Following the enactment of international standards, unprecedented attention has become focused on the ramp rate of Temperature Cycle Tests. We have performed comparative testing to determine the life and failure mode of solder joints, investigating solder joints used on BGA and QFP packages.

1 Introduction

Notable trends in electronics today include progress in high-density mounting technology, and the miniaturization of electronic parts that incorporate greatly advanced functionality. Recent years have seen a dramatic increase in the performance capabilities of information technology equipment, creating a corresponding increase in the amount of heat generated by such equipment. In addition, environmental stress is no longer seen as coming from the external environment, but rather from the internal environment of the equipment itself. This results in a greater demand for reliability against thermal fatigue within the equipment. Also, changes in mounting configurations have introduced more complex thermal fatigue mechanisms than have previously been seen. These changes necessitate the development of reliability evaluation methods with greater market reproducibility.

For these reasons, this research focuses on solder joints of mounted parts. Temperature Cycle Tests are run to evaluate thermal fatigue in solder joints. The major acceleration factors include cycling temperature range, soak time, and ramp rate. Among these factors, soak time has been the major subject of discussion within Japan, while ramp rate has as yet received little scrutiny. Reports have been published concerning the rate of bulk body distortion, but the rate of solder distortion in Temperature Cycle Tests is slower than the bulk body distortion rate. Also, due to the complexity of the configuration of the mounted parts, interest has in the effect of the ramp rate has been generated. Reports have been published concerning the ramp rate used in simulations using the finite element method, and these have been compared with actual test results, but few examples exist of actual analyses of failure modes. On the other hand, the internationally accepted ramp rate of 10 to 15°C per minute is required by test standard IEC60749-25 Temperature Cycling (JESD22-A104-B), established for evaluating the reliability of semiconductor parts and assembly PWBs. This ramp rate is widely used in the United States and Europe.

This report investigates the life and failure modes of solder joints according to the ramp rates used in Temperature Cycle Tests.
2 Test Method

2-1 Test samples

The samples used in this research were BGA (Ball Grid Array) and QFP (Quad Flat Package) packages, which are multi-pin packages with micro-joints. These were mounted on evaluation PWBs. The packages utilized an internal daisy-chain structure. Fig.1 shows an evaluation PWB, and Table 1 shows the package specifications. Two types of solder were used: Sn-37Pb eutectic solder, and Sn-3.0Ag-0.5Cu (mass %) solder.

![Evaluation PWB](image)

Table 1  Solder types and mounting parts

<table>
<thead>
<tr>
<th>Solder type</th>
<th>Sn-3.0Ag-0.5Cu (mass%)</th>
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| Package           | BGA: 196-pin, 1.0 pitch, 15 mm sq  
QFP: 208-pin, 0.5 pitch, 28 mm sq |
| PWB specifications | 100mm x 140mm x 1.6mm FR-4 (Cu + pre-flux) |

![Test conditions](image)

2-2 Test conditions

Fig.2 shows the test conditions. Soak time is standardized at 10 minutes, and the ramp rates are given as the parameters. The ramp rates are 6, 15, and 35°C per minute (actual measurements from 30 to 40°C per minute, hereafter given as 35°C per minute). In Japan, the ramp rate of 35°C per minute is a widely-employed Temperature Cycle Test condition for evaluating the reliability of samples such as BGA and CSP packages. For these tests at 35°C per minute we used an Air-to-Air Thermal Shock Chamber (Espec model TSA-101) that uses a damper to switch the air environment between pre-heating and pre-cooling.
The ramp rate of 15°C per minute is the stipulated condition in the JEDEC standard (United States) JESD22-A104-B (IEC60749-25). Depending on the thermal capacity, an appropriate condition in the range of 10 to 15°C can be selected. For tests at this ramp rate, we used the Rapid-rate Thermal Cycle Chamber (Espec model TCC-150) temperature cycle tester that changes the test area temperature without the use of a pre-cooling or pre-heating chamber. For tests at the 6°C per minute ramp rate, we used the Fast Cycle Chamber (Espec model HC-120) temperature cycle tester.

In the latter two models (6 and 15°C/min.), as Fig.3 shows, the air temperature wave form exhibits a left-right trapezoidal symmetry in response to the temperature control in the ramp-up and cool-down processes. The previous model (35°C/min.) exhibits a temperature wave form that differs from wave forms generally obtained with temperature shock testers. These temperatures were recorded at the center of the evaluation PWBs. Table 2 shows the ramp rate and soak time for these processes. The definition of the methods for calculating the ramp rate and the soak time conformed to JESD22-A104-B.

To evaluate the solder joint conditions, we monitored changes in the electrical resistance of the BGA daisy chains every three minutes and determined the time to rupture. For QFP packages, we performed tensile tests on the leads. After the temperature cycle tests, we cross-sectioned, polished, and examined both the BGA and QFP packages with an SEM microscope (composition images), and we analyzed the failure modes.

![Fig.3 Test profile](image)

Table 2  Ramp rate distribution (°C/min.)

<table>
<thead>
<tr>
<th></th>
<th>Target ramp rate</th>
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<tbody>
<tr>
<td></td>
<td>6°C/min.</td>
</tr>
<tr>
<td>Ramp rate (°C/min.) ±40 to 125°C</td>
<td>5.8-6.3</td>
</tr>
<tr>
<td>Ramp rate (°C/min.) 125 to -40°C</td>
<td>5.8-6.3</td>
</tr>
<tr>
<td>Soak time (min.) ±35 to 135°C</td>
<td>8.9-12.5</td>
</tr>
<tr>
<td>Soak time (min.) ±35 to 50°C</td>
<td>9.7-10.8</td>
</tr>
</tbody>
</table>
3 Test results

3-1 BGA rupture life results

Rupture life was defined as the number of cycles to reach twice the initial resistance. Weibull analysis was performed for the results of each test on BGA packages. The scale parameter was set as the Weibull average life, with Fig.4 showing those results with "m" values. To show sample life uniformity for these tests, the graph in Fig.5 presents standard deviation for Weibull life, as well as for maximum, minimum, and average life. Sn-37Pb eutectic solder exhibited roughly equivalent results in cycle life at all ramp rates. Sn-3.0Ag-0.5Cu solder exhibited somewhat shorter life at higher ramp rates.

Previous research on ramp rates that has employed simulations using the finite element method has reported declining cycle life as the ramp rate goes up.\(^4\)-\(^6\) That research reports an approximately 20 percent difference in CSP life between a 10°C per minute ramp rate and a 35°C per minute rate. However, our results found a difference of only approximately 10 percent between a 6°C per minute ramp rate and a 35°C per minute rate for Sn-3.0Ag-0.5Cu solder.

The reason for the differences in life cycles are thought to stem from the fact that localized strong distortion can occur at the 35°C per minute ramp rate, while distortion is much milder at lower ramp rates such as the 6°C per minute rate.\(^5\),\(^6\) It is thought that when localized strong distortion is concentrated, the internal stress of the solder is not dispersed, and creep and granular growth are less likely to occur.\(^5\),\(^6\) As a result, it is thought that at lower ramp rates, the effect of creep depends more on the elapsed time.

Fig.4 Weibull analysis results for BGA rupture life (−40°C/+125°C)
The effect of ramp rate on temperature cycle fatigue in solder joints

Fig.5 Comparison of BGA rupture life for each ramp rate (-40°C/+125°C)

3-2 Results of BGA cross section observation

3-2-1 Sn-37Pb eutectic solder failure modes

The sites on the BGA samples in these tests exhibiting the most marked progression of cracking were at the bottom of the end of the Si chips. (Fig.6 shows observation sites.) That is to say, the detection of rupturing using resistance measurements depended primarily on the rupture life of the bottom of the end of the Si chips. The analysis focused on these sites. Fig.7 shows the cross sectional observation results for Sn-37b eutectic solder after 2000 test cycles for each ramp rate. We confirmed cracking rupture sites and rupture shape, but no differences were exhibited at different ramp rates.

Fig.6 Analysis of cracking progression (-40°C/+125°C)
Heat and stress accelerated the Pb granulation of Sn-37Pb eutectic solder. We hypothesize that since lowering the ramp rate extends the test time, the lower the ramp rate test condition, the greater the effect of heat on the progression of granulation. However, repeated stress focused on the corner sections of the solder. Because of this, we compared the average particle diameters of Pb in the center and corners of the solder joints. Fig.8 shows the calculation method used to find the average particle diameter. Four point-to-point lines were drawn from the corners to the center, and the average Pb particle diameter was determined along each line. The same method was used for Sn-3.0Ag-0.5Cu solder, measuring the particle diameter of Ag3Sn. Fig.9 shows a graph comparing the particle diameter seen at the center and at the corner on the line with the greatest particle growth.

Looking at Fig.8 and Fig.9, we can see that the lower the ramp rate, the larger the particle diameter in the center area. We can surmise that the larger particle size results from the increasingly longer times required for each cycle as the ramp rate becomes lower. The corner areas are thought to be affected by both heat and mechanical stress. While the rupture life is approximately the same for these areas as for the center, we believe more investigation is required into the differences in failure modes.
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Fig. 9  Average particle diameter measurements (-40°C/+125°C)

3.2.2 Failure modes for Sn-3.0Ag-0.5Cu solder

Next, we observed cross sections of the BGA Sn-3.0Ag-0.5Cu solder after 3000 test cycles for each ramp rate. Fig. 10 shows the observation results. At the 6 and 15°C per minute ramp rates, the cracking began with solder rupturing and then later proceeded to peeling at the interface between the land and the alloy layer. At the 35°C per minute ramp rate, only solder rupturing and solder-alloy interface rupturing were found. One possible explanation for this could be that the lower ramp rate temperatures result in longer exposure times at high temperatures, yielding further progression in the interface metallic reaction. On the other hand, localized distortion is more likely to occur at the higher ramp rate. These results lead us to presume different failure modes for the different ramp rates.

Fig. 10  Results of cross sectional observation
(Sn-3.0Ag-0.5Cu, 3000 cycles, -40°C/+125°C)
3-3 Results of QFP lead tensile tests

Fig. 11 shows the results of the QFP lead tensile tests. The tests used a draw rate of 10 mm per minute and uniformity was within standard deviation. No remarkable differences were found in uniformity at any of the ramp rates.

![Graph showing tensile strength results for Sn-37Pb and Sn-3Ag-0.5Cu under different ramp rates.](image)

Fig. 11  Results of QFP lead tensile strength tests (−40°C/+125°C)

3-4 Results of observing QFP lead cross sections

Fig. 12 and 13 show the results of observing cross sections of QFP solder leads with Sn-37Pb eutectic solder and Sn-3.0Ag-0.5Cu solder after 3000 test cycles for each ramp rate. As Fig. 12 shows, the Sn-37Pb eutectic solder exhibits a tendency for cracking in the solder fillet. However, no significant differences in either cracking sites or shape were attributable to the different ramp rates.

As Fig. 13 shows, the Sn-3.0Ag-0.5Cu solder exhibited cracking at the lead interface. A comparison of rupture surfaces indicated an obvious grain boundary at 6 and 15°C per minute, with obvious rupturing at the grain boundary. At 35°C per minute, the progression of cracking was presumed to be dependent on the shape of the grain boundary. However, no obvious grain boundary rupturing such as that seen at 6 and 15°C per minute was evident, and so it was surmised from the sites at which cracking occurred that forced rupturing had occurred. This evidence leads us to conclude that the lower the ramp rate, the greater the affect on solder creep fatigue. At the 6°C per minute ramp rate, the formation of Kirkendall Voids was conspicuous. We obtained the same results in our BGA analysis, leading us to surmise that these results stem from the fact that the 6°C per minute ramp rate results in longer high temperature exposure time.
The effect of ramp rate on temperature cycle fatigue in solder joints

The above results indicate the possibility that lower ramp rates exhibit marked creep, while higher ramp rates affect creep less. Because of this, we believe that when performing Temperature Cycle Tests, in addition to considering market reproducibility, the appropriate ramp rate must also be considered.
4 Conclusion

We performed Temperature Cycle Tests at different ramp rates to determine the effects on solder joints of mounted parts, and we examined the rupture life and failure modes these ramp rates had with Sn-37Pb eutectic solder and Sn-3.0Ag-0.5Cu solder. We obtained the following conclusions.

(1) BGA rupture life occurred at approximately the same number of test cycles for all ramp rates (6, 15, and 35°C per minute). However, Sn-3.0Ag-0.5Cu solder exhibited slight differences, requiring further study.

(2) When examining the BGA failure modes, we found that Sn-37Pb eutectic solder exhibited no differences in cracking shape at different ramp rates, but the lower the ramp rate, the greater the progression in granular coarsening exhibited by Pb. For Sn-3.0Ag-0.5Cu solder, the failure mode at the lower ramp rates of 6 and 15°C per minute was a mixture of solder cracking and land-alloy interface peeling.

(3) When examining the QFP failure modes, we found that Sn-37Pb eutectic solder exhibited no differences in cracking shape at different ramp rates, but with Sn-3.0Ag-0.5Cu solder, we confirmed that the lower the ramp rate, the more obvious the rupturing that occurred at the grain boundary. Conversely, the higher the ramp rate, the greater the evidence of forced rupturing at the cracking sites.

[Terminology]

*1. Kirkendall Voids

Voids caused by the Kirkendall effect.

The Kirkendall effect was discovered in 1947 by E.O. Kirkendall, and is an experimental result in regard to diffusion. When metal A and metal B come into contact and diffusion occurs, differences in the coefficient of diffusion between metals A and B cause the diffusion to occur at different rates of speed, resulting in the formation of voids.

[Bibliography]


4) C. J. Zhai, R. Blish, "Board Level Solder Reliability vs. Ramp Rate & Dwell Time during Temperature Cycling", IEEE Device and Materials Reliability, 2003
