ - the plastic strain range;
- $B$ and $C$ - constants.

Since room temperature is approximately one-half of the absolute melting temperature of solders, a variety of different creep, fatigue and environmental processes may interact during cycling and can contribute to solder failure at low strain. For example, fatigue crack initiation, fatigue crack propagation, void (creep) initiation, void (creep) propagation, or a combination of these phenomena, which may also be affected by environment, can be present and lead to non-linearity between fatigue life and strain range. Fatigue lives at low strains shorter than expected by extrapolation of the high strain fatigue data were previously reported by our research group for high-Pb Sn-Pb solder in air [5-7] and in vacuum [8,9], and for eutectic Sn-Pb solder [10,19] in air.

While the frequency effect on the fatigue of lead [11] and Sn-Pb solders [5,6,12-17,19] was studied extensively, the effect of hold times was
not investigated in detail prior to our research of fatigue of low-Sn Sn-Pb [5-8,15] and 63Sn-37Pb [10,18,19] solders. Tensile hold time was found to dramatically reduce the number of cycles to failure. The longer hold times lead to saturation in the Nf. Also, the effect of hold time was shown to be much stronger than effect of ramp time [15].

This paper discusses the effects of strain range, ramp time, tensile and compressive hold times, and temperature on fatigue life of near-eutectic 62Sn-36Pb-2Ag solder. These are the most important variables of isothermal fatigue.

EXPERIMENTAL PROCEDURE

Bulk cast specimens of near-eutectic (62wt.%Sn-36wt.%Pb-2wt.%Ag) solder were used in this research. To standardize testing conditions, specimens were heat-treated 2 hours at 150°C 6-10 days before testing. Such procedure was chosen because it was found previously that mechanical and fatigue properties of low-Sn Sn-Pb [5] and eutectic [10,19] Sn-Pb solders change rapidly during the first few days of room temperature aging and then stabilize after approximately one week of aging.

Fatigue tests were done in pull-pull, i.e., the strain was varied from zero to a maximum value. While the total strain varied from zero to maximum strain during cycling, the values for peak tensile and compressive stresses were almost equal due to high plastic strain in the solder. A few types of total strain controlled isothermal fatigue tests are discussed here: continuous saw tooth wave tests, tests with hold time at maximum strain (tensile load hold time), tests with hold time at zero strain (compressive load hold time) and tests with combination of both hold times.

Tensile stress for this solder like for other near-eutectic Sn-Pb solder [10,12-14,18,19,37] starts to drop almost from the very beginning of the fatigue tests due to work softening and crack propagation. The cycle number when the tensile load was reduced in half was defined as the number of cycles to failure, Nf, for this solder, following H.D. Solomon definition [12-14].

RESULTS AND DISCUSSION

Tests without Hold Time

1. Effect of Strain Range

The fatigue data for 62Sn-36Pb-2Ag solder obtained during the present study are plotted in the Figure 1 together with the results of some tests performed with simulated solder joint specimens under plastic shear strain control by H.D. Solomon [12,13]. In this graph equivalent von Mises strain ranges are plotted. A comparison of the fatigue data obtained in tensile fatigue tests to data obtained in shear fatigue tests is possible by utilizing the equivalent von Mises strain (6 VM). Of course other testing conditions must be the same and the same definition of failure must be used. Tensile strain (6 VM) is equivalent to von Mises strain. Shear strain relates to von Mises strain as follows:

\[ \gamma = \sqrt{3} \epsilon_{VM} \]  \hspace{1cm} (2)

or:

\[ \epsilon_{VM} = \sqrt{3} \gamma = 0.577 \gamma \]  \hspace{1cm} (3)

According to Eq. (3), a tensile strain of 0.577% will lead to the same damage as 1% shear strain.
It is evident, that fatigue life of 62Sn-36Pb-2Ag solder is similar to that of 60Sn-40Pb solder. The differences in fatigue lives may be attributed to different solder compositions and microstructures as well as specimen size and geometry. Figure 1 is very important because it shows that bulk and solder joint specimens of very different geometry and loading mode can give comparable results. This subject deserves further study.

It is evident from the Figure 1 that 62Sn-36Pb-2Ag solder does not obey the Coffin-Manson relation at low strain ranges. A break in the Coffin-Manson plot occurs at approximately 0.3% plastic strain range similar to that previously reported for 63Sn-37Pb solder [19]. For 63Sn-37Pb solder the break in the Coffin-Manson plot was correlated with a different maximum tensile stress dependence on the plastic strain below and above a transition region: below the transition, the maximum stress increased steeply with increasing plastic strain range whereas above the transition the maximum stress increased much more slowly with increasing plastic strain range [19]. A similar maximum tensile stress - plastic strain range relationship is observed for 62Sn-36Pb-2Ag also with a transition at approximately 0.3% plastic strain (Figure 2).

2. Effect of Ramp Time (frequency)

At temperatures well below one half of the absolute melting point, frequency has relatively little effect on the fatigue life of most metals. When the temperature is increased over half of the absolute melting point, a reduction in frequency decreases the number of cycles to failure in isothermal fatigue for many metals including solders. This behavior arises because at high temperatures, processes such as thermally activated plastic flow, creep and environmental attack, which are time dependent, play important roles in damage accumulation.

A general trend in the effect of frequency on the number of cycles to failure is expected [20]. Almost no frequency effect is observed at very high and very low frequencies with a strong effect at intermediate frequencies. Of course, the frequency effect depends on the character of the material and on testing conditions.
J.F. Eckel [11] found a marked influence of frequency on fatigue life of lead. The time to failure, $t_f$, and the number of cycles to failure were related to frequency, $f$, by the following empirical relations:

$$t_f = b f^m$$  \hspace{1cm} (4)$$

$$N_f = b f^{m-1}$$  \hspace{1cm} (5)$$

where $b$ and $m$ are constant.

For 62Sn-36Pb-2Ag solder the fatigue life depends very little on frequency above approximately $10^2$ Hz and at lower frequencies fatigue behavior follows the Eckel’s relation (Eq. (5)) (Figure 3). At 1% total strain and at 25°C frequency exponent $m$ was found to be approximately 0.6. The frequency dependence for this solder is similar to that reported previously for 60Sn-40Pb [12-14], low-Sn Sn-Pb [5,6,16,17], and 63Sn-37Pb [19] solders.

Tests with Hold Time

Hold (dwell) times introduced in the cycle at maximum and/or minimum strains, stresses or temperatures affect the fatigue life of materials depending on the kind of material and testing conditions.

1. Effect of Tensile Hold Time

Tensile hold time is very damaging during high temperature fatigue of many materials such as steels [21-25], other metal alloys [23,26,27] and solders [5-9,15,18,19,28-30], in that, the number of cycles to failure decreases when tensile hold time is increased. A saturation in the number of cycles to failure with increasing hold time is detected for a number of metals, including solders. Time to failure, however, may increase or decrease depending on ramp time and hold time duration.
Hold time at maximum strain has a dramatic effect on the number of cycles to failure of low-Sn Sn-Pb [5-10,15] and Sn-Pb eutectic [18,19] solders; a few minutes of tensile hold time reduces the number of cycles to failure almost by an order of magnitude and further increase in hold time eventually lead to saturation in number of cycles to failure, as already mentioned.

Often the reduction in fatigue life of metals due to tensile hold is accompanied by a transition from the transgranular to the intergranular mode of fracture. Such transition was found for low-Sn Sn-Pb solder [5-7] at high strains. Cavitation on grain boundaries was observed [9,36], therefore, the effect of tensile hold time on fatigue life of the solder was attributed mainly to creep (cavitation).

The experimental data for 62Sn-36Pb-2Ag solder obtained under tensile hold time with short (1sec) ramp time is depicted in Figure 4. The first 30 sec of tensile hold time reduces $N_f$ by more than half, but further increase in hold time does not reduce $N_f$ so dramatically. The tendency for the number of cycles to failure to saturate with increased hold time is evident. The method of calculation of this $N_f$ limit developed earlier for low-Sn Sn-Pb solder [5,6,31] and shown to be applicable to eutectic Sn-Pb solder [10,18,19] as well as to other alloys [32], is applicable to 62Sn-36Pb-2Ag solder also. There exists a linear relation between the time to failure and tensile hold time (Figure 5). The limit in the $N_f$ was shown to be equal to the slope of the line in this graph [5,6,31].

2. Effect of Compressive Hold Time

The effect of compressive hold alone on fatigue life has been studied for a number of metals, but not near-eutectic solders. Previously, we demonstrated that compressive hold time alone in the cycle does not affect the cycles to failure of low-Sn Sn-Pb solder in air [5]. However, compressive hold time dramatically reduces the number of cycles to failure of 62Sn-36Pb-2Ag solder (Figure 4); the degree of reduction in $N_f$ by compressive hold time is even more than that by tensile hold time. This was the case also for low-Sn Sn-Pb solder in vacuum [9].
When the experimental results are plotted as time to failure versus compressive hold time, a linear relation as previously demonstrated for tests with tensile hold time exists (Figure 5). The limit in the $N_f$ is again equal to the slope in time to failure versus hold time line.
3. Effect of Combined Tensile and Compressive Holds

Figure 6 shows that addition of tensile hold time to the cycle containing compressive hold time increases the $N$. This increase is significant at short compressive hold times. At longer compressive hold times the difference between the $N$ in tests with compressive hold alone and combined hold times becomes smaller. Combined effect of both holds on cycles to failure of this solder demonstrates that some kind of recovery occurs during cycling when both holds are present in the cycle. By contrast, during fatigue of low-Sn Sn-Pb solder \([5]\) compressive hold time added to the cycle containing tensile hold time gave fewer cycles to failure than tensile hold time alone.

No obvious differences in the failure mechanisms of specimens made of 62Sn-36Pb-2Ag solder and tested without hold time, with tensile hold alone, compressive hold alone and combined tensile and compressive hold were observed. Further study of the effects of holds on failure of this solder is needed.

![Diagram](https://example.com/diagram.png)

**Figure 6.** Effect of compressive hold time on the number of cycles to failure in tests with tensile hold time.

4. Effect of Ramp Time and Tensile Hold Time

All previously presented hold time data were obtained with a short, 1 sec ramp time. Results of tests with different tensile hold times as a function of ramp time are shown in Figure 7. Results of tests with longer than 1 sec ramp time as a function of tensile hold time are depicted in the Figure 8. It is obvious from these graphs that when hold times of 120 and 360 seconds duration are present in the cycle, the $N$ practically is not affected by the duration of ramp time, i.e. practically all damage per cycle is done during hold time. It is an important indication that the life prediction methodologies for solder joints have to be based on experiments involving hold time.
Effect of Temperature

The isothermal fatigue life of most metals decreases as temperature increases. However, the degree of fatigue life change depends on the material and testing conditions. For near eutectic tin-lead solders (63Sn-37Pb [10,18,19,37] in the 25 to 80°C, 60Sn-40Pb in 35 to 150°C [12-14] and -60 to 150°C [33] temperature ranges) the temperature effect was found to be insignificant for all strain ranges and modes of loading investigated.