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FATIGUE PROPERTIES OF SOLDER JOINTS

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Tests show how soldered electronic connections fail, and recommendations for optimizing joint strength are given

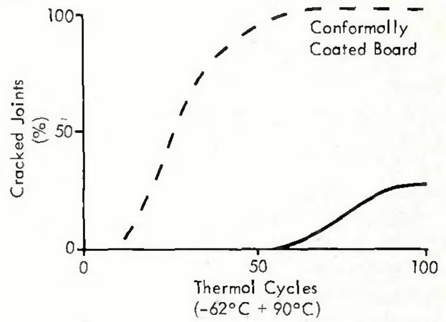

Fig. 1—Cycling effect on solder joints

ABSTRACT. Several past extensive failure analysis studies have shown that the primary cause of solder joint failure in the electronics industry is a slow cycle fatigue failure of the solder joint. Seldom does a solder joint fail because its ultimate strength has been exceeded in either testing or system environments. Joint failure is usually caused by exceeding the fatigue limits of the solder alloy in the various system thermal environments. This is usually a result of solder joint strains caused by the large differences in coefficient of thermal expansions of the various materials in the component or assembly.

This study describes typical system solder joint failures and discusses initial stress conditions through complete joint failure, as well as failure correction. Also presented are the results of a series of tests made to determine the mechanical properties and the fatigue characteristics of some solders. The tests were made on joints consisting of a pin in a plated through-hole and on some lap shear solder joints with a cyclic test speed from 1/15 to 5 cycles/min.

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Introduction

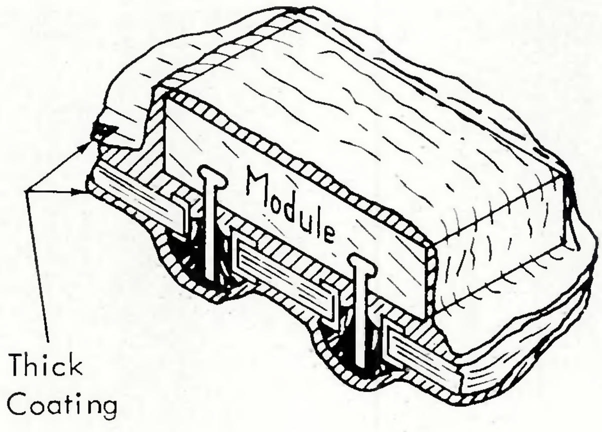
Several extensive failure analysis studies on cracked solder joints have shown that low cycle fatigue is the primary cause of solder joint failure in the electronic industry. Seldom does a solder joint fail because its ultimate strength has been exceeded in either testing or system environments. Joint failure is usually caused by exceeding the cyclic fatigue limits of the solder alloy in the various system environments. This is usually the result of large solder joint displacements (strains) caused by differences in coefficient of thermal expansions of the various materials used in the component or assembly.

This paper discusses some of the physical and metallurgical changes and the stress modes that occur in solder joints during severe thermal stressing. The mechanical and especially the fatigue properties of solders are also discussed.

Typical Stress Conditions

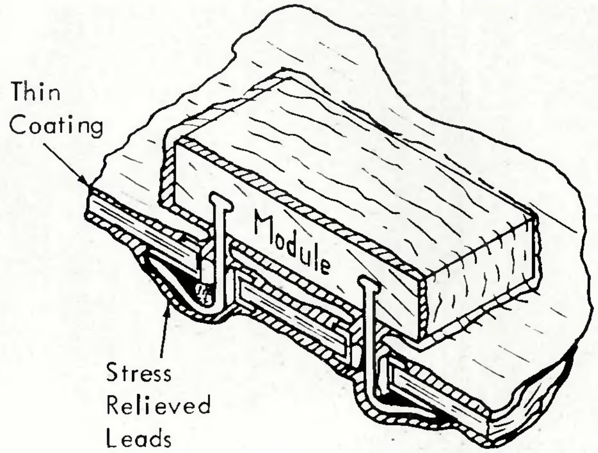
During the past several years, industry has experienced a series of solder joint stress problems related to the severe environmental requirements of space and avionics systems. Many of these aerospace systems require numerous thermal cycles with extreme temperature variations ranging from -62 C (-80 F) to 140 C (284 F). Thermal cycling requirements have also ranged as high as 1,000 thermal cycles.

Without proper mechanical support or component lead strain relief, or both, these thermal environments can create severe solder joint stresses with resulting low cycle fatigue failure of the joint. Low cycle fa-



Stress Condition Caused by Conformal Coating being Placed Between Module and Circuit Board

Fig. 2—High solder joint stress configuration



Note the Thin Non Bridging' Conformal Coating and Stress Relief on Component Leads

Fig. 3—Low solder joint stress configuration

tigue is defined as fatigue failure which will occur under 100,000 cycles [1,2] as a result of stress levels sufficiently severe to produce measurable cyclic plastic strain.

This would be especially applicable to solder joints since solders generally creep readily at and above room temperature; therefore, relaxation of stresses within the solder occurs very rapidly. This especially occurs during the elevated temperature portion of the thermal cycle where solder joint strength is further reduced. These types of solder joint failures are considered to be strain-dependent failures as the joints fail without the presence of any significant stress buildup within the solder.

This paper does not dwell on the various designs of solder joints; however, it is desirable to stress the effects of conformal coatings or potting materials on multilayer and circuit board assemblies. A thick conformal coating, such as an epoxy or a polyurethane which is normally an aerospace requirement, coats the complete assembly to provide a barrier against dust and contaminants, and serves as a moisture seal against humidity.

Such coating can create significant joint stresses when the coating fills the space between the components and board (see Fig. 1). This is especially true of larger flat bottom components such as resistor networks and transformers. In many cases, detrimental solder joint stresses can be reduced by preventing the coating from filling the space under the component or by providing proper strain relief for the component leads, or both,[3] (see Fig. 2 and 3).

Physical Solder Joint Changes

Initial Stress Indications

The first visual evidence of cyclic damage to a solder joint is a dulling of the normally bright shiny solder surface. This would appear as an annular crazing or a frosty condition occurring in the higher stress areas of the solder joint. The effect is the result of physical slip displacements occurring within the solder matrix of the joint (see Fig. 4).

These displacements occur in a relatively narrow slip band, normally within the smaller cross-sectional areas of the joint. As the solder is work hardened, grain growth and recrystallization occurs. The slip will then occur in a slightly different (non-strain hardened) position within the solder joint. This produces several slip bands until one is weakened due to Pb-rich phase alignment to a point where subsequent fracturing occurs.

High Stress Low Cycle Failure

A high stress (high strain), low cycle solder joint fatigue failure is evidenced by a complete fracturing of the solder joint with very little distortion of the surface of the solder (other than crack areas) or significant recrystallization of the solder structure in the high stress areas of the joint (see Fig. 5).

Low Stress High Cycle Failure

A low stress (low strain), high cycle solder joint fatigue failure is evidenced by extreme dulling and crazing of the solder surface. Significant recrystallization and grain growth also occurs in the high stress areas of the solder joint (see Fig. 6). The Pb-rich phases will align themselves in the high stress direction within the solder matrix. Failure normally propagates through these aligned Pb-rich or softer phases within the solder matrix.

Stressing Conditions

It is important for corrective action to be able to determine the major stressing direction of the solder joint during thermal cycling. A visual examination can in many cases show these stress directions. The position of the component lead and the position of the fracture can usually indicate the major stress direction

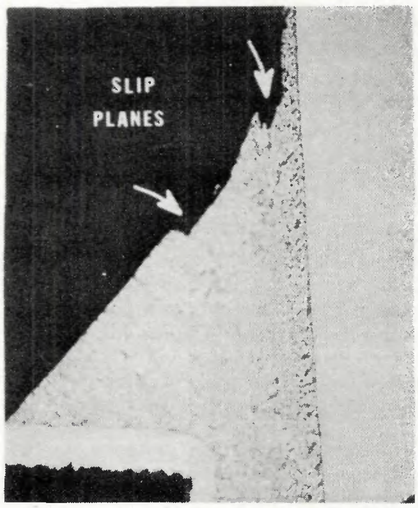


Fig. 4—Initial stress condition. The frosty joint condition is caused by a rough solder surface due to slip movements within the high stress areas of the solder joint (stress relaxation)

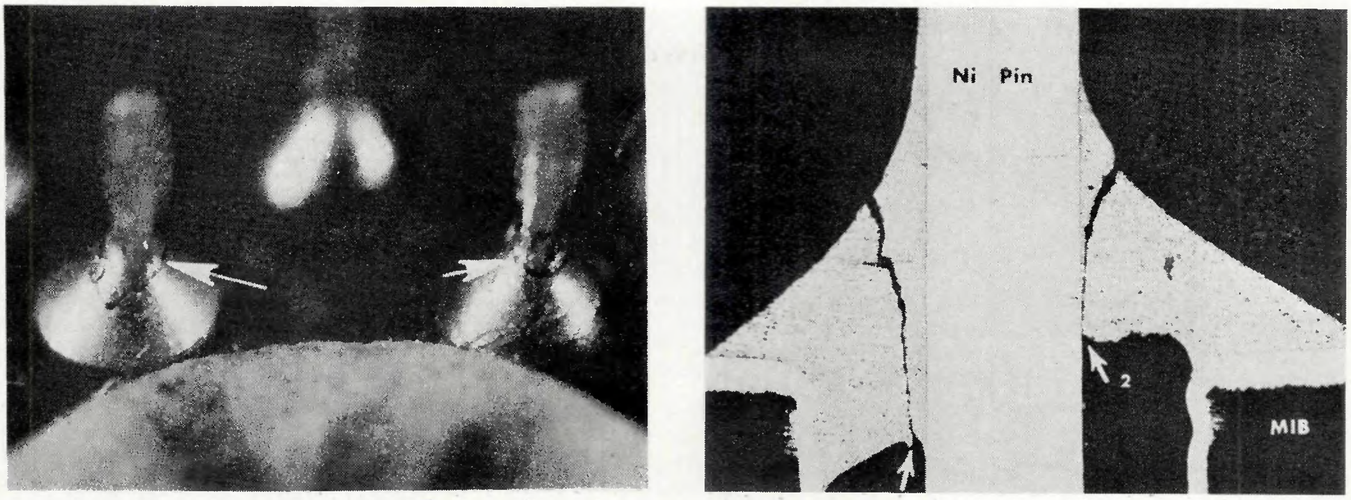


Fig. 5 — High stress low cycle failure. (Left) note how the joint cracks with little distortion of the solder surface. (Right) note there is no significant recrystalization of the solder structure

through the solder joint. A component lead that pushes or pulls the solder into the through-hole will cause a compressive-shear loading of the solders with the joint fracture occurring near the top of the solder fillet and along the pin (see Fig. 7A). The solder joint is stronger in this compressive-shear stress direction.

A component lead pulling the solder from the through-hole creates a tensile-shear loading of the solder and also a crack position lower on the solder fillet of the joint (see Fig. 7B). The weaker tensile-shear stress condition will also produce more of a separation of the solder fracture. Caution must be used in these stress interpretations as these types of solder joints are normally hysterisis sensitive and thus the solder joint will take on a displaced position that would be dependent on the previous thermal cycle (see Fig. 8).

At elevated temperatures, the joint is significantly weaker and thus stress relaxation of the solder joint occurs rapidly through joint displacements. At the lower temperature portion of the thermal cycle, the solder joint is significantly stronger and less ductile, thus higher joint stresses are encountered.

Mechanical Properties

A substantial amount of data had been previously gathered on the mechanical properties of solders and solder joints[4,5]. A review of some of this data will provide better understanding of the reactions of solders in thermal or fatigue environments.

Effects of Strain Rates and Temperature. The strength of the solder normally used, eutectic tin-lead solder (Sn 63), and most other solders are very sensitive to both strain rates and temperature. Solder joint strengths are normally reduced very rapidly with slow strain rates or higher solder joint temperatures (see Fig. 9). In actual electronic assemblies, this would relate to the rapidity of thermal profile changes and also to the temperature extremes of the profile.

Stress Relaxation Properties. Solder joints not mechanically supported will creep very rapidly under applied loads (see Fig. 8 and 10), especially at the higher stress levels and at elevated temperatures. The solder joint normally will relax the built-up stresses by movement within the solder matrix to the point where the stress rupture limits of the solder joint is reached or in extreme cases, to the point that the solder joint fails.

Stress Rupture Properties. The stress rupture properties of eutectic Sn-Pb solder were determined at 25 C (75 F) and at 60 C (140 F).[5] The test specimen was a lap shear solder joint with a joint thickness of 0.002 in. The stress rupture properties were determined by gripping the top

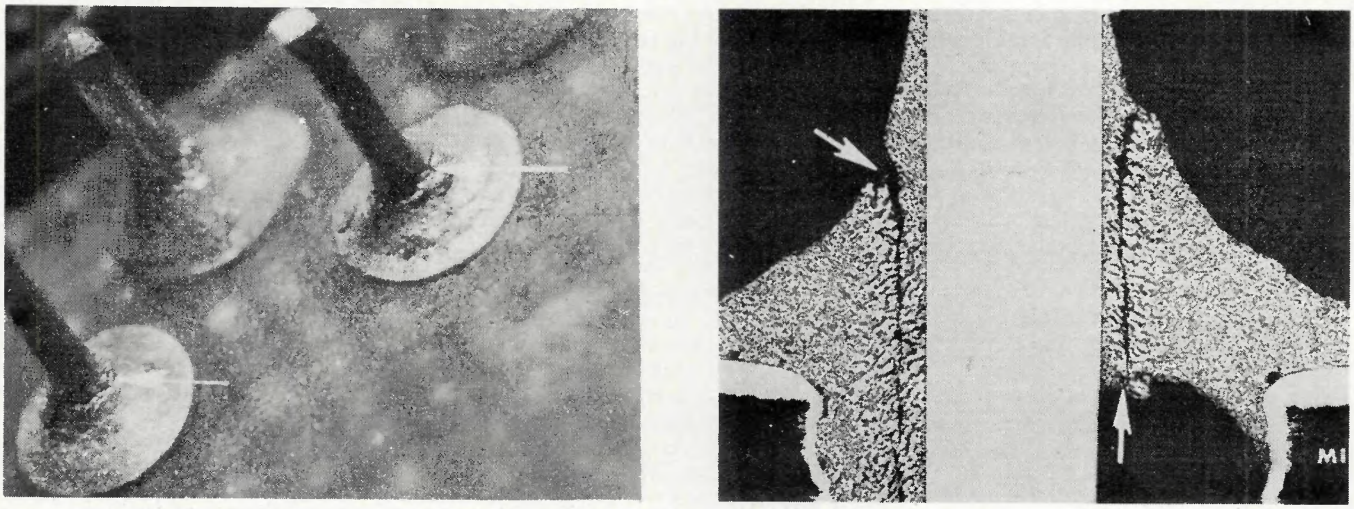
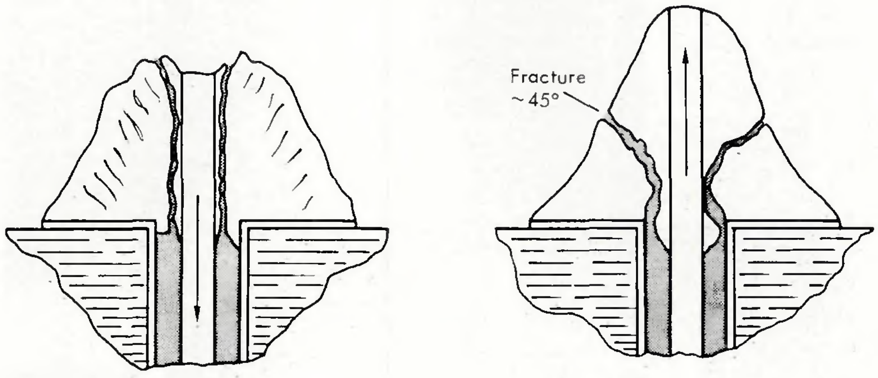


Fig. 6 — Low stress high cycle failure. (Left) note the rough solder surface caused by many small joint deflections. (Right) note recrystalization in the high stress areas of the solder joint



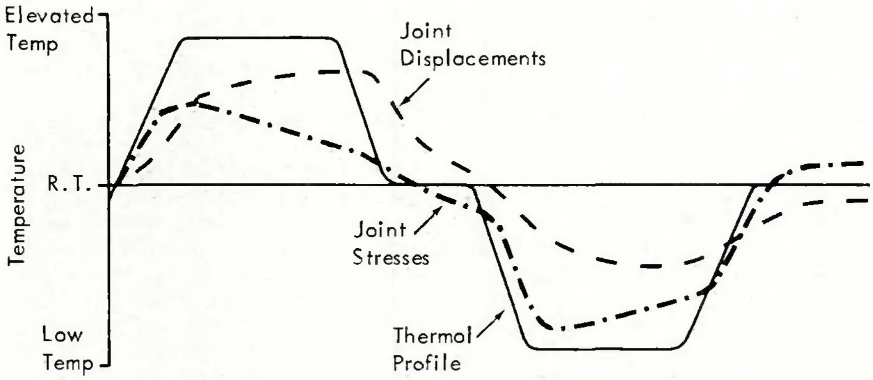
A

B

This is a Compressive Shear Loading of the Solder. Note that the Fracture is Along Pin Interface.

This is a Tensile Shear Loading of the Solder. Note Crack Position at ~ 45°.

Fig. 7—Joint stressing conditions



At Elevated Temperature, the Solder Joint Relaxes Rapidly Thus Joint Stresses are Reduced. At Low Temperature, the Solder Relaxes More Slowly thus Stresses are Higher and Deflections are Lower. Note Permanent Set of Joint

Fig. 8—Joint conditions during thermal cycling

half of the test specimen and then suspending a predetermined weight from the bottom of the specimen. This produced a constant shear-stress loading on the joint. Total time to failure was then plotted (Fig. 11).

These tests showed that the Sn Pb eutectic solder joints are very weak under a constant stress condition. These joints while under constant loading will fail rapidly unless the initial joint stress is very low or the stress is reduced by relaxation of the solder.

Fatigue Properties

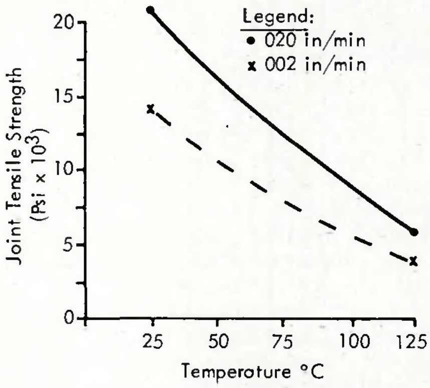
Since the majority of joint failures are of the low cycle fatigue type, a special fatigue tester was designed and fabricated to determine the fatigue properties of solder joints under different conditions.

Low Cycle Fatigue Tester. The fatigue tester was designed to apply a predetermined strain on the solder joints at very low stress rates (see Fig. 12). The tester was rigidly constructed to maintain the predetermined strain levels on the test specimens throughout the test. This equipment is capable of cyclic test speeds from 40 min/cycle to greater than 200 cycles/min (cpm). These very low testing speeds are desirable as they can simulate strain conditions in thermal environments.

As was previously stated, solder joints will creep very rapidly at the lower strain rates. Normal fatigue testing rates (1800 to 2000 cpm) can simulate system vibrational effects; however, they cannot simulate the low strain rates created by thermal changes. An elliptical cam on the tester can be adjusted to produce joint deflection of from 50×10^{-6} to ~ 5/16 in. This cam produces a sine wave strain deflection of the solder joints (see Fig. 13). The tester is designed to apply a constant strain level independent of the stress loading on the solder joint or the change in that stress level due to strain-softening or cracking of the solder joint. This equipment does not compensate for the metallurgical changes (recrystallization) that will occur during the elevated temperature portion of a thermal cycle.

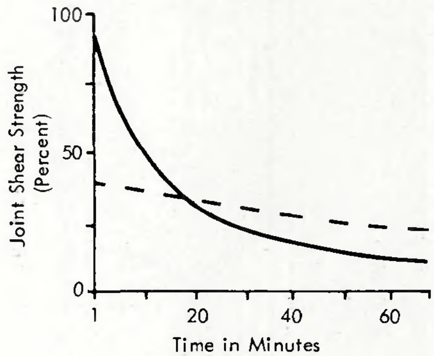
Fatigue Specimens. Two type of fatigue specimen were evaluated in this study, lap-shear and pin-in-hole (circuit board) configurations. They are considered the most commonly used joint configurations in electronic assemblies (see Figs. 14 through 16). Special alignment fixtures were used in soldering these specimens to provide alignment for testing and uniform solder joint thickness. Solder joint thickness is considered very important in these tests to determine the percentage of shear strain in the solder joint and to produce repeatability of results.

Lap Shear Fatigue Life. Up to now, the majority of fatigue tests were



Note the Reduction in Joint Tensile Strength with Higher Temperatures and Lower Strain Rates

Fig. 9—Effects of temperature and test rates on Sn63 solder



Note Joint Relaxation is Very Rapid, Especially at the Higher Initial Joint Loadings

Fig. 10—Stress relaxation properties

conducted on pin-in-hole solder joints on multilayer interconnection boards; however, some tests were made on the lap shear configuration shown in Fig. 14. This curve represents approximately 40 test specimens to approximate the fatigue life of the eutectic Sn-Pb solder joints. Fatigue failure occurred at a test speed of 5 cpm, and produced a noticeable solder joint crack at ≥10 times magnification. Actual joint failure was very difficult to determine because of the infinite degrees of crack and stress conditions that can be found on this type of solder joints. Also, at the time these tests were conducted, we were not able to electrically monitor crack conditions in the solder joints.

These tests showed crack initiation within less than 10 cycles with about 1.6 mils deflection (approximately 35% shear strain) of the solder joint. A 0.4 mil joint deflection (approximately 9% shear strain) produced cracking at approximately 550 fatigue cycles.

Strain Rate Effect on Fatigue Life. A series of pin-in-plated-hole solder joints were fatigue tested at different testing speeds to determine the effect of strain rate on fatigue life. The specimen was a 0.025 in. diam nickel pin in a 0.040 in. through-hole with solder filling the through-hole completely.

At the 5 cpm test speed, the samples were tested to approximately 1,400 cycles. Joint failure was a solder joint crack detected at ≥10 times magnification. Fewer tests (15 to 20) were made at each of the lower test speeds, however, they showed a significant reduction in fatigue life with the lower straining rates.

The shorter fatigue life at the lower strain rates is believed related to a more complete relaxation of the solder during each thermal cycle. This produces greater stress relaxation and higher plastic deformation of the solder joints.

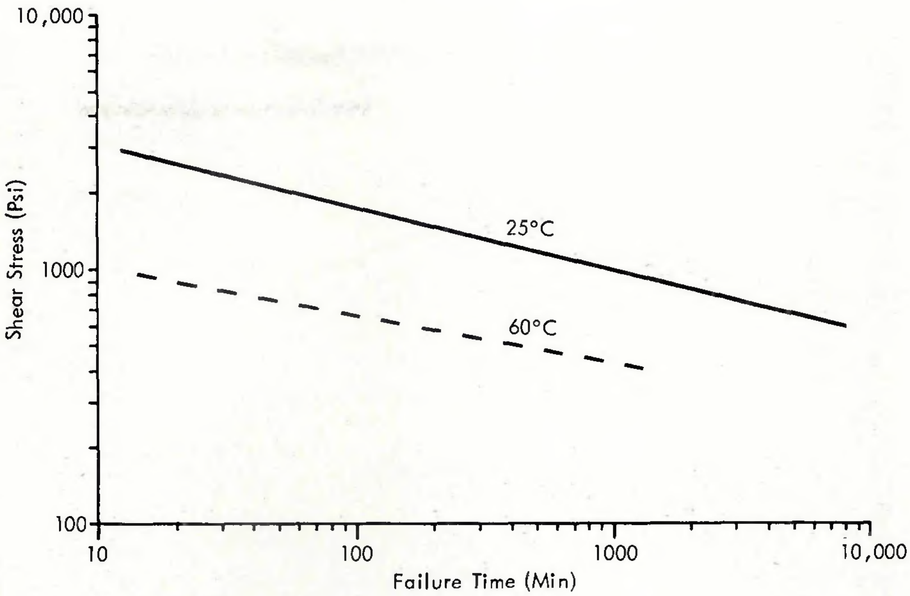


Fig. 11—Stress rupture properties (Sn-Pb eutectic solder)

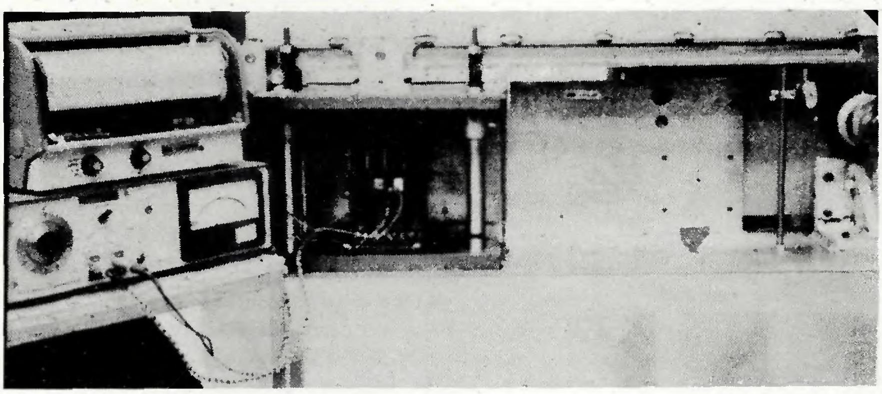


Fig. 12—Low cycle fatigue tester. Speed range is 1/40 to 200 cycles/min; test range is 50 microin. to about 5/16 in. Shown at left is the milliohm meter and chart recorder

Solder Joint Fatigue Life (Pin-in-Hole). This test was significantly different from the previous two tests in that both crack initiation and electrical failure of the joint were determined. Crack initiation was again a noticeable crack at ≥10 times magnification. Electrical failure was a 10% resistance change in the solder connection. Electrical monitoring was continuous with resistance changes plotted on a milliohm resistance recorder. The test specimen was a fillet type solder joint with a 0.026 in. diam, copper plated steel pin in a 0.036 in. diam plated-through hole. A black oxide coating was applied to the inside of the plated-through holes to prevent solder penetration into the hole.

Figure 16 shows that crack initiation occurs much sooner than any significant electrical resistance changes in the solder joint. There were, however, slight resistance changes less than 0.005 milliohm within the solder joint prior to any noticeable crack conditions. This condition is not understood at this time. It is thought to be related to structural changes and perhaps to internal cracking within the solder joint (see Fig. 17).

Metallographic Analysis. Metallographic analysis of fatigue tested solder joints showed that the solder joint fracture normally propagated through the Pb-rich phases of the solder structure and generally along the interface of the pin in the pin-in-hole solder joints. The lap shear solder joints normally failed in the solder matrix, not at the soldered interfaces. The fillet type solder joints normally failed at a 45 deg angle to the pin while the full pin-in-hole solder joint failed near the tip of the pin.

Summary

These tests show that in severe thermal environments there can be significant physical and metallurgical changes within the solder joint configurations normally used. Thus, high stress components should be mounted with proper strain relief or mechanical support, or both, to improve reliability in the more severe

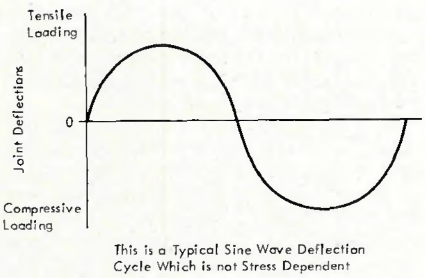
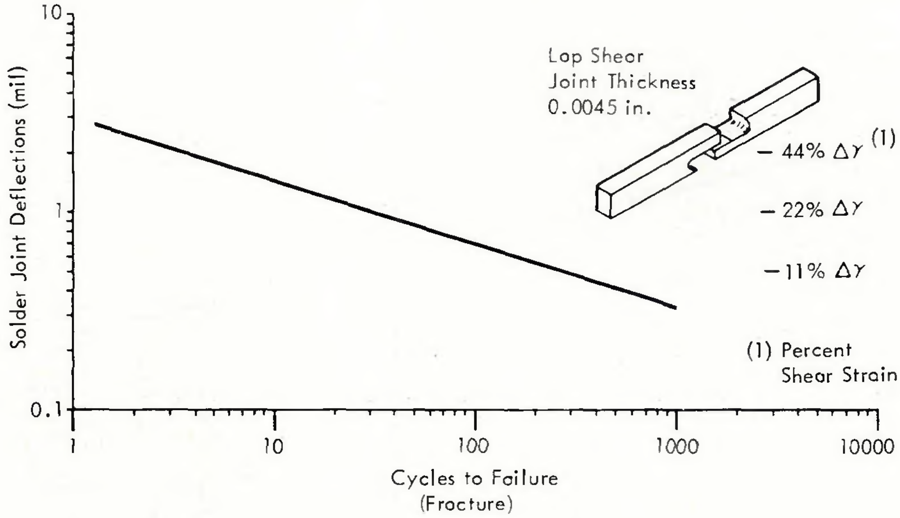
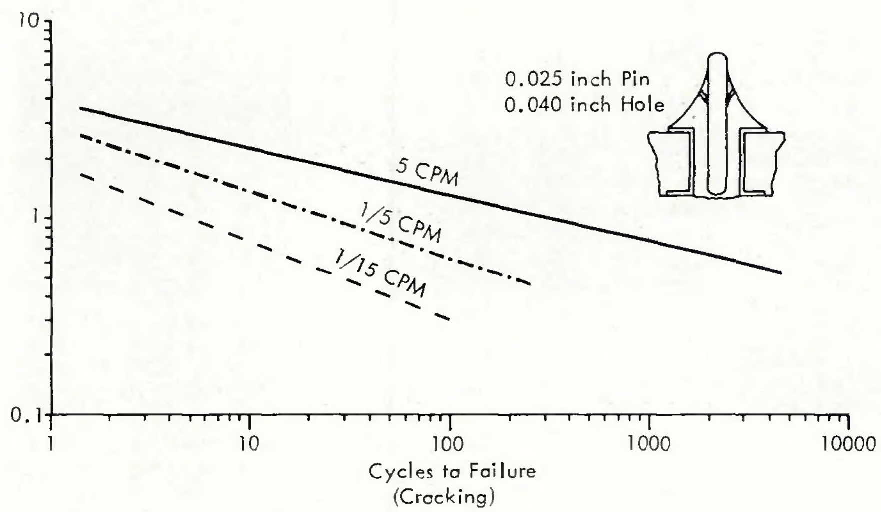


Fig. 13—Fatigue cycle



Joint Failure was a Distinct Crack Condition at ≧ 10 x Magnification

Fig. 14—Lap-shear fatigue life (eutectic Sn-Pb solder)



Note Joint Cracking Occurs More Rapidly with Lower Strain Rates

Fig. 15—Strain rate effect on fatigue life

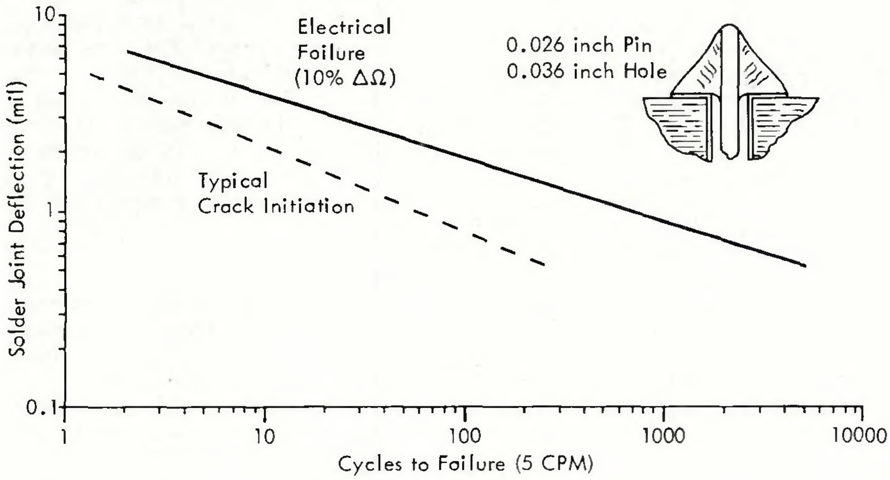
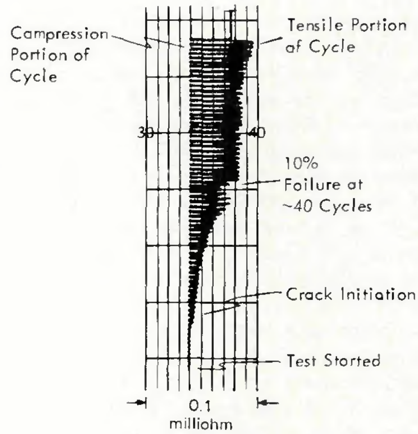


Fig. 16—Solder joint fatigue life (pin-in-hole)



This is a Typical Electrical Profile of a Pin-in-Hole Joint During Fatigue Testing. Note the Resistance Change During Cycling and During Each Thermal Cycle

Fig. 17—Electrical testing (typical chart)

thermal environments. Also, conformal coating should not fill completely the space under large flat bottomed components.

In thermal cycling type stressing, cyclic strains are considered more important than cyclic stress as solder joints will normally relax any significant stress buildup within the solder joint by plastic movement within the solder. These solder joints normally fail under a cyclic strain condition.

Although the fatigue tests in this study are valuable in establishing some fatigue properties of Sn Pb solder, much more work needs to be done to understand the full impact of fatigue on solder joints especially with different solders under different test conditions, such as temperature and strain rates.

Acknowledgements

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