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STRESS RELIEF TECHNIQUES FOR REDUCING
THERMAL FATIGUE IN SOLDER JOINTS

MASTER

Topical Report

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**Kansas City
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STRESS RELIEF TECHNIQUES FOR REDUCING THERMAL FATIGUE IN SOLDER JOINTS

BDX-613-1655 (Rev.), UNCLASSIFIED Topical Report, Published February 1978.

Prepared by D. M. Jarboe, D/814.

The most effective method for relieving stress on foam encapsulated solder joints caused by thermal cycling is using silicone sleeving over component lead wires. The use of 128 kg/m³ (8 lbs/ft³) polyurethane foam rather than 320 kg/m³ (20 lbs/ft³) foam was advantageous only when the component leads were not sleeved. Special lead configurations were no better than a standard 90 degree bend. None of the other methods used or devices tested was better than silicone sleeving.

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SUMMARY

Thermally cycling electronic circuit boards can cause solder joints to fail. A solution is to provide stress relief at the joint to reduce the effect of this externally applied stress. A number of previously accepted stress relief methods were tested; these methods were the use of silicone sleeving over component leads, potting with two polyurethane foam densities and evaluating three component-lead configurations.

The results of this study were somewhat surprising. Only the use of silicone sleeving over component lead wires was found to be an effective solder joint stress relief technique in all cases. A secondary role was played by polyurethane foam density. Lowering the foam density does reduce solder joint failure rates, but only when the component leads are not sleeved. The incorporation of special lead configurations appears to be of no value. In fact, stress relief loops may result in higher failure rates when sleeving is not used.

Aside from the specific findings of this study, there is a subtle implication that universal solder joint stress relief techniques do not exist. This may be the reason for differences between the results of this study and others. As an example, this study dealt only with foam encapsulants. Since the foam does not penetrate the gap between the component lead and its sleeving, a very effective decoupling is afforded by the sleeving. In an epoxy encapsulated assembly where vacuum evacuation of the epoxy is performed, however, the effectiveness of sleeving in reducing solder joint damage would be reduced since the epoxy will be forced into the component lead-silicone sleeving gap. Results of this study suggest that the particular stress relief technique that provides the most protection against mechanical damage due to thermal expansion of an encapsulant may very well be dependent on which encapsulant is involved.

DISCUSSION

SCOPE AND PURPOSE

This project was undertaken to evaluate the effectiveness of various stress relief techniques in reducing thermal fatigue failures of solder joints in two electronic assemblies. The materials and components tested were confined to those being considered for these assemblies. The term stress relief is not used in the metallurgical sense in this report. It designates techniques for reducing externally applied stress on solder joints.

The evaluation was based on an empirical study in which specially designed printed wiring assemblies (PWAs) were thermal cycled. The results of this experiment were then used to compare solder joint failure rates and to recommend packaging techniques.

PRIOR WORK

The various types of thermally induced stresses on solder joints in electronic assemblies have been studied by several investigators.¹⁻⁸ Since the role of these stresses in solder joint cracking was identified, there has been a great deal of effort directed towards developing processing and packaging techniques which afford protection to the joints.⁹⁻¹³ It has become a preferred practice to form component leads into various configurations when they are to be used in high reliability encapsulated assemblies. The use of sleeving over component leads is also favored. In addition to these add-on features, the encapsulation material is selected on the basis of low coefficient of linear thermal expansion (CLTE) and bulk modulus when other encapsulant requirements permit.

These packaging design recommendations have been arrived at as a result of numerous studies of solder joint thermal fatigue. It would seem, therefore, only natural that they be incorporated into every electronic assembly. This is not the case, however, for two reasons. First, the use of special component lead configurations is not possible in some devices because of dimensional requirements which cannot tolerate the extra space taken. Second, the forming and sleeving of component leads require additional manpower, thereby increasing the costs of the assembly. It has, therefore, been a general practice to experimentally determine the advantages to be gained by employing stress relief measures and compare these to the additional costs and space limitations involved for separate assemblies.

ACTIVITY

Test Variables and PWB Identification

The test variables for this study consisted of three component-lead configurations, the use and non-use of silicone sleeving over component leads, and two polyurethane foam densities. Component leads were either bent at the conventional 90 degree angle (straight for the transistor), looped (bent through a 360 degree angle for the transistor and a 270 degree angle for the other components), or humped. Sleeving, where used, was a silicone elastomer. The polyurethane foam was formulated to produce a free rise density of either 128 kg/m³ (8 lbs/ft³) or 320 kg/m³ (20 lbs/ft³).

Twelve groups with four boards in each group were used to evaluate the test variables. An additional six boards were constructed as control boards. These six were not encapsulated. The variables for each group are shown (Table 1).

Test Printed Wiring Assembly Design and Construction

The printed wiring boards for this study were fabricated measuring 101.6 by 101.6 by 0.8128 mm (4 by 4 by 0.032 inch). These PWBs contained nine plated through holes to accommodate the components chosen for the study. Standard production techniques were used to construct the boards. Four components were chosen for this study: a small axial resistor (SA659-145), a large axial resistor (SA659-41), a cube-shaped capacitor (SA2055), and a transistor (SA2045). These components were soldered into the test PWBs by production personnel using Sn63 solder (63Sn-37Pb). Spacing of the components off the PWB surface was 0.76 mm (0.030 inch) for the axial resistors and 7.6 mm (0.300 inch) for the transistor. The capacitor was bonded to the PWB surface with Epon 934 epoxy adhesive (Shell Chemical Company). Paper phenolic tubes were then bonded to both sides of the PWB also with Epon 934. The tubes on the component side of the PWB provided a method for supporting the board inside the encapsulation mold. The tubes on the side opposite the components were centered over the solder joints. These tubes were to be sealed during encapsulation, thereby providing ports for viewing the solder joints (Figures 1 and 2). The test boards were then placed in molds and encapsulated with polyurethane foam. After curing at 71°C for 1 hour, the assembly was removed, and the viewing ports were opened (Figure 3). Additional urethane foam blocks were then made to cover the viewing ports during thermal cycling, thereby minimizing any unusual temperature gradients around the ports (Figure 4).

The first four encapsulated PWBs were warped inside the foam block. This was a result of unequal foaming pressures on the

Table 1. Variables of Stress Relief Study

Board Group	Lead Type	Free Rise Foam Density	
		kg/m ³	(lbs/ft ³)
A	90 Degree Sleeved	128	8
B	90 Degree Unsleeved	128	8
C	90 Degree Unsleeved	320	20
D	90 Degree Unsleeved	320	20
E	Looped Sleeved	128	8
F	Looped Unsleeved	128	8
G	Looped Sleeved	320	20
H	Looped Unsleeved	320	20
I	Humped Sleeved	128	8
J	Humped Unsleeved	128	8
K	Humped Sleeved	320	20
L	Humped Unsleeved	320	20

two sides of the board during the foaming of the polyurethane. To avoid this in the remaining boards, a 12.7 mm (0.500 inch) hole was drilled in the center of the PWB to relieve foaming pressures. This action eliminated the PWB warpage in the balance of the test boards.

Testing Procedure

The test printed wiring assemblies were thermal cycled from 71°C to -54°C. This was accomplished with a special two chamber temperature cabinet. The samples were placed in a chain driven cage which automatically moved them between the hot chamber and the cold chamber at preset time intervals. The dwell time at each temperature was experimentally determined by monitoring the PWA temperature with thermocouples imbedded in the encapsulated test boards. It was found that approximately 2 hours at each temperature extreme were required in order for the PWAs to reach thermal equilibrium. Based on these measurements, the decision was made to set the dwell time in the hot and cold chambers at 2.5 hours each. This would allow for some experimental variation without unduly lengthening thermal cycling times.

Figure 1. Top of PWB With Components

Figure 2. Bottom of PWB With Viewing Ports

Figure 3. PWB After Cure With Viewing Ports Open

Figure 4. PWB After Cure With Additional Cover

Visual examination of the solder joints was performed after 0 (after encapsulation), 5, 10, 25, 50, 100, 150, 200, and 500 cycles. All inspections were made using a stereo microscope capable of 70X magnification. The maximum magnification was used in order to locate and determine the extent of any solder joint cracking.

The solder joints were illuminated with a high intensity tungsten halogen fiber optic lamp. This was not adequate, however, for looking down into the viewing ports. The paper phenolic tubes absorbed enough light to make observation of the solder joints almost impossible. This problem was solved by using aluminum foil liners inside the viewing ports (Figure 3). The high reflectivity of the aluminum foil provided enough light to fully illuminate the solder joints.

During the course of the thermal cycling, a description of each joint was made during the visual observations. The extent and location of any thermally induced fatigue damage were noted on a form (Figure 5). For the purpose of this study, a solder joint failure was defined as a 360 degree crack in the surface of the fillet around a component lead. This failure criterion was chosen for two reasons. First, it was felt that a 360 degree crack would more nearly approximate the condition present when joint electrical resistance would be increasing. Second, the judgement of the extent of cracking was thought to be less subjective than the perception of the beginning of cracking.

Control Board Failures

It soon became apparent during thermal cycling that there was a major design flaw in the control boards. Solder joint failure rates on these boards were substantially higher than those of the test boards. Using laser holographic techniques, it was determined that the paper phenolic viewing ports rigidly bonded to the PWB surface were sources of additional stressing mechanisms around the solder joints. The difference in coefficient of linear thermal expansion between the PWB material (12 to $15 \times 10^{-6}/^{\circ}\text{C}$) and the rigid epoxy adhesive used to bond the phenolic tubes to the PWB (50 to $60 \times 10^{-6}/^{\circ}\text{C}$) was sufficient to cause localized deflection of the board in the vicinity of the solder joints during thermal cycling. This effect was greatly reduced on the encapsulated boards because of the additional support provided to the PWB from the polyurethane foam.

Additional control boards were constructed with the viewing ports bonded to the PWB with syntactic polysulfide. The pliable nature (lower elastic modulus) of this adhesive provided a decoupling effect between it and the PWB. In addition to this modification, small cans made of the paper phenolic were bonded over the components, also with polysulfide, and the boards encapsulated. This

STRESS RELIEF
TEST SAMPLE
BOARD

BOARD NUMBER: _____
DATE _____
NUMBER OF CYCLES _____
OBSERVER _____

Figure 5. Data Form

was done to provide thermal insulation to the control boards similar to that on the test boards. The cans prevented polyurethane foam from encapsulating the components.

Test Board Data Deletions

Analysis of the failure rate data of the encapsulated test boards (Table 1) early in this study indicated there were unusually high numbers of cracked joints in particular groups. Specifically, almost 100 percent of the transistor solder joints had failed. In addition, two of the test boards in both Groups C and D had a substantially higher failure rate than the other PWBs in the same groups.

It was decided that the transistor failures were caused by the large offset distance of that component from the PWB surface. Since this distance (7.62 mm or 0.300 inch) is not representative of the normal production offset (0.762 mm or 0.030 inch), the failure rate data for the transistor solder joints were eliminated from the overall data accumulation and analysis. This offset distance was necessary to incorporate the stress relief loops and humps.

The test boards in Groups C and D which exhibited the abnormally high failure rates were found to be those first boards which had appeared warped after encapsulation. X-ray radiography was used to determine the extent of warpage in these boards. The X-ray radiographs in Figure 6 compare the warpage in one of these boards in Group C with a test board with no warpage from Group G. Because of the deleterious effect this PWB warpage was having on the solder joints, the high failure rates boards were eliminated from further examination and the data analysis.

Solder Joint Failure Rate Data and Analysis

The following data are presented in test variable groups only, not on a per board group basis. Comparison of the various stress relief techniques within a test variable group was done by tabulating the number of failed joints for each stress relief measure, irregardless of stress relief measures in the other test variable groups. For example, when comparing the two foam encapsulant densities, no distinction was made between boards with looped, humped, or 90 degree component leads. Similarly, the use or non-use of silicone sleeving was not differentiated. The data were split into only two groups, 128 and 320 kg/m³ foam. This is a statistically valid approach since all other variables are present to an equal degree in the stress relief techniques being compared.

It should be noted that the data in this report should only be used for relative comparisons. The effect of the rigid epoxy adhesive on these failure rates is not known. Although there is

PWB WARP AFTER ENCAPSULATION

NO WARP AFTER ENCAPSULATION

Figure 6. Radiographs of PWBs Illustrating Warped Group C Board and Unwarped Group G Board

sufficient evidence that the deleterious effect of this adhesive was reduced by mechanical support of the PWB by the polyurethane foam, it was no doubt present and accelerated overall failure rates. Since, however, this factor was present on all the test boards, there should be no bias of the data to favor one stress relief technique over another.

Lead Configuration

The percentage of solder joints for components having looped, humped, and 90 degree bend leads is shown as a function of the number of thermal cycles in Figure 7. Less than 10 percent difference is seen between any of these lead configurations, even after 500 thermal cycles. If these data are replotted to show the effect of lead configuration on failure rates only when sleeving is used, the data points become more tightly grouped (Figure 8). The opposite effect is seen, however, when the lead configuration data are compared for the case of no sleeving (Figure 9). It is apparent from these three graphs that the role played by stress relief loops and humps has little impact on solder joint thermal fatigue life, particularly when there is sleeving over the component leads. In fact, the looped leads appear to result in a higher rate of solder joint cracking.

These results do not agree with the general theory that additional bends in the component lead afford protection to the solder joints. They are not, however, unexplainable. A rationale for these results is that the looped leads offer more surface area for the encapsulant to act upon as it expands and contracts during temperature changes.

Sleeving

Sleeving was found to be very effective in reducing solder joint fatigue. Failure rates for solder joints with silicone sleeving over the component lead wires were consistently below those with bare leads by a substantial amount throughout the course of this study (Figure 10).

Unlike the test results for lead configurations, this portion of the study agrees well with current beliefs of solder joint protection. Silicone sleeving fits loosely over component leads by necessity in order to facilitate slipping it onto the lead. During encapsulation, foam will not penetrate the gap between the lead and the sleeving wall and a tunnel is formed in which the lead wire has some freedom of movement independent of the encapsulant. This decoupling effect allows the lead wire itself to absorb some of the thermally induced strain rather than transmitting it directly to the solder joint.

Figure 7. Solder Joint Failure Following Thermal Cycles With Various Component Lead Configurations

Figure 8. Solder Joint Failure Following Thermal Cycles With Various Sleeved Component Lead Configurations

Figure 9. Solder Joint Failure Following Thermal Cycles With Various Bare Component Lead Configurations

Figure 10. Solder Joint Failure Following Thermal Cycles With and Without Sleeving

Foam Density

The effect of the two different foam densities is shown in Figure 11. Once again the difference in the two groups of data is less than 10 percent. This is also true when the foam density effects are compared for only those PWBs with sleeving (Figure 12). When the foam density data are plotted for only those boards with bare component leads, however, there is a definite difference, as shown in Figure 13. In this case the 128 kg/m³ foam produced significantly fewer failed solder joints than the 320 kg/m³ foam.

These results indicate that the lowering of the foam bulk modulus by reducing its density can be an effective solder joint stress relief technique if sleeving is not used. There is no advantage, however, to lowering foam density if silicone sleeving is placed over component lead wires.

Control Boards

The first group of control boards which had experienced problems early in the study continued to exhibit high failure rates. Failure rate data for these boards are presented in the Appendix. Solder joints in the second generation control boards, however, were only slightly affected. Only 11 percent of these joints failed, most likely due to the difference in CLTE between the copper lead wires and the epoxy-glass laminate PWB material.

These results are quite informative in themselves. It is evident that rigid adhesive applied to a PWB surface can introduce an additional source of board warpage and solder joint stress. It is not possible to suggest any specific design guidelines on the use of rigid adhesives at this time. Rather it is suggested that a pliable adhesive be used where possible. If the rigid material must be used, it should be applied as sparingly as possible.

ACCOMPLISHMENTS

It was determined that the most effective solder joint stress relief technique for the polyurethane foam encapsulated assemblies is the use of silicone sleeving over the component lead wires. The use of 128 kg/m³ rather than 320 kg/m³ foam is, from a solder joint fatigue viewpoint, advantageous only when there will be no sleeving over the component leads. It was also found that the use of special lead configurations offer no additional protection to solder joints when compared to the standard 90 percent bend.

These unexpected results indicate that there may not be universal solder joint stress relief techniques. Methods which have been found effective in other studies involving different materials

Figure 11. Solder Joint Failure Following Thermal Cycles With Various Urethane Foam Densities

Figure 12. Solder Joint Failure Following Thermal Cycles With Various Urethane Foam Densities and Sleeving

Figure 13. Solder Joint Failure Following Thermal Cycles With Various Urethane Foam Densities and No Sleeving

were found to play a minor role in this investigation. It appears that the selection of stress relief techniques should be based on knowledge of individual device materials and processes rather than on generalized guidelines.

In addition to the specific test variables addressed in this study, it was found that the application of a rigid epoxy adhesive has the potential for increasing thermal stresses on solder joints. No specific recommendations on this subject can be made at this time however.

The use of cutting dikes to trim off unused component leads after soldering may also affect solder joint fatigue life. During the course of this study it was observed that in many cases the fatigue cracks in the fillet were originated either at, or very close to the dike marks left in the fillet. This may be one area of study that deserves attention for future high reliability electronic assemblies.

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Appendix

COMPARISONS OF JOINT FAILURES TO THERMAL CYCLES FOR INDIVIDUAL BOARD GROUPS

Figure A-1. Evaluation of Board Group A,
Sample Size: 32 Joints

Figure A-2. Evaluation of Board Group B,
Sample Size: 32 Joints

Figure A-3. Evaluation of Board Group C,
Sample Size: 16 Joints

Figure A-4. Evaluation of Board Group D,
Sample Size: 16 Joints

Figure A-5. Evaluation of Board Group E,
Sample Size: 32 Joints

Figure A-6. Evaluation of Board Group F,
Sample Size: 32 Joints

Figure A-7. Evaluation of Board Group G,
Sample Size: 32 Joints

Figure A-8. Evaluation of Board Group H,
Sample Size: 32 Joints

Figure A-9. Evaluation of Board Group I,
Sample Size: 32 Joints

Figure A-10. Evaluation of Board Group J,
Sample Size: 32 Joints

Figure A-11. Evaluation of Board Group K,
Sample Size: 32 Joints

Figure A-12. Evaluation of Board Group L,
Sample Size: 32 Joints

Figure A-13. Evaluation of Board Group M (Control),
Sample Size: 6 Joints

Figure A-14. Evaluation of Board Group N (Control),
Sample Size: 6 Joints

Figure A-15. Evaluation of Board Group O (Control),
Sample Size: 6 Joints

Figure A-16. Evaluation of Board Group P (Control),
Sample Size: 6 Joints

Figure A-17. Evaluation of Board Group R (Control),
Sample Size: 6 Joints

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