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Parameters Affecting Thermal Fatigue Behavior of 60Sn-40Pb Solder Joints

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Solder joints in electronic packages experience cyclical thermally induced strain when temperature fluctuations are encountered in service. This study investigates three parameters that affect the microstructure and therefore the thermal fatigue behavior of 60Sn-40Pb solder joints. These parameters are: 1) the effect of a tensile component in thermal fatigue, 2) solder joint thickness variations, and 3) hold time variations at the elevated temperature portion of the thermal cycle. Solder joints were thermally fatigued in a tension/compression deformation mode. Cracks developed both in the interfacial intermetallic layer (early in thermal fatigue) and in the coarsened regions of the microstructure of the solder joint (after many more cycles). The effect of joint thickness on solder joints thermally fatigued in shear was also explored. Solder joint thickness was found not to significantly affect fatigue lifetimes. The effect of an increase in the hold time at the elevated temperature portion of the thermal fatigue cycle was also investigated. It was found that time spent at the high temperature end of the fatigue cycle does not determine solder joint lifetime, rather it is the combination of the amount of deformation induced during thermal fatigue in concert with the elevated temperature.

Key words: 60Sn-40Pb solder, thermal fatigue, microstructure, shear strain, tensile strain, joint thickness

INTRODUCTION

Sn-Pb solder joints are used extensively in the packaging of electronic devices. The solder joint acts both as an electrical connector and also provides mechanical support for the package. The alloy most commonly used for these applications is 60Sn-40Pb solder. In service the packages experience thermal fluctuations. The differences in the thermal expansion coefficients of the materials used in the electronic package cause cyclical strains in the solder joints upon thermal cycling. Solder joints often fail in service under these conditions.[1-11]

Previous work on the thermal cycling of 60Sn-40Pb solder joints in shear has shown that the failure of joints is preceded by a heterogeneous coarsening of the solder microstructure.[12-14] The coarsening initiates as a thin band within the solder, parallel to the direction of shear, which increases in width with an increasing number of cycles. Upon further cycling cracks develop within the coarsened regions, primarily through the Sn-rich phase at Sn-Sn grain boundaries. Furthermore, it was found that the elevated temperature portion of the cycle induced the greatest damage in the solder joint.[14] All the above observations correlate well with observations made on joints that fail in service.[1,9]

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The aim of the work described above was to gain some initial understanding of how a solder joint performs during thermal cycling in simple shear. However, actual solder joints in service encounter a more complex set of strain conditions. This paper presents results from three sets of experiments that were performed to gain insight into the behavior of solder joints under variations in the conditions of strain during thermal fatigue.

1) Variation in Deformation Mode: Although simple shear is the primary deformation mode for solder joints a tensile component may also be present, especially in Surface Mount Technology (SMT) applications. Figure 1 shows where tensile and shear strains develop in a typical SMT joint. Both types of strain are due to thermal expansion differences between the chip carrier and the printed circuit board. The maximum tensile strain occurs at the outside of the solder joint while the maximum shear strain is found underneath the joint. A tensile strain may also result when an electronic package experiences thermal variations that are not uniform which cause either the board or chip carrier to bend ("oil-can").[15] The non-uniform heating and cooling imposes a cyclic tensile/compressive strain on the solder joints. The tensile deformation behavior of solder joints was examined in this study and compared to that of shear deformation.

2) Solder Joint Thickness Variations: In the sol-

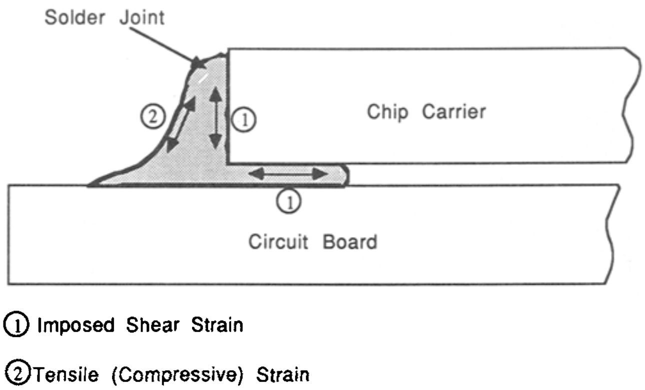


Fig. 1 — Illustration of how and where a tensile/compressive component can develop in SMT solder joints.

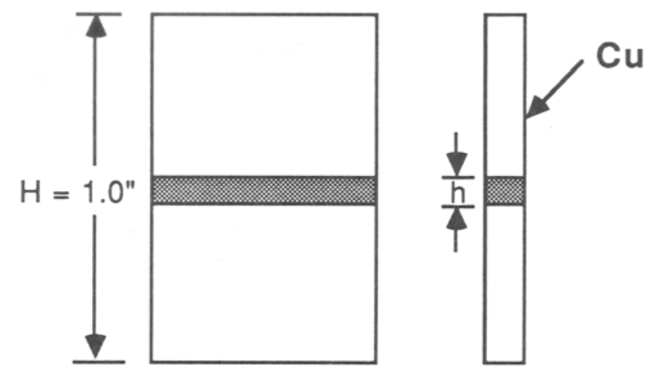
dering of SMT applications variations in solder joint thicknesses may occur. It has been proposed that thicker solder joints delay thermal fatigue failures. This study examines the effect of solder joint thickness on joint deformation behavior in shear.

3) Hold Time Variation at Elevated Temperature: Work described previously[12–14] on the thermal fatigue behavior of 60Sn-40Pb solder joints deformed in shear had a hold time constant of 5 minutes at each temperature extreme. The influence of hold time was studied here by increasing the hold time at the elevated temperature end of the thermal cycle to one hour. This study is relevant since packages tend to experience long hold times in service. These results help evaluate the ability of accelerated thermal fatigue tests to simulate the behavior of solder joints in service.

EXPERIMENTAL PROCEDURE

A specimen composed of two Cu plates joined by a solder joint, Fig. 2, was designed to test solder joints under tensile strain conditions. The specimen fabrication process is described elsewhere.[16] Tensile strain is applied on the solder joint by an aluminum fixture that is shown in Fig. 3. The sample fits into the center of the fixture and is affixed by threaded screws. When the system is thermally cycled between −55° C and 125° C tensile strain is imparted to the solder joint because of the difference in thermal expansion between the Al fixture and the Cu sample. In the low temperature portion of the cycle the Al fixture contracts more than the Cu causing the solder joint to be in compression. In the elevated temperature portion of the cycle the Al expands more than the Cu causing the joint to go into tension. The complete thermal cycle provides 6.2% strain in compression and 8.6% strain in tension.

Thermal fatigue tests in shear were performed on the specimen shown in Fig. 4. The specimen consists of an Al plate (electroplated with 0.05 mm of Ni, to act as a diffusion barrier, followed by a plating of 0.025 mm of Cu) soldered between two Cu plates. The specimens were manufactured as described in a previous paper.[13] The coefficient of thermal expansion of Al is 25 μm/mm° C while that of Cu is 16.6 μm/mm° C, hence thermal cycling imposes a strain that is a maximum at the ends of the specimen and decreases linearly to zero in the center. When the solder joint thickness is decreased the length of the specimen must also be decreased to retain the same amount of shear strain. The solder joint thicknesses tested were 2 mil (0.051 mm), 10 mil (0.254 mm), and 20 mil (0.51 mm). For the 2 mil and 10 mil thick solder joint specimens 19% maximum shear strain was imposed. The 20 mil thick solder joint specimens were too long to fit in



$$\varepsilon = \frac{\Delta\alpha\, \Delta T\, H}{h}$$

Fig. 2 — Specimen used to test solder joints in tension/compression in tension.

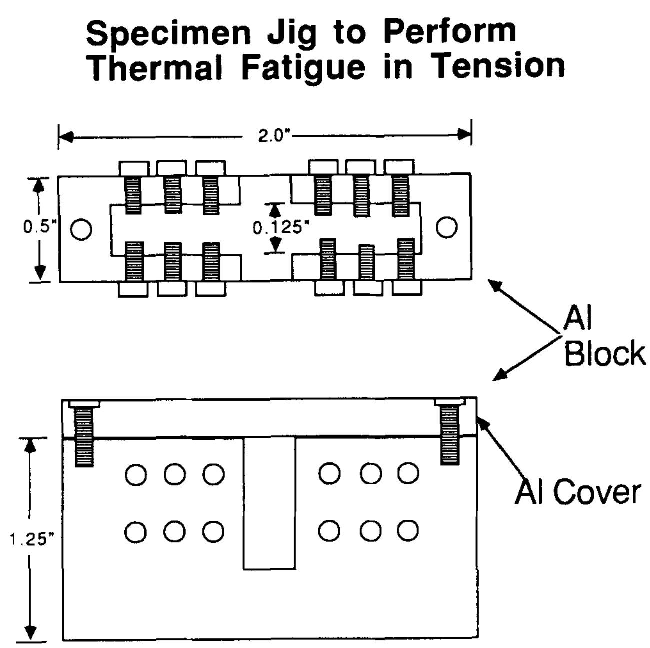


Fig. 3 — Fixture used to induce tensile/compressive strains in solder joints.

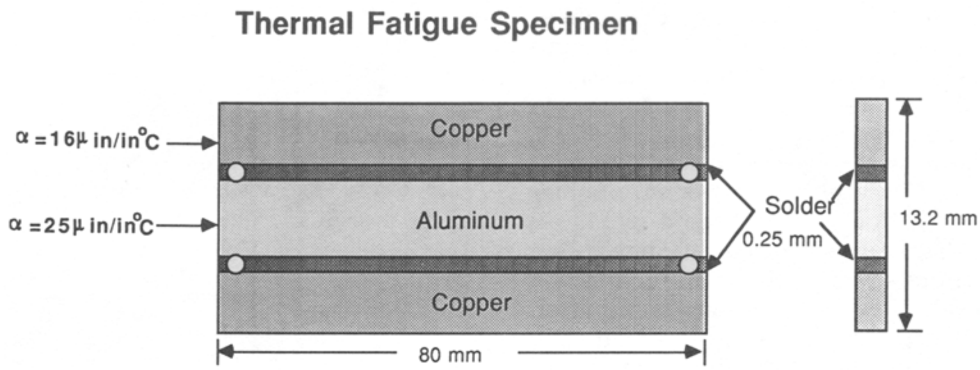


Fig. 4 — Specimen used to test solder joints in thermal fatigue in simple shear.

the thermal cycling apparatus. Therefore the 20 mil specimens were tested at 10% shear strain.

Thermal cycling was accomplished with an apparatus that is described in detail elsewhere.[13] The device consists of a digitally controlled crane that automatically cycles specimens between two thermal baths. The high temperature bath contains oil that is resistively heated and controlled to ±1° C. The low temperature bath contains ethyl alcohol that is cooled by a freon refrigerator (accurate to ±5° C).

The hold time in the experiments that tested variations in joint thickness and tensile/compressive strain experiments was 5 min in each bath with a 30 sec transfer time. To examine the effect of hold time the time spent at 125° C was increased to one hour while keeping the transfer time between baths constant. The microstructural evolution versus the number of thermal cycles was evaluated by placing a number of specimens in the cycling device and removing individual specimens after specified numbers of cycles.

The microstructure of the specimens was observed using optical microscopy. Specimens for optical microstructural observation were successively ground down to 600 grit silicon carbide paper under flood cooling. The samples were then polished on a felt surface using an Al_3O_3/kerosene mixture. Final polishing and etching were performed simultaneously using a colloidal slurry of 0.03 μm SiC particles in a slightly acidic solution. Special care was necessary in the polishing of the Al/Cu sandwich specimens to avoid galvanic coupling between the Cu and the Al which causes the Al to severely pit, particularly near the joint interface. This problem was solved by polishing the specimen for only short times (on the order of 5 min) in the colloidal solution.

RESULTS AND DISCUSSION

Thermal Cycling in Tension/Compression

The effect of a tensile/compressive strain cycle on the thermal fatigue behavior of 60Sn-40Pb solder joints was studied on specimens that were cycled from −55° to 125° C up to 1500 cycles. The solder joint microstructure was examined after increasing numbers of cycles. The imposed strains (6.2% in compression and 8.6% in tension) are well below the strain to failure of a 60Sn-40Pb joint[17] and are similar to the levels of strain which may be imposed on joints in service.

Figure 5 shows optical micrographs of 60Sn-40Pb joints as a function of increasing number of cycles. Two significant observations were made after cycling in tension/compression. First, the 60Sn-40Pb microstructure coarsens throughout the solder, primarily at the eutectic cell boundaries. This is in contrast to the preferential heterogeneous coarsening observed in shear deformation where a thin band of coarsened material forms parallel to the shear orientation. In the tension/compression strain cycle the plastic deformation of the solder must also

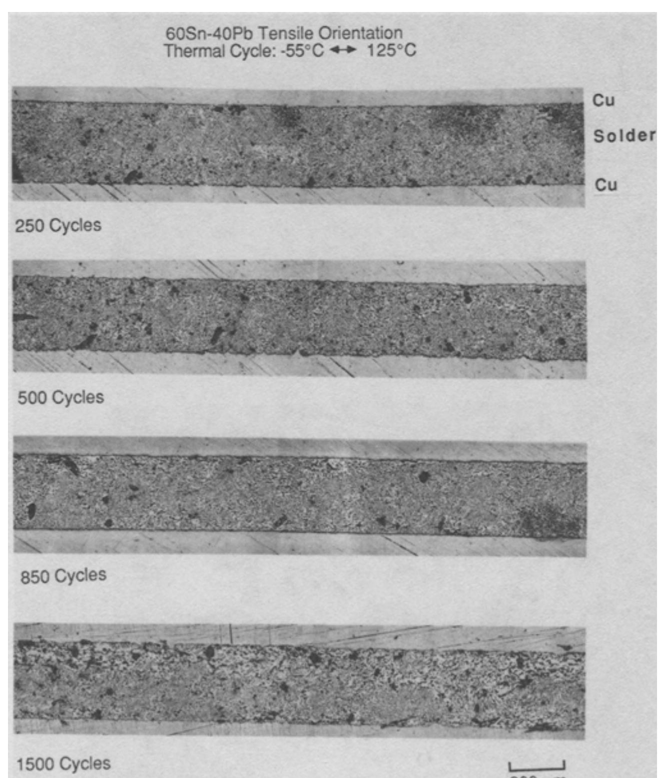


Fig. 5 — Optical micrograph cross section of 60Sn-40Pb/Cu joints in tension/compression as a function of number of cycles between −55° and 125° C revealing coarsening at cell boundaries.

be in a shear mode but it is distributed throughout the joint, not just localized into a thin band. Figure 6 shows examples of the coarsened regions and cracks that have developed in the Sn-rich regions after cycling in tension/compression.

The second significant observation is the presence of cracks near the interface between the solder and Cu. This observation is documented in Fig. 7, where the 60Sn-40Pb microstructure is shown as a function of the number of cycles. The cracks develop early, before 250 cycles. A closer examination of these interfacial cracks, Fig. 8, reveals that they propagate through both the intermetallics at the interface and the solder immediately adjacent to the interface.

It is interesting to note that some portions of the joint fail through the interfacial intermetallics before 250 cycles while in other regions of the same joint the solder coarsens and cracks form in the Sn-rich phase much later, after 1500 cycles. A possible explanation for these two concurrent failure modes is the following. Early in the fatigue life some cracks form in the interfacial intermetallics and propagate both through the intermetallics and the coarsened region adjacent to the intermetallics. However, the entire solder joint does not fail completely because

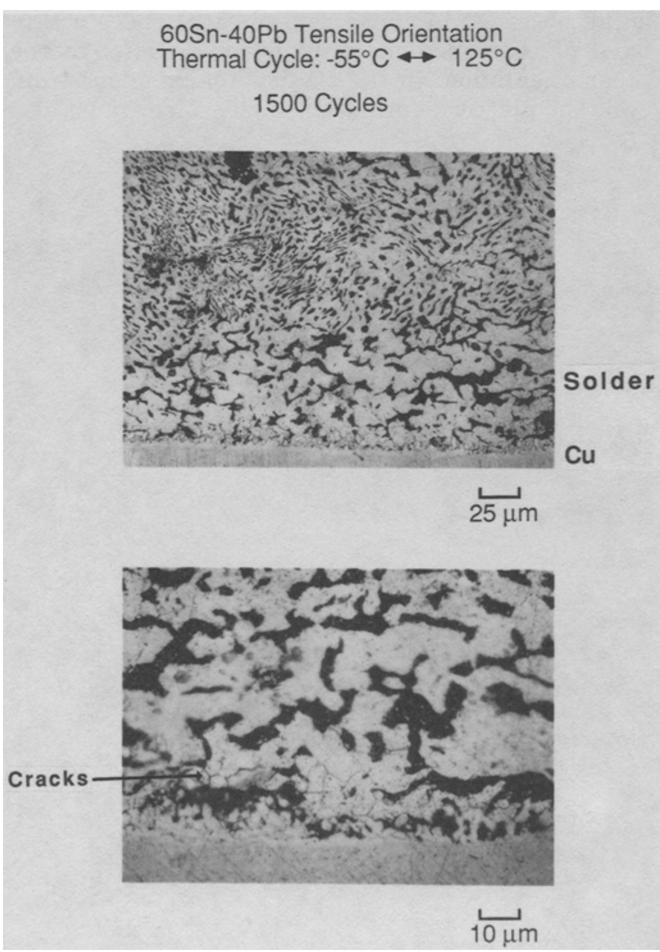


Fig. 6 — Optical micrograph cross section of 60Sn-40Pb joints in tension/compression after 1500 cycles showing small cracks in the Sn-rich regions after 1500 cycles.

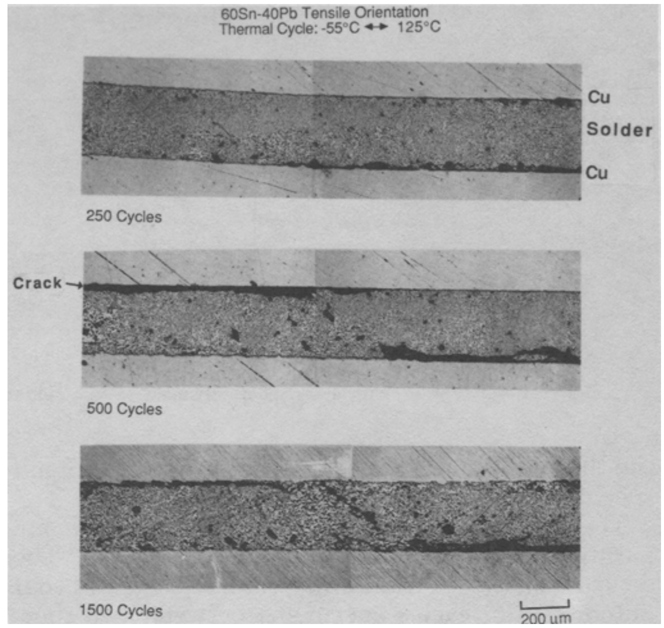


Fig. 7 — Optical micrograph of 60Sn-40Pb joints thermally cycled in tension/compression revealing interfacial cracks.

deformation occurs in the bulk of the solder joint. In regions where the interface remained intact repeated cycling causes deformation in the solder which results in coarsening.[14] The coarsening that occurs is not a distinct heterogeneous band as found in shear deformation but occurs at cell boundaries. Cracks then form within the coarsened Sn-rich regions. The tensile thermal fatigue of solder joints can be thought of as the deformation of two materials in series, the solder and the interfacial intermetallics. The weaker of the two materials fails whether it be the inter-

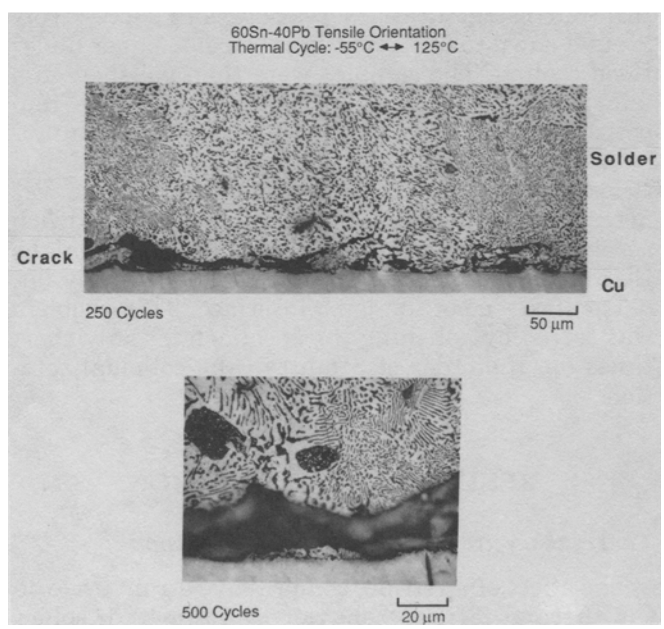


Fig. 8 — Optical micrograph of 60Sn-40Pb/Cu joints revealing cracks through interfacial intermetallics and coarsened regions adjacent to the interface.

facial intermetallics or the coarsened solder (which forms later because of the time needed for coarsening).

The above results indicate that a tensile/compressive strain component is detrimental to the thermal fatigue life of a solder joint. Thermal fatigue in tension occurs much more rapidly than thermal fatigue in shear. Samples prepared in a similar fashion crack after 1000 cycles of thermal fatigue in a shear orientation, whereas in tension/compression failures occur before 250 cycles through the failure of the interfacial intermetallic layer. A solution to this problem is difficult in that the interfacial intermetallics must be present to ensure that a good bond has formed in the Sn-Pb solder/Cu system. Even in an SMT joint, where the maximum tensile component is not near the interfacial intermetallics (as diagrammed in Fig. 1) the tensile stresses may eventually result in coarsening and failure in the bulk of the joint. Therefore in order to avoid this problem it is necessary to design solder joints with a minimum tensile strain component.

Joint Thickness Variations

To investigate the effect of joint thickness on thermal fatigue behavior in shear joints, three different joint thicknesses were thermally cycled. The thicknesses were 2 mil (0.051 mm), 10 mil (0.254 mm), and 20 mil (0.51 mm). Both the 2 mil and 10 mil joints were tested at 19% shear strain. Specimen size constraints required that the 20 mil joint be tested at 10% shear strain. Figure 9 shows specimens of 10 mil thickness after various numbers of thermal cycles between −55° and 125° C. A single heterogeneous coarsened band developed in these specimens. Cracking and failure occurred through the Sn-rich regions after 1000 cycles.

Figure 10 shows 20 mil thick joints after cycling between −55° and 125° C. In this thicker joint two heterogeneous coarsened regions develop and grow with increasing number of cycles. Cracks were observed in these specimens after 1000 cycles even with half the strain imposed on the 10 mil joint.

Figure 11 shows 2 mil thick solder joints as a function of the number of cycles between −55° and 125° C. The entire solder region of the joint coarsens very rapidly. At 250 cycles there is only a small region at the lower right portion of the joint in the photograph that has not yet coarsened. Cracks develop within the solder before 850 cycles. A continuous crack the length of the joint was observed after 1500 thermal cycles.

A closer examination of a portion of a 2 mil thick solder joint after 1500 cycles is shown in Fig. 12. In this case a crack has developed through the interfacial intermetallics as well as through the bulk solder. Failure through interfacial intermetallics was never observed in the thicker joints. The reason the interfacial intermetallics fail in shear in the 2 mil joint could be that they represent a significant cross sectional area of the joint. Therefore a flaw in the intermetallic layer is much more detrimental in a thinner joint and may cause a crack to propagate through the interfacial intermetallic.

An indication of how much influence strain has on the coarsening of the solder joint is shown in Fig. 13 for a 2 mil thick joint after 1500 cycles. On this sample some solder remained on the ends of the specimen after manufacture and was not removed. This region is shown on the right side of the figure.

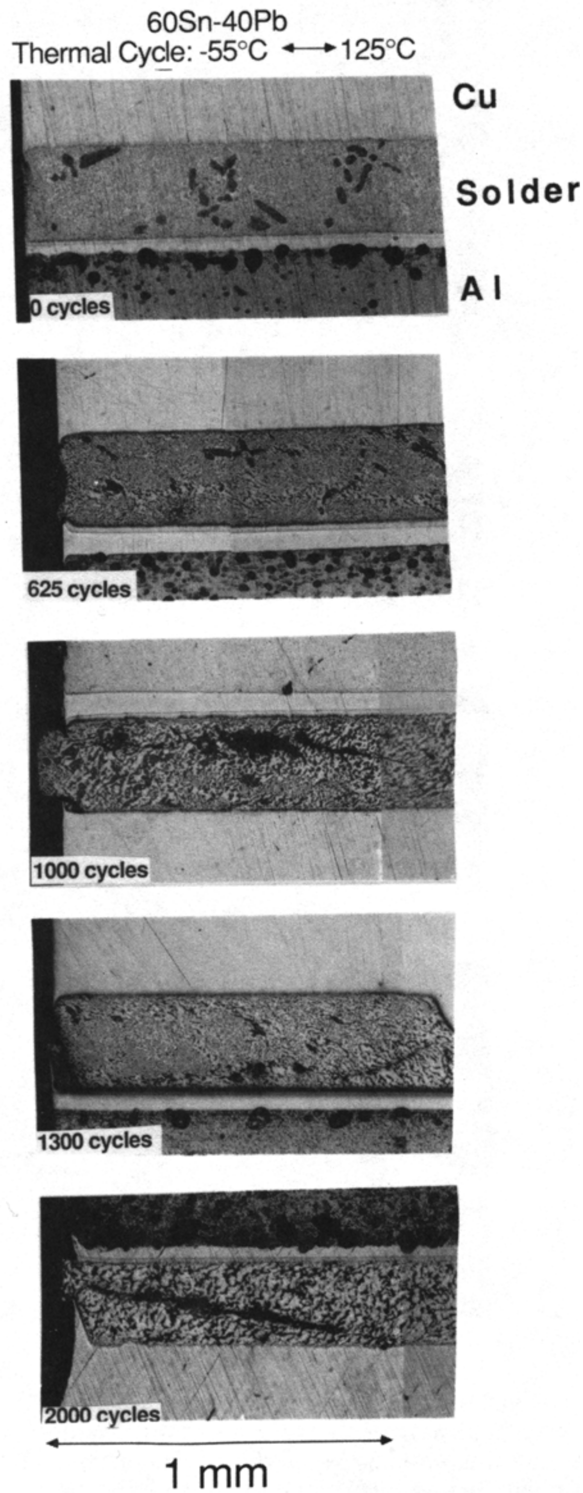


Fig. 9 — Optical micrograph of 10 mil thick 60Sn-40Pb solder joints cycled between −55° and 125° C in shear.

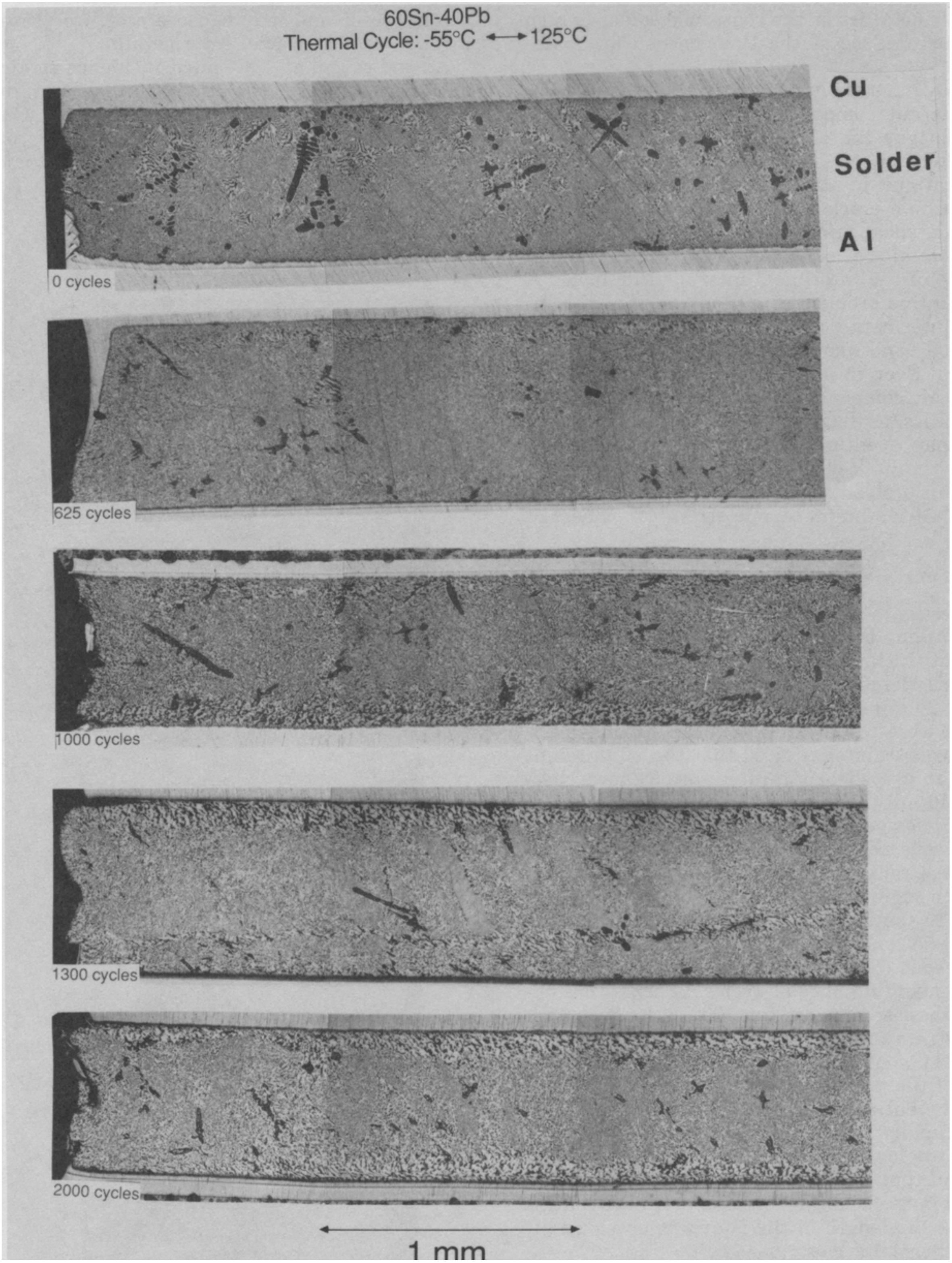


Fig. 10 — Optical micrograph of 20 mil thick 60Sn-40Pb solder joints cycled between −55° and 125° C in shear.

The solder microstructure within the joint which has been cyclically strained in shear is much coarser than the fine microstructure of the solder outside of the joint which has been exposed to the thermal fluctuations but was not constrained so as to deform in shear. This is direct evidence that temperature alone does not cause heterogeneous coarsening; coarsening results from a combination of temperature and plastic deformation in shear.

Increasing joint thickness, for a given package geometry, decreases imposed shear strain by the equation:

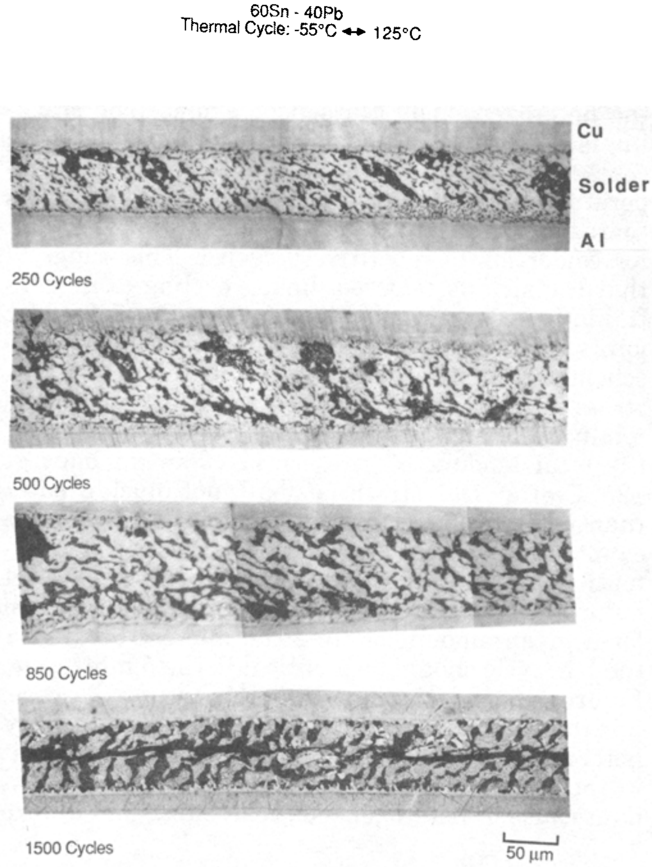


Fig. 11 — Optical micrograph of 2 mil thick 60Sn-40Pb solder joints cycled between −55° and 125° C in shear.

$$\gamma = \Delta\alpha\Delta T\frac{a}{h},$$

where:

$\Delta\alpha$ = difference in thermal exansivities between the materials,

ΔT = temperature change,

a = distance from the joint to the center of the chip carrier, and

h = thickness of solder joint.

Given this equation the shear strain is inversely proportional to the joint thickness. Increasing joint thickness, and therefore decreasing the strain, has been suggested to help minimize strain due to thermal cycling. In addition to becoming more difficult to process, the results discussed above indicate that, for large strains, increasing thickness may not be that beneficial. The 10 mil thick joints were tested at 19% strain and the 20 mil joints at almost half the strain, 10%, but cracks were observed to occur after approximately the same number of cycles in both samples. A possible reason for the similarity in the number of cycles before cracking, despite the differing strain levels, is the development of the heterogeneous coarsened band. Once a heterogeneous coarsened region develops any further shear deformation concentrates in the coarsened band, and the overall joint thickness becomes less important.

Variation in Hold Time

The following experiments were performed to determine the importance of hold times in thermal fatigue in a shear orientation. Also, by increasing the hold time it is possible to determine whether accelerated thermal cycling is applicable to the real situation in an electronic package where thermal cycles can be much longer in duration than in thermal cycling tests.

In our previous thermal cycling experiments the hold time at the high and low temperatures was kept to 5 min. In that work it was found that the high temperature portion of the thermal cycle is responsible for most of the damage incurred in thermal fatigue.[14] Therefore to study the effect of an increase in hold time the specimen was held at 125° C for 1 h then cooled to −55° C until the specimen reached temperature (1 min). To examine whether it is the time spent at the elevated temperature, rather than the number of cycles, that determines when a joint will fail, a correlation of the number of cycles to failure between the 5 min per cycle and the 1 h per cycle hold time was made. The time spent at 125° C for one 1 h cycle corresponds to the time spent at 125° C for 12 cycles at 5 min/cycle. Thus:

21 cycles (1 h/cycle) =252 cycles (5 min/cycle)

41 cycles (1 h/cycle) =492 cycles (5 min/cycle)

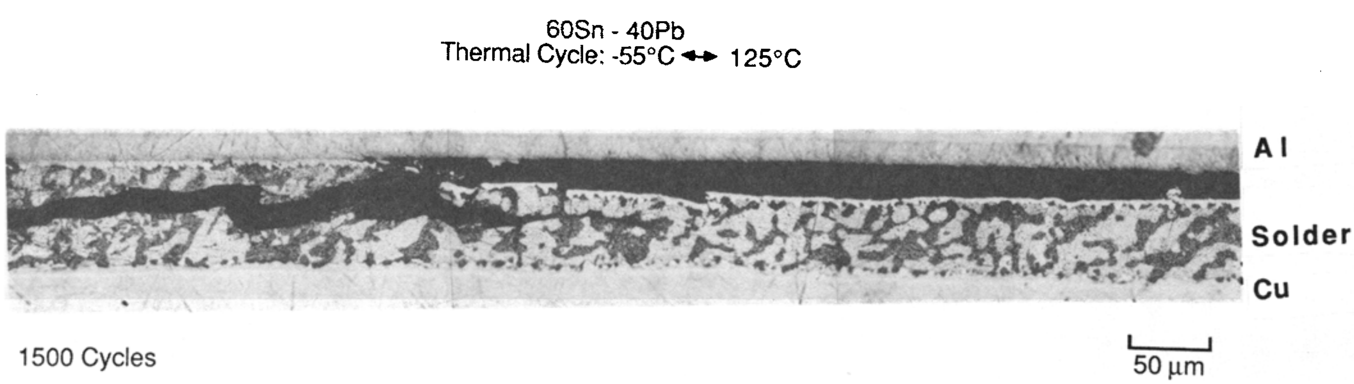


Fig. 12 — Optical micrograph of 2 mil thick 60Sn-40Pb solder joints revealing cracks through both the solder in the joints and the interfacial intermetallics.

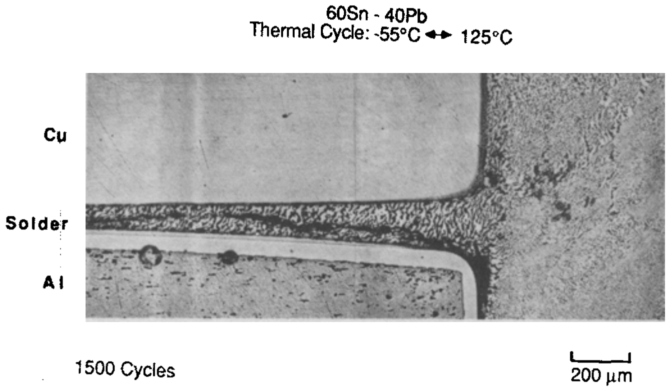


Fig. 13 — Optical micrograph of 2 mil thick 60Sn-40Pb solder joints with additional solder attached outside the joint.

90 cycles (1 h/cycle) = 1080 cycles (5 min/cycle)

170 cycles (1/cycle) = 2040 cycles (5 min/cycle).

Figure 14 shows the optical microstructure for 60Sn-40Pb samples as a function of the number of cycles between −55° to 125° C for 1 h hold time at 125° C. The heterogeneous coarsening that is typical of shear deformation is 60Sn-40Pb solders is apparent and increases with the number of cycles. However, the extent of the heterogeneous coarsening observed is not nearly as great as found for shorter hold times and greater number of cycles. Figure 15 shows cracks within the Sn-rich phase in the heterogeneously coarsened regions. The cracking is not extensive and in no sample was a single contiguous crack present. A lengthy elevated temperature exposure with occasional cycling produces coarsening and failure at a much slower rate than for solder joints repetitively cycled. This suggests that the strains imposed during cycling are essential to the coarsening and eventual failure of solder joints in thermal fatigue. This is explained in the schematic illustration in Fig. 16. In this schematic, stress is plotted as a function of time for both the 5 min/cycle and 1 h/cycle. From work by Tribula[18] the total amount of stress relaxed in an hour at 125° C after 19% strain is small, not much greater than what occurs in 5 min. Thus stress relaxation cannot be held accountable for the increased deformation. Therefore if we assume that solder joint failures are determined by time at temperature then for a given amount of time the microstructure for the 1 h/cycle should be identical to the 5 min/cycle. Figures 10 and 15 show that this is not the case. For the same amount of time at 125° C much more heterogeneous coarsening and cracking is present in the 5 min/cycle specimens. Therefore the dominant cause of heterogeneous coarsening and failure

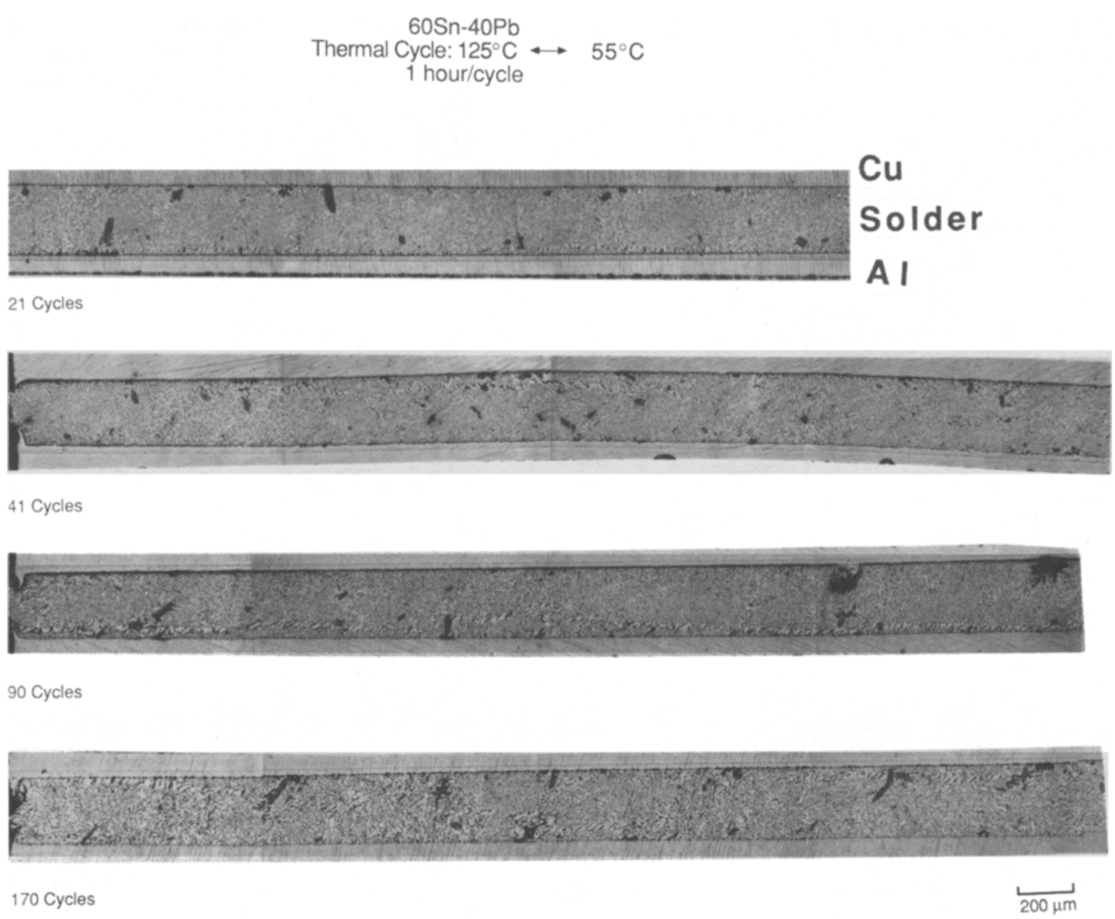


Fig. 14 — Optical micrograph cross sections of 60Sn-40Pb solder joints thermally cycled between −55° and 125° C with a 1 h hold time at 125° C.

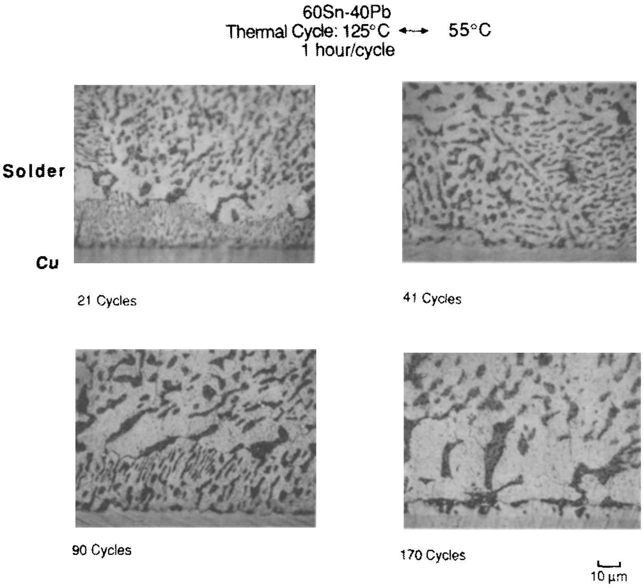


Fig. 15 — Optical micrograph cross sections of 60Sn-40Pb solder joints thermally cycled between −55° and 125° C with a 1 h hold time at 125°C at a higher magnification.

in 60Sn-40Pb joints in shear thermal fatigue is the cumulative strain imposed by the repeated cycling plus the thermal energy present at the elevated temperature. The total number of cycles to failure may be shorter, as has been suggested by Solomon[19] for longer hold times than shorter due to the added thermal energy available for coarsening during the longer time at temperature. This study can not make a conclusive statement on this but in the range of 5 min to 1 h cycles the number of cycles determines failure more so than total cumulative time to failure. However, it is possible that for much longer hold times the hold time itself becomes more important.[20] Work is underway exploring this in more detail.

A qualitative explanation of how repeated cycling can lead to coarsening and eventual failure is as follows. Upon thermal cycling in shear, deformation concentrates at eutectic cell boundaries parallel to the shear orientation. Deformation at cell boundaries, in combination with the thermal energy at the elevated portion of the thermal cycle, results in a coarsened region developing the solder joint. The coarsened region is weaker than the rest of the solder so deformation is located there resulting in further coarsening. In addition to both Pb and Sn phases coarsening the Pb and Sn grains themselves coarsen. Eventually cracks form at the Sn-Sn grain boundaries. To produce heterogeneous coarsening it is necessary to have both the cyclical strain to induce deformation in the solder and thermal energy at the high temperature portion of the cycle to induce mass flow. Therefore failure in solder joints in thermal fatigue is dependant on a combination of both the number of cycles (to induce deformation) and time at elevated temperature (to induce mass flow).

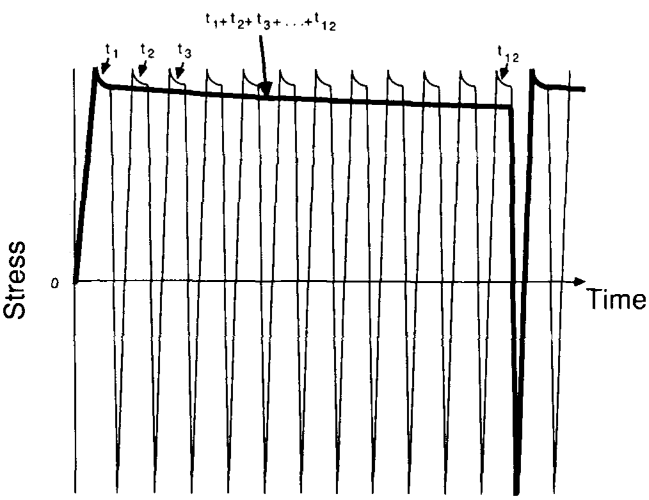


Fig. 16 — Schematic diagram of stress versus time illustrating stress relaxation for short and long hold times at the elevated temperature portion of the thermal cycle.

CONCLUSIONS

The effect of tension/compression deformation cycles in thermal fatigue was explored on 60Sn-40Pb joints. Cracks occurred in the joint through interfacial intermetallics after a short number of cycles. Portions of the joints that did not fail early in the fatigue cycle coarsened at cell boundaries, and cracks formed in the coarsened regions later in the fatigue cycle.

Solder joints of three thicknesses were thermally fatigued in shear. The thinner solder joints failed slightly sooner than the thicker ones. However, joint thickness does not appear to significantly affect fatigue life even for samples shear strained at different levels (10% vs 19%). Once a heterogeneously coarsened region develops, the imposed strain on the joint concentrates in this coarsened region while the rest of the joint remains relatively unstrained.

The effect of increasing hold time at the maximum temperature of the thermal cycle was also investigated. The heterogeneous coarsened region (the precursor to a failed joint) develops only with the strain induced during repeated cycling acts in concert with the elevated temperature. This suggests that it is possible to use accelerated thermal fatigue tests on 60Sn-40Pb solder joints to model the thermal cycling conditions of solder joints in service.

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