

An analysis of solder cracking mechanisms

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High-density mounting of circuit parts on electronic equipment makes the reliability of solder joints more crucial than ever. To grasp trends and improve reliability in solder joints, studies must be undertaken on printed circuit boards, mounted parts, and mounting technology. Solder cracking is directly involved in equipment failure, and controlling its occurrence has become a major problem.

This report looks at one cause of solder cracking—the roughening of the solder grain boundary field—and verifies the relation of the problem to both thermal and mechanical stress. The results indicate that the solder grain boundary experiences roughening from both types of stress, although thermal stress exerts the greater influence. Degradation of solder strength due to roughening was also confirmed.

1. Introduction

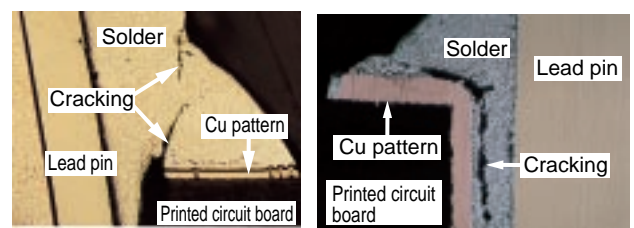
Solder is used to join many of the circuit parts in modern equipment, and maintaining the reliability of solder joints is crucial to maintaining the reliability of electronic equipment. However, use of miniaturized electronic equipment in recent years has brought the equipment into contact with a wide variety of environmental conditions leading to a wide range of external stress, which can lead to solder cracking.

Because of this, this report will detail the following studies on the relationship between stress and the roughening of the grain boundary that leads to solder cracking:

- (1) An investigation of the solder load and stretching caused when mechanical stress is applied to solder joints,
- (2) An investigation of the changes caused in the solder grain boundary when load fatigue is applied to solder joints, and
- (3) An investigation of the changes in the solder grain boundary caused by thermal stress, as well as how changes in the grain boundary affected the strength of solder.

2. Mechanisms of solder cracking

Solder cracking can occur either internally within the solder or in the area where the solder joins to another surface. Both types of cracking have been confirmed to commonly occur in the field, and are a major cause of electronic equipment failure. (Photo 1, Fig. 1)



(a) Solder internal cracking in electronic equipment left outside for 5 years (IC lead section) (b) Solder joint surface cracking at connector lead pin

Photo 1 Failures occurring in the field

Internal solder cracking is caused by roughening of the α phase (Pb rich) of the solder structure. This occurs when the α phase roughening is promoted by thermal energy of temperature cycles. When stress is applied, cracks are thought to grow at the grain boundary surface within the grain boundary of the α phase and the β phase (Sn rich).^{2), 3), 5), 6), 7)} (Fig.1 section (1), Fig. 2)

Solder joint surface cracking occurs primarily in the vicinity of layer roughening at the solder joint surface of the intermetallic compound. (Fig. 1 section (2))

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When the metallic layer of the intermetallic compound grows and thickens due to high temperature, fine cracks appear in the solder joint layer, making it less resistant to shock, and giving the solder a tendency to peel.⁴⁾ However, it has also been reported that in actual use the intermetallic compound does not cause cracking.⁵⁾

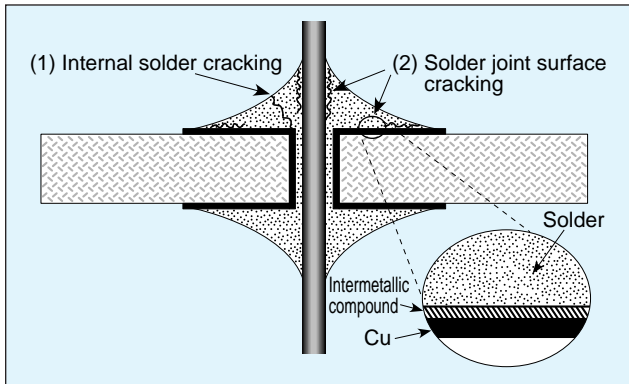


Fig. 1 Forms of solder cracking

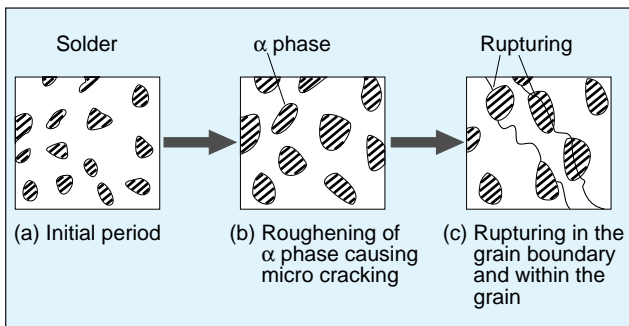


Fig. 2 Solder cracking mechanisms (solder internal cracking)

Reported countermeasures for solder cracking include such means as the following.

- (1) By adding Ag, In, and Sb to the solder, the additive elements (Ag, In, and Sb) diffuse throughout the grain boundary of the Sn-rich phase and the Pb-rich phase, and the resulting intermetallic compounds (In-Sb and Ag-In) control the diffusion of Sn.
- (2) A metal such as Ni is used as a non soldering joint material with a slow rate of growth between the Sn and the intermetallic compound, suppressing roughening of the Pb-rich phase in the vicinity of the solder joint field surface, and thus improving fatigue life.^{6), 8)}

3. Results and discussion

Testing was performed for the following:

- (1) Roughening of the grain boundary due to mechanical stress, and
- (2) Roughening of the grain boundary due to thermal stress.

The two types of stress were compared in regard to their influence on the grain boundary.

3-1 Specimen

The specimen was a flexible copper wire passed through the through hole of a copper plated glass epoxy printed circuit board and soldered with solder dip (63 Sn wt%) for 10 seconds at 260°C. Fig. 3 shows the arrangement of the specimen.

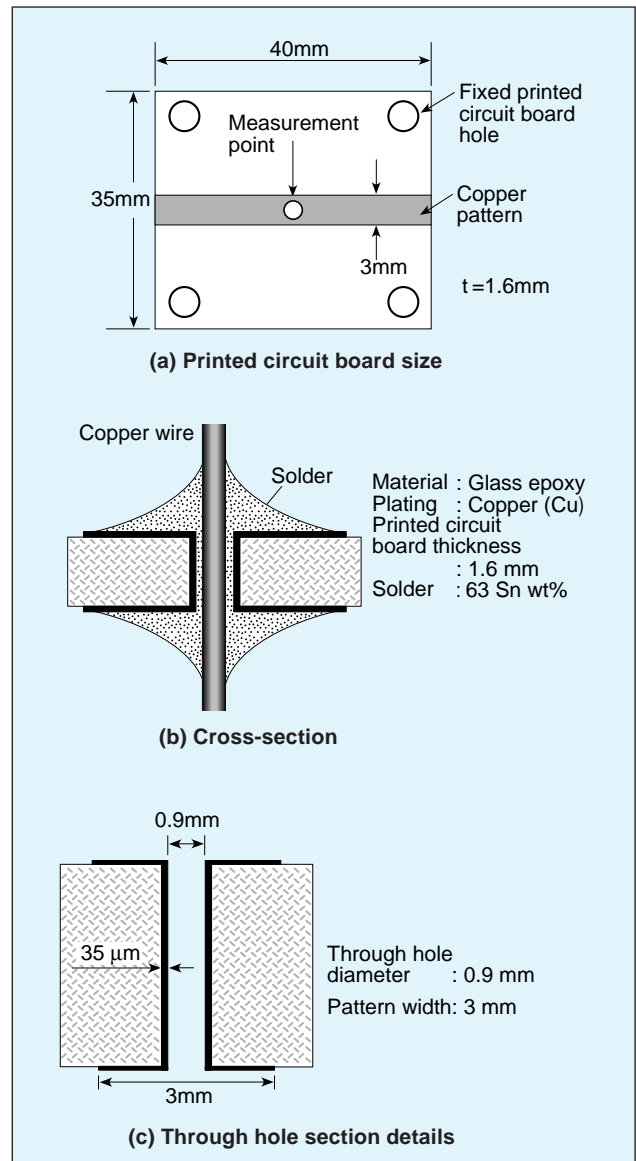


Fig. 3 Specimen for tensile test

3-2 Testing for roughening of the grain boundary due to mechanical stress

(1) Experiment 1: Tensile testing (the relationship between load and solder elongation)

To determine the testing conditions under which mechanical stress is applied to the solder, tensile testing was performed on copper wire of various diameters. Table 1 shows the test conditions, and Fig. 4 shows the test equipment. The method consisted of using a load cell to measure the load applied to the specimen, and then analyzing the load characteristics.

Table 1 Tensile testing conditions

Test conditions	Copper wire diameter (mm)
Stretching speed = 0.3 mm/min	ϕ 0.45, ϕ 0.55 ϕ 0.65, ϕ 0.80

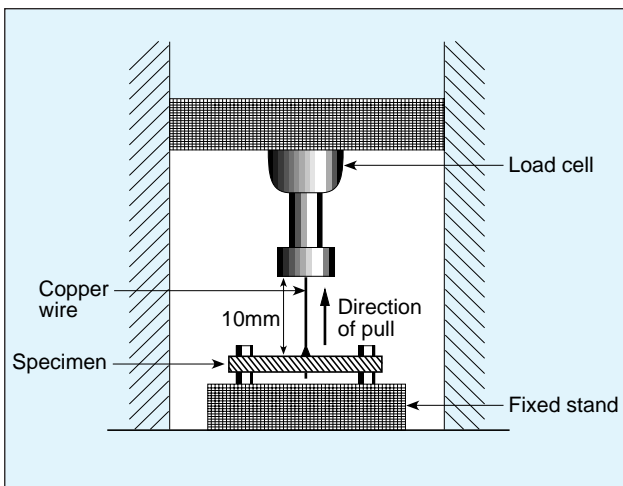


Fig. 4 Tensile testing equipment

Fig. 5 shows the test results. The larger the diameter of the copper wire, the greater the load endurance until the copper wire finally breaks. Breaking occurred at around the middle of the length of all the copper wires. In the initial stage, all copper wires, regardless of the diameter, showed a consistent trend. This can be thought of as the elongation of the solder, copper wire, and printed circuit board.

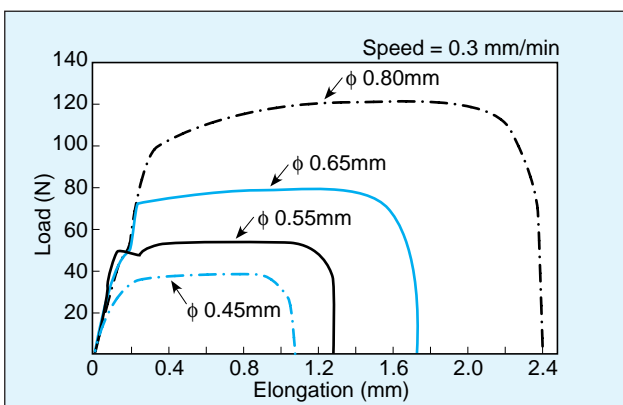


Fig. 5 Load-elongation diagram for copper wire diameters

Fig.6 shows the load-elongation diagram for the initial stage of the ϕ 0.55 mm copper wire. The elongation amount up to about 0.2 mm in section (1) shows a consistent trend, then in section (2) it shows a declining trend, and finally in section (3) it shows an rising trend once more.

In section (1), the external force is within the flexibility limit, so the flexibility prevents distortion. If the external force is removed, the object returns to its original shape. However, when the external force exceeds the flexibility limit in section (2), the relationship between stress and distortion suddenly changes, slipping occurs, and large, marked stretching occurs. As external force is applied again in section (3), tensile resistance can be assumed to increase gradually until breaking occurs.¹⁾

These results indicate that when applying stress to solder, the stress must remain within the range of region (1) when applying load to the solder joints.

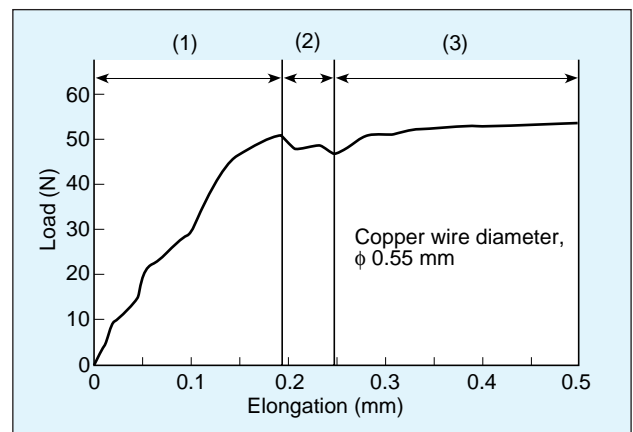


Fig. 6 Load-elongation diagram (Initial stage)

(2) Experiment 2: Load cycle testing

To investigate the relationship between cracking and cyclic stress, we performed load fatigue testing.

For test conditions, the results of Experiment 1 were used to determine the cyclic load. In addition, the test speed was set at 3 mm/min as an appropriate value for applying stress to the soldered section.

These values were determined according to the following preliminary tests.

- (1) At test speeds exceeding 10 mm/min, the sudden change caused stress to the specimen that exceeded the test condition load (29.42N), resulting in the copper wire breaking.
- (2) Using the same speed as the tensile test (0.3 mm/min) required excessive testing time.

Therefore, preliminary testing was performed in the range from 0.3 mm/min to 10 mm/min, and the appropriate speed was set at 3 mm/min.

Testing was done at 0, 10,000, and 100,000 cycles, and cross-sections were observed after each test, and the condition of the solder grain boundary was compared.

Table 2 Load fatigue test conditions

Load	0 \leftrightarrow 29.42 N (\approx 3kgf)
Number of cycles	0, 10,000, and 100,000 cycles
Temperature and humidity conditions	Room temperature and humidity

Photo 2 shows cross-sectional surfaces after load cycle testing.

In the load fatigue testing, cracking was confirmed at around 40,000 cycles. Furthermore, cross-sectional observation confirmed roughening of solder sections where greater stress was applied.

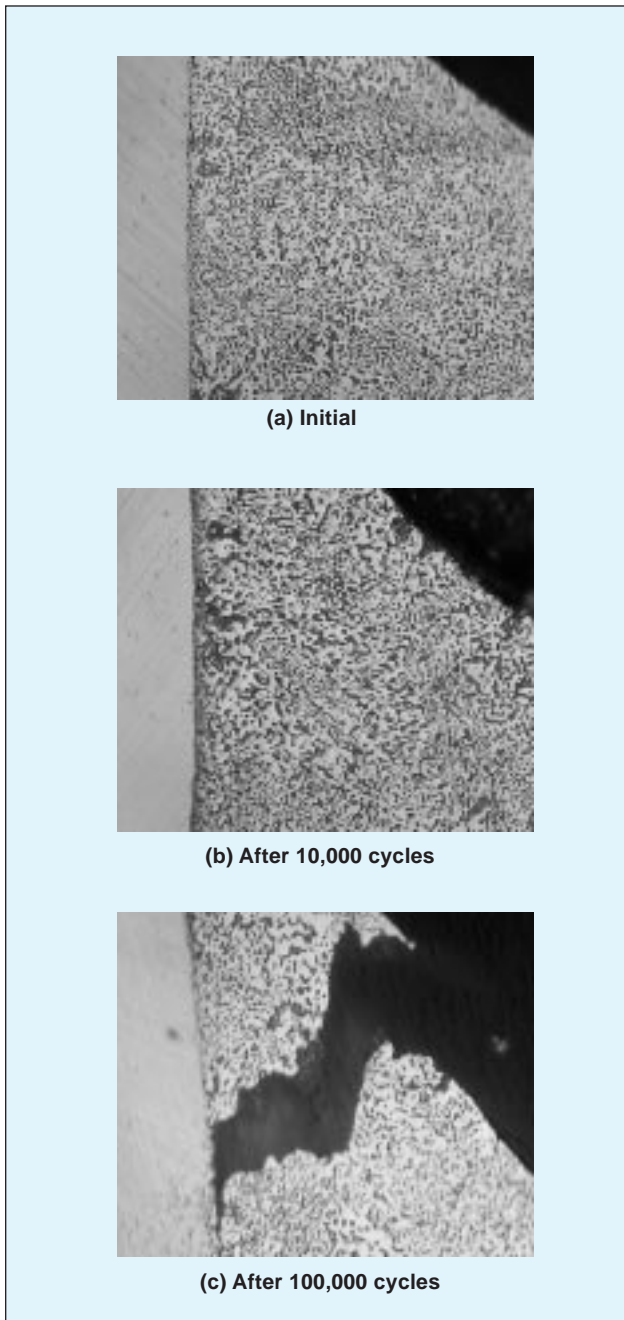


Photo 2 Cross-sectional observation after load fatigue testing (200×)

3-3 Testing for roughening of the grain boundary due to thermal stress

Solder is an alloy with a low melting point, and so even at room temperature roughening can easily occur in the solder grain boundary.

However, higher temperatures accelerate the roughening of the solder grain boundary, and the speed of growth of the intermetallic compound also increases. As the grain boundary becomes larger, solder becomes less resistant to thermal stress, and since the intermetallic compound is mechanically fragile, it has low resistance to stress in the direction of the interface.

Because of this, we tested the relationship between thermal stress and the roughening of the grain boundary.

Experiment 3:

Tensile testing after exposure to high temperature

To accelerate thermal stress, specimens were exposed to a 150°C atmosphere for 100 hours and for 200 hours. Photo 3 shows the results of cross-sectional observation.

The results confirm that the longer the exposure to thermal stress, the greater the roughening of the grain boundary.²⁾

Mechanical stress caused roughening only in the sections to which stress was applied, but after exposure to high temperature, the entire grain boundary showed roughening.

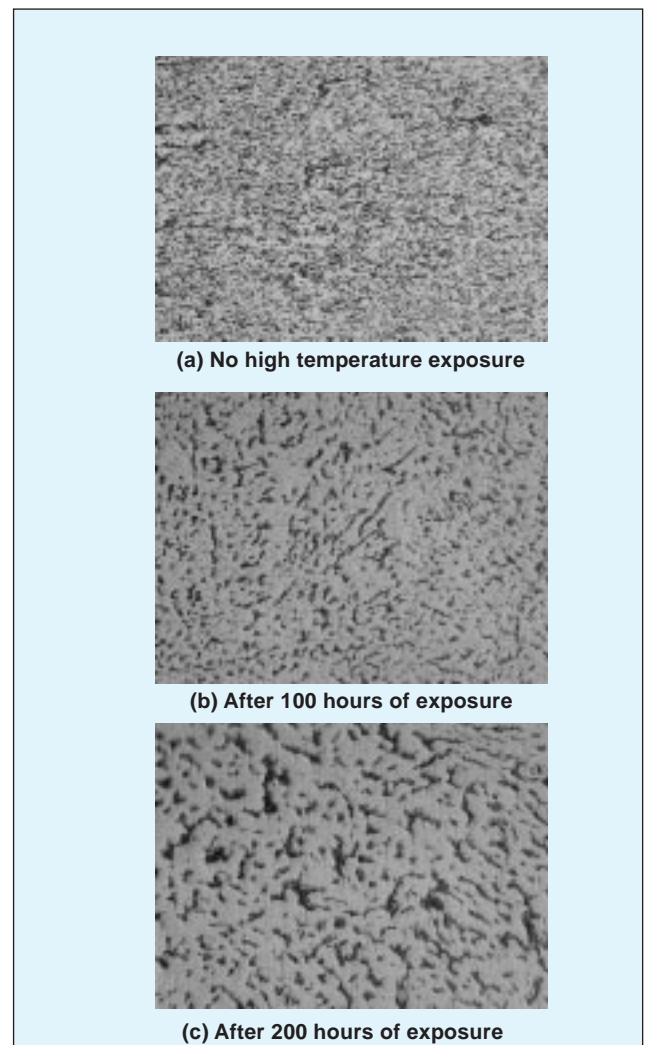


Photo 3 Cross-sectional observation after exposure to high temperature (200×)

To confirm the solder strength of specimens exposed for 100 hours and 200 hours, tensile testing was performed using the test conditions given in Table 1 and the test equipment shown in Fig. 4. Solder strength was measured and load change characteristics were analyzed.

Fig. 7 shows test results. The changes in solder load characteristics after high temperature exposure show that the longer the exposure to high temperature, the greater the stretching of the solder.

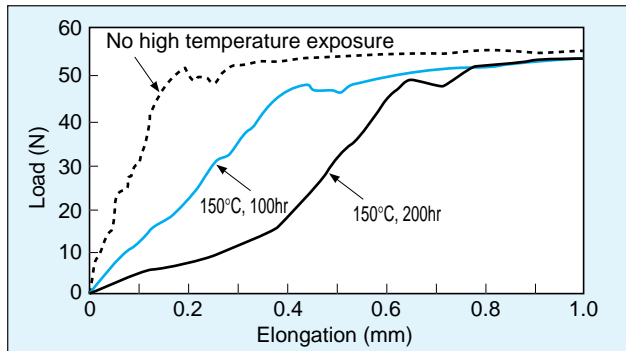


Fig. 7 Roughening of the solder grain boundary and changes in load characteristics

4. Conclusion

- (1) In these tensile tests using specimens, the characteristics of the load on the soldered section can be separated into three regions. These experiments show the necessity of testing within the region prior to the occurrence of solder slipping.
- (2) With mechanical stress, roughening of the solder grain boundary occurred only in the sections bearing the stress. However, with thermal stress, roughening occurred throughout the entire solder grain boundary. These results confirm that thermal stress has a greater influence on roughening of the solder grain boundary.
- (3) The tests show that roughening of the solder grain boundary causes greater stretching of the solder, and degrades mechanical characteristics.

Solder joints are a vital technology supporting electronic equipment. However, the occurrence of solder cracking causes failure of electronic equipment. From the standpoint of product safety as well, as reflected in the recent enactment of the product liability law, maintaining reliability is crucial.

The authors observed the relationship between the cracking in solder joints and the changes in the grain boundary, and so performed these experiments. As a result, changes were confirmed in both thermal and mechanical stress, and were also confirmed to be a factor in degradation of the reliability of solder joints.

These types of external stress are certain to occur in the environments in which electronic equipment is used, and if conditions such as shock, vibration, and temperature cycles were added, they would cause complex interactions that would accelerate degradation. It is vital to thoroughly comprehend the types of stress actually occurring in the usage environments and to build reliability into the equipment at the design stage.

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