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MECHANICAL BEHAVIOR OF AN AXISYMMETRIC
SOLDER JOINT-COMPONENT SYSTEM DURING
ENCAPSULATION AND THERMAL CYCLING

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MECHANICAL BEHAVIOR OF AN AXISYMMETRIC SOLDER JOINT-COMPONENT
SYSTEM DURING ENCAPSULATION AND THERMAL CYCLING

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Axisymmetric solder joint models were instrumented with strain gages and deflectometers to monitor mechanical behavior during encapsulation and thermal cycling. After encapsulation with glass microballoon-filled epoxy, the joints were cycled between -54°C and 74°C . Thermal ratcheting was indicated by cyclic work hardening of the copper lead wire and plastic flow in the 63Sn-37Pb solder.

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SUMMARY

The mechanical behavior of an axisymmetric solder joint-component system was measured during encapsulation and thermal cycling. To measure strain in the encapsulated portion of the lead wire, simulated components resembling thumbtacks were strain gaged on the shaft and soldered into a printed wiring board with 63Sn-37Pb solder. Two wires were then coated with a silicone rubber compound to simulate sleeving. A deflectometer was attached to the wire exiting the backside of the board to measure movement of the wire within the joint. The side of the board having the thumbtack head was encapsulated with glass microballoon-filled epoxy to produce a right cylinder concentric with the lead wire.

Strain and deflection were monitored during encapsulation and subsequent thermal cycling between -54°C and 74°C . The encapsulated portion of the lead wire underwent cyclic compressive strain of sufficient magnitude to produce yielding. At the same time, measurement of plastic flow in the solder indicated a progressive cyclic movement of the wire relative to the board surface (thermal ratcheting).

The joints which had wires coated with the silicone rubber suffered the greatest strains and deflections. The mechanical decoupling of the wire and encapsulant allowed the thermally-induced forces to be transmitted to the joint unrestricted. The detrimental effect of sleeving is thought to be unique to axisymmetric configurations where no shear stresses parallel to the board surface are present.

DISCUSSION

SCOPE AND PURPOSE

The objective of this project was to experimentally determine basic information regarding the behavior of a solder joint during encapsulation and thermal cycling. To accomplish this, simulated components resembling thumbtacks were to be instrumented with strain gages and deflectometers, soldered into a printed wiring board, encapsulated in glass microballoon (GMB) filled epoxy, and thermal cycled. The driving force for thermal stresses and fatigue would be the difference in the coefficient of linear thermal expansion (CLTE) between the GMB/epoxy and the copper wire. Both the strain in the encapsulated lead wire and the movement of the lead wire within the solder joint were to be monitored during encapsulation and thermal cycling.

PRIOR WORK

Solder joint thermal fatigue, creep, and stress relaxation have been investigated at Bendix Kansas City, SLA, SLL, and elsewhere.¹⁻⁵ In general, solder joint studies have been limited to visual appraisals of the joint conditions because of the lack of techniques for instrumentation. Recent work at Bendix was successful in using newly developed techniques by which strain gages could be directly attached to a component lead wire.⁶

ACTIVITY

Sample Design

To minimize unusual stress effects caused by an asymmetrical component and to simplify data analysis, an idealized simulated component was decided on. The thumbtack design, successfully used by Munford,² was chosen because it was axisymmetrical and relatively simple to construct.

OFHC copper wire, 0.76 mm in diameter was chosen as the "component" lead wire. The diameter had to be increased to 0.81 mm, however, to assure reliable bonding of the strain gage.

Stainless steel (Type 302) washers were selected for the thumbtack heads. The dimensions of the washers were 6.35 mm outside diameter, 0.89 mm inside diameter, and 1.27 mm thick.

The printed wiring board (PWB) for this project was designed to provide dimensions which were typical of boards currently in production. The laminate selected was type GH, 0.76 mm thick, with 1-ounce copper cladding (0.03 mm thick). A plated-through

hole diameter of 1.27 mm and a pad diameter of 3.18 mm were selected.

To maintain the idealized model situation, each solder joint was to be individually encapsulated within a cylinder of the potting material, glass microballoon-filled epoxy (GMB/epoxy). This would assure an axisymmetrical condition. The diameter of the cylinder was to be 19.1 mm, and the depth of the cylinder was set at 38.1 mm. These dimensions were selected to create a semi-infinite distance-to-wall condition, thereby avoiding unusual edge effects.

Experimental Procedure

Three thumbtacks were constructed by percussive arc welding the washers to 2.5-cm lengths of the copper wire. Each wire was then preloaded to 111 N to assure linear stress/strain behavior. Three miniature strain gages were then bonded to each wire near the head at 120-degree (2.1 rad) intervals around the wire.

Each thumbtack transducer was individually load calibrated at ambient conditions and then soldered into the PWB using 63Sn-37Pb solder. (Although a component offset of 2.54 mm was planned, this had to be increased to 12.7 mm to prevent burning the strain gages during soldering). Figure 1 illustrates the assembled sample configuration and dimensions. A horse-shoe shaped deflectometer was attached to the side of the PWB opposite the thumbtack head, deflection calibrated, and soldered to the copper lead wire. Thermocouples were then attached adjacent to each lead wire and deflectometer. Figures 2 through 4 show an instrumented thumbtack, deflectometer, and final test PWB configuration.

Prior to encapsulation, the PWB was thermal cycled from -54°C to 74°C while monitoring the strain gages, deflectometers, and thermocouples. These measurements were retained for subsequent thermal expansion corrections. After this was complete, the thumbtacks were encapsulated with GMB/epoxy using a split mold technique. After curing, the mold was removed, and thermal cycling began.

When the data from the three thumbtacks were reduced, it was found that, during any given thermal cycle, the deflectometers indicated movement of the leads in directions opposite the loading. After extensive re-evaluation of the model, a second set of the three joints was constructed with several changes. First, the deflectometers were bonded to the PWB only at the tip next to the solder joint (the first set were bonded along the entire length of the deflectometer leg). This change, it was felt, would minimize the effects of board warpage on the deflectometer readings. The second alteration was to incorporate lead wire coating with silicone rubber and PWB coating with syntactic polysulfone foam in various combinations. One thumbtack had only the wire coating,

Figure 1. Axisymmetric Model of Solder Joint/Encapsulation System

Figure 2. Simulated Component With Strain Gages and Thermocouple Attached

the second had only the PWB coating, and the third had both. The purpose of the PWB coating was to decouple the encapsulant from the board surface to assist in reducing board warpage during thermal cycling by essentially allowing the PWB and encapsulant to expand and contract independently along the plane of the board. Wire coating was applied to two joints to simulate lead wire sleeving. This coating would prevent contact between the copper wire and encapsulant, thereby providing a "tunnel" through the encapsulant, allowing some relative movement between the wire and encapsulant. (The use of lead sleeving has been shown to be significant in reducing thermal fatigue.¹⁻⁴) The second set was calibrated, encapsulated in the same manner as the first, cured at 79°C for 24 hours, and thermal cycled. Because of the experimental problems confronted with the first sample set, only the thermal cycle results from set 2 will be presented.

Figure 3. Deflectometer Attached to Wire on Side of Board Opposite Thumbtack Head

Data Acquisition and Reduction

The various signals being monitored were input to a 24-channel signal conditioner. The channels were scanned by a multiplexer and the signals input to an amplifier. The amplified signal was converted to digital information through a digital voltmeter and then to strain by a minicomputer. The final data were output on paper tape for further reduction and calibration corrections by computer.

Data Analysis Reference Frame

To discuss the measured lead wire strain and deflection, a sign convention is needed. Strain in the encapsulated portion of the wire is compressive if negative and tensile if positive. Likewise, a negative deflection is one which results from a compressive loading on the wire. This convention is graphically depicted in Figure 5.

Encapsulation Data Analysis

The first group of three solder joints was encapsulated and cured at 68°C, and the second group was encapsulated and cured at 79°C.

STRAIN GAGE SIDE

DEFLECTOMETER SIDE

Figure 4. Test Board Prior to Encapsulation

Figure 5. Sign Convention for Strain and Deflection Measurements

The postcure cooling to room temperature produced a compressive strain in the encapsulated portion of the copper lead wire in both groups. The magnitudes of the strain and deflection are, however, greater for the second group (Table 1), because of the greater temperature change experienced by the second group in reaching room temperature. These results correlate well with previous work, which found that increased cure temperatures produced higher rates of solder joint failure.²

Thermal Cycle Data Analysis

The thermal cycle used in this study is shown in Figure 6. Measured strain in the copper wire is shown plotted versus temperature for thermal cycles one, two and 10 in Figures 7 through 9 for the three solder joints. Beginning at Point A (room temperature) on each graph, all three wires were under a compressive strain. This compression is caused by the higher rate of shrinkage of the GMB/epoxy than that of the copper wire during cooling from the cure temperature. As the first thermal cycle begins, the temperature decreases and produces a corresponding compression in the wire. During the subsequent heating phase of the cycle, the wire strain becomes less compressive. The observed strain is generally proportional to the temperature up to about 57°C. It does not, however, follow the same path as the cooling portion of the curve. Above 57°C, little change in strain is seen, even though the temperature continues to rise. This phenomenon is thought to be caused by additional curing of the GMB/epoxy. Apparently, the shrinkage of the encapsulant (which would produce compressive strain in the wire) was sufficient at this time to match its thermal expansion. At no time does the wire strain reach zero.

As the temperature returns to room temperature at the end of the first cycle, the wire strain again becomes more compressive. In each case, the compressive strain is greater than that prior to the thermal cycle.

A similar pattern is observed for the second thermal cycle. Some additional curing is seen at the elevated temperature portion of the cycle, resulting in even greater compressive strain. The magnitude of the shift in strain is, however, much less than that observed during the first cycle.

The final curve in each graph, showing the effects of the tenth thermal cycle, is below the first two curves. This indicates that the strain shift has been occurring throughout the 10 cycles. The magnitude of the shift per cycle decreased rapidly with each succeeding cycle, as evidenced by the fact that more than half the strain shift at room temperature after 10 cycles occurred within the first two cycles. In fact, very little shift occurred during the tenth cycle.

Table 1. Effect of Encapsulation Cure Temperature on Wire Strain

Sample	Cure Temperature (°C)	Strain (m/m)
Set 1	68	-0.0009
Set 2		
Joint 1	79	-0.0014
Joint 2	79	-0.0012
Joint 3	79	-0.0013

The result of the thermally-induced strain on wire movement within the solder joint is shown in Figures 10 through 12 for the three solder joints. Again, each graph contains the data for thermal cycles one, two, and 10.

Beginning at Point A, the wire is observed to have a negative deflection after postcure cooling. As the temperature drops during the beginning of the first thermal cycle, the wire continues to move downward. This is a result of the compressive stress being applied along the wire within the encapsulant.

On further cooling, the negative deflection continues, but at an increased rate as the temperature drops. A maximum downward deflection of 60 to 70 μm is measured at the low temperature extreme. Upon heating, the deflection-temperature curve follows the same pattern as during cooling, with the slope of the curve decreasing as temperature increases. It does not, however, follow the same path.

The same pattern is seen for the second and tenth thermal cycles. However, these charts show that the thermal cycling has resulted in an overall positive shift in deflection.

In reviewing the lead wire strain and deflection data, there are apparent inconsistencies. As was noted, the strain in the encapsulated portion of the wire is seen to become more compressive as thermal cycling proceeds. This would, it seems result in successively greater negative deflection with thermal cycling. The opposite is observed, however. This means that as the head of the thumbtack moves downward, from cycle to cycle, the wire exiting the opposite side of the board is moving upward. This upward movement is observed commonly in thermal-cycled printed

Figure 6. Thermal Cycle Used for Study

wiring assemblies. The strain and deflection are, however, in phase during any given cycle. This discrepancy is explained by the fact that the strain in the encapsulated portion of the wire is not a measure of the actual force acting along the wire. If, for example, the wire has undergone plastic compressive deformation during cooling, a negative strain would be indicated by the strain gage until sufficient tensile stress was applied to compensate for the initial compressive set. Thus, a compressive strain could exist although the wire is actually under a tensile stress.

This is most likely the case in this instance. If the maximum compressive strain (which occurred at -54°C) during the first cycle is converted to load, values slightly greater than the original 111 N preload are obtained, and the copper wire would yield. The additional curing of the GMB/epoxy at the high temperature phase of the thermal cycle continues this process, because

Figure 7. Strain in Copper Wire Versus Temperature for Thermal Cycles 1, 2, and 10: PWB Coating Only

Figure 8. Strain in Copper Wire Versus Temperature for Thermal Cycles 1, 2, and 10: PWB and Wire Coatings

Figure 9. Strain in Copper Wire Versus Temperature for Thermal Cycles 1, 2, and 10: Wire Coating Only

Figure 10. Wire Deflection Versus Temperature for Thermal Cycles 1, 2, and 10:
PWB Coating Only

Figure 11. Wire Deflection Versus Temperature for Thermal Cycles 1, 2, and 10: PWB and Wire Coatings

Figure 12. Wire Deflection Versus Temperature for Thermal Cycles 1, 2, and 10:
 Wire Coating Only

additional compressive loading is applied on the wire. This cyclic change in strain (length) is called thermal ratcheting.

Another discrepancy in the data is the shape of the deflection-temperature curves. If the continuous change in slope was caused by yielding of the solder, a significant hysteresis effect should be seen during the heating phase of the thermal cycle. This effect is not present, however. The possibility of a significant temperature dependence of the coefficient of thermal expansion and elastic modulus for GMB/epoxy was dismissed, based on previous work. The only explanation for the unusual shape of these curves is that, during the thermal cycling, some PWB warpage occurred. Because of the difference in CLTE between GMB/epoxy and the PWB in the lateral direction (along the plane of the board), a board warpage could occur during thermal cycling. This warping would give the appearance of more deflection at lower temperatures and less deflection at higher temperatures than actually was present.

Neither the strain nor deflection curves followed identical paths on cooling and heating during the initial cycles. This indicates that thermodynamic work is being done on the system. In the case of the strain-temperature curves, the energy is being input to the copper wire to produce cyclic yielding. The work hardening of the wire results in successively less yielding. By the time the tenth cycle is reached, the wire has been work hardened such that little yielding, and therefore work, is done. At this point the strain-temperature curve follows nearly identical paths during cooling and heating.

The deflection-temperature curves indicate that work is being input to the solder. Unlike the copper, however, solder does not work harden. The temperatures used in thermal cycling are sufficiently high, relative to the solder melting temperature, to allow interrelated, thermally-activated mechanisms, such as recovery, recrystallization, grain growth, diffusion, and stress relaxation, to occur. The mechanical strain energy generated by the thermal cycling is used to initiate these processes in the solder. Thus, the curves for the tenth thermal cycle show no tendency to follow the same paths on cooling and heating.

The effect of the silicone coating placed on two of the three lead wires can be seen in the strain and deflection curves. Comparison of Figures 7 through 9 show that the compressive strain shift per cycle is greater for the coated wires. This shifting indicates that the coated wires are being subjected to greater thermal stresses. The effect of this stress on the solder joint can be observed by comparing the deflection-temperature graphs (Figures 10 through 12). Each curve, with the exception of the cycle 1 curve for the uncoated wire, contains a crossover point.

Once the temperature climbs above the crossover point during heating, the wire deflection indicates an upward pull, caused by the tensile forces in the wire. These forces are the result of the thermal ratcheting discussed previously. Above this crossover point, upward movement of the wire occurs because of plastic flow of the solder. The crosspoint on each of the three graphs occurs at roughly 10°C for the coated wires and at 30°C for the bare wire. In addition, the area, and therefore the thermodynamic work, contained by the curve above the crosspoint is much greater for the coated wires. These findings indicate that the coated wires are allowing more plastic deformation of the solder over an increased temperature range than is the bare wire.

Past studies have determined that the use of sleeving is highly beneficial in reducing thermal fatigue of solder joints. The results obtained in this study, however, indicate the coated wires offered less protection than the bare wire. This experimental finding does not contradict present views on sleeving, but does modify them for the specific model used in this evaluation. For the axisymmetric condition, no shear forces act along the surface of the board which would apply a bending stress on the lead. The only thermally-induced stress is acting along the length of the copper wire.

When shear forces are present in actual PWB electronic assemblies, the sleeving allows the movement of the component bodies to be absorbed gradually by flexing of their component leads with the tunnel created by the sleeving. If the sleeving were not present, the leads would be held securely by the encapsulant, and thermal shear stresses would be highly localized at the solder fillet.

In the axisymmetric case, sleeving is unnecessary to reduce shear force. Sleeving does, however, decouple the wire from the encapsulant. This effect is detrimental because, in this case, adhesion between the lead and encapsulant acts to reduce the magnitude of force transmitted to the joint through the lead. Sleeving, or coating, allows unrestricted axial movement of the wire and thus promotes rather than reduces thermal fatigue of encapsulated axisymmetric solder joints.

ACCOMPLISHMENTS

An axisymmetric solder joint-encapsulant system was instrumented to determine the behavior of lead wires and solder joints during normal production encapsulation and specified product thermal cycling. Although some experimental problems arose which prevented complete evaluation of the system, better insight has been gained into the mechanism of solder joint thermal fatigue.

Thermal ratcheting in the component lead wire was observed which, in effect, shortens the length of the encapsulated portion of the wire, thereby maintaining a stress in the solder fillet. This applied stress, combined with the elevated temperature, produces a hot working situation in which the solder is continually undergoing plastic deformation and stress relaxation.

Use of a wire coating (simulated sleeving) on the axisymmetric model was found to be detrimental in regard to thermal fatigue. The silicone coating decouples the wire from the encapsulant and allows thermally-induced forces to be axially transmitted to the joint unrestricted.

FUTURE WORK

Additional study of mechanism of solder joint thermal fatigue should be pursued. This information can be used in assembly design and material selection to minimize the occurrence of solder joint thermal fatigue.

Two specific recommendations are made. First, the model should be redesigned to avoid PWB warpage. Second, the effect of shear stress (asymmetric) and slow cycle rates (one cycle/day) should be evaluated. The effectiveness of sleeving at various levels of shear stress also should be evaluated. These modifications would provide mechanical behavior information under conditions more nearly approaching actual electronic assemblies in stockpile.

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