NOTE

Approaches to Technology of Thermal Fatigue Life Prediction of Solder Joints

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1 Introduction

Electronic parts for in-vehicle products must endure for fifteen or twenty years, longer than electronic parts used for other products. Therefore, these electronic parts require longer reliability evaluation to verify and guarantee their endurance.

On the other hand, shorter development cycle has been in strong demand and the evaluation has to be completed one time during the development phase. Specially, the life of solder joints to various parts must be checked, and it is a challenge to develop a technology of thermal fatigue life prediction to make the evaluation efficient.

FUJITSU TEN has been developing power train ECUs as in-vehicle products for nearly thirty years and we have been developing the technology of thermal fatigue life prediction for ten years. In those years, technological changes that affect fatigue life of solder joints occurred. Among them, the technology that enables parts to be mounted on all sides was developed from 1997 to 2000. In 2004, lead-free solder was adopted for environmental conservation. In addition, the BGA was adopted for small densified ECUs in 2006. The technology of life prediction has been used in designing various products and it has produced positive results.

Along with case examples, this paper introduces the technology of thermal fatigue life prediction of solder joints, which employs finite element method (FEM) simulation that FUJITSU TEN has used for life prediction.

2 Characteristics of Technology of Fatigue Life Prediction of Solder Joints

Fig. 1 shows the outline of life prediction of solder joints.

One of the stress[1] on in-vehicle products is temperature change in the environment where the products are installed, such as cabin, engine room, etc. and the change due to the heat produced by the products themselves during their use in vehicle. Generally, the heat cycle test is conducted to evaluate the stress.

The stress caused by the temperature change appears as plastic strain and creep strain on the solder joints due to the difference in coefficient of linear expansion between the printed wiring board and the electronic part. It is well known that the life of solder joints mainly depends on these strains. In order to predict the life of a solder joint, first, the fatigue life of the solder is verified by a heat cycle test; second, the fatigue life curve is plotted based on the correlation between inelastic amplitude

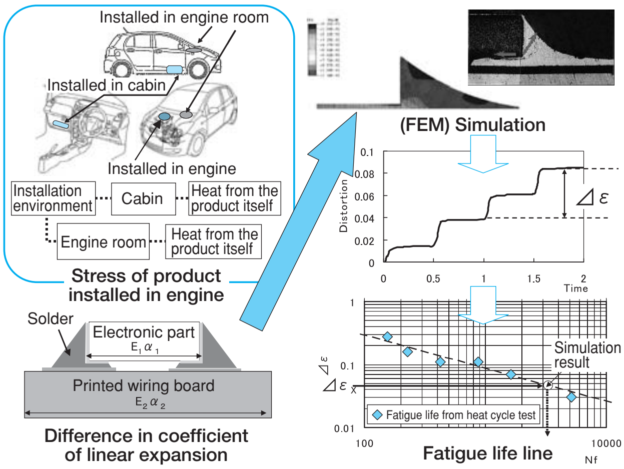

Fig.1 Outline of Thermal Fatigue Life Prediction of Solder Joints

$\Delta\varepsilon$ which is the sum of plastic strain and creep strain gained from the simulation; thirdly, the part to be mounted is simulated based on its shape to calculate inelastic amplitude $\Delta\varepsilon$; and finally, the fatigue life of the solder joint is predicted by calculating it back from the gained life curve.

Specially, inelastic amplitude and fatigue life are known to follow the Coffin-Manson Law and they are expressed in the following equation.

$$Nf=C\times\Delta\varepsilon\,\hat{}\,\text{-}n$$

Wherein, the values of C and n depend on the fatigue strength properties of solder joints, and they change from one material to another. $\Delta\varepsilon$ is inelastic amplitude gained from simulation, and Nf is the number of cycle gained from the test. What should be noted here is that many companies report that the above formula is valid in the correlation of a breaking cycle and strain amplitude because they consider that the breaking cycle where a joint is broken is more important than the cycle where the first crack appears although it is widely accepted that Nf should be the cycle where a crack appears first. Like other companies, FUJITSU TEN has established the life curve based on the breaking cycle to failure (**Fig. 2**).

Fig. 2 shows an example of the life curve plotted from the correlation between the breaking cycle of eutectic-soldered chip resistors in the size of 2125, 3216, 4532 and 4632 from the heat cycle test in the range of -40 to 125℃ and their strain amplitudes gained from simulation. This figure shows that those points are laid on a straight line and follow the Coffin-Manson Law.

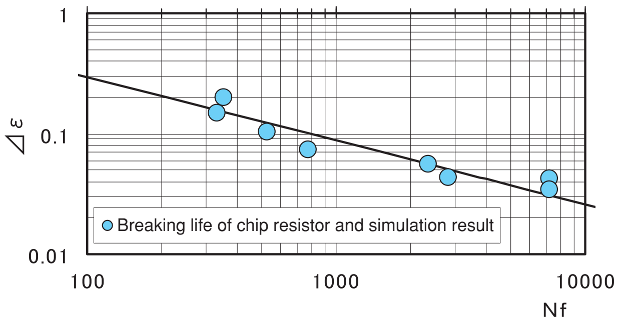

Fig.2 Fatigue Life Curve

Like this, the life of solder joints can be predicted from the strain amplitude ⊿ε calculated by simulating each part and fatigue life of the solder from the test. The life of a part can be predicted according to its shape and temperature range where it is used.

3 Approaches and History of Fatigue Life Prediction Technology

3.1 Approaches to Fatigue Life Prediction Technology

Around the time when FUJITSU TEN began the discussion on life prediction technology, Mr. Shiratori of Yokohama National University and others made public the validity[2] of simulation by using Sn-Pb eutectic-soldered sample. Toshiba, Hitachi and some other electronic part manufacturers began examination to adopt the technology for their IC packages.

Meanwhile, Fujitsu launched in 1998 an advanced analysis study group, for the purpose of establishing life prediction of BGA solder joints, under the leadership of the simulation department of Fujitsu. In 1999, the study group gained its original nonlinear properties of eutectic solder, and was verifying whether the technology was valid for the 1mm-pitch BGA. FUJITSU TEN joined the study group in 1999. Since then, we have learned the simulation technique and studied application of the simulation.

Fig. 3 shows what the study group has studied.

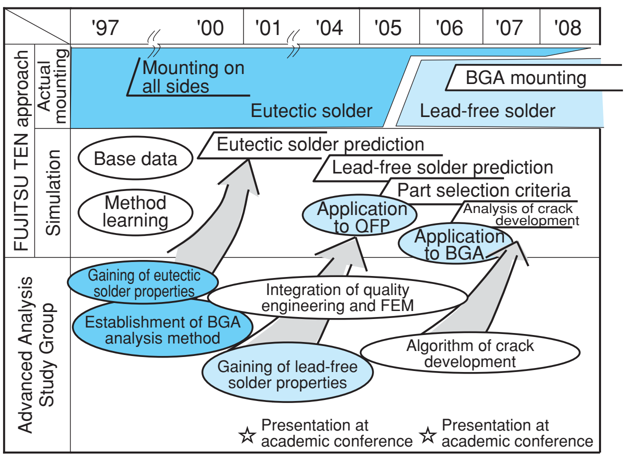

Fig.3 Research Theme of the Advanced Analysis Study Group

We have made presentations at academic conferences twice as collaborative results of the study group. In 2001, we gained properties of lead-free solder materials and released results[3] of BGA test and simulation to verify the results. Those properties have been used as the base to predict the life of lead-free solder joints of SMD since then. In 2005, we made public the case[4] where we established selection criteria of parts for the QFP, employing quality engineering and FEM. The case is detailed in Section 4.

We explained what we have studied in the advance analysis study group. We will move onto the advances made in this technology.

3.2 Advance of Life Prediction Technology

When we began the discussion about the life prediction technology, simulation tools were not displayed in GUI. Simulation conditions had to be entered in command lines, which made simulation difficult. At that time, computer processing speed was slow, and it took all night to calculate the strain of a solder joint of a chip resistor. In these circumstances, it became important to simplify models. In many cases, companies adopted a two-step analysis **(Fig. 4)** where the entire structure was analyzed in as simple model as possible and then a solder joint to be focused upon was picked up and analyzed in detail.

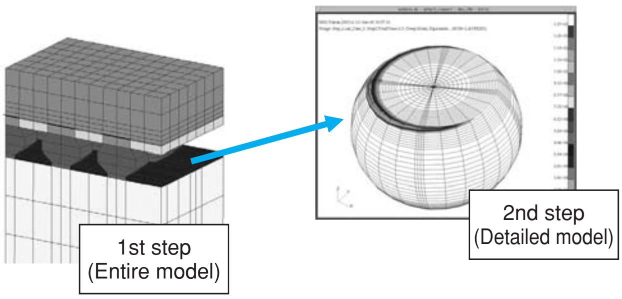

Fig.4 Two-Step Analysis

However, for in-vehicle products at that time, miniaturization and diversification was mainly required for the chip parts whose structure was simpler than the BGA package. Therefore, FUJITSU TEN focused on 2-D analysis that needed less computing capability than the two-step analysis and began to employ it for SMD design. **Fig. 5** shows our progress of analysis technology of solder life.

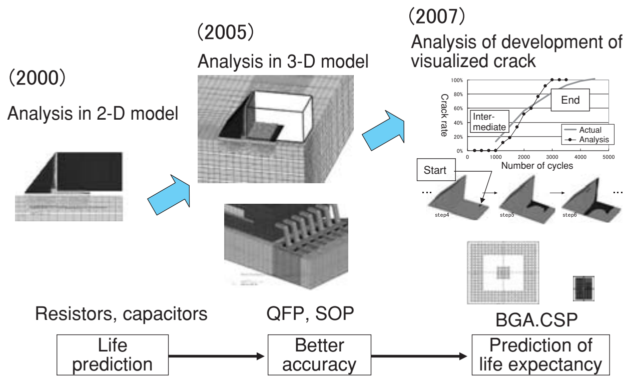

Fig.5 Progress of Fatigue Life Analysis Technology

After that, lead-free solder started to be adopted to reduce environmental burden. It became understood that the creeping speed of lead-free solder is slower than eutectic solder when the stress is same. **Fig. 6** shows the creep properties of the two types of solder.

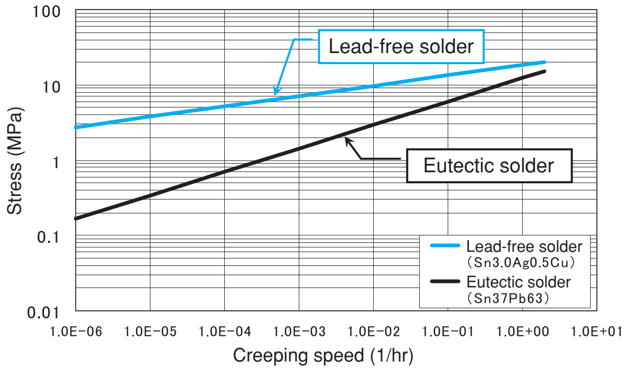

Fig.6 Relationship between Stress and Creep Strain Rate of Solder

In short, rather than lead-free solder's properties that are hard and less stretchable, the parts soldered with lead-free solder brought concerns about their reliability although the same parts soldered with eutectic solder had been used without any problems. In addition, responding to the trend of miniaturization of in-vehicle products, thin packages such as the SOP and the QFP were adopted. Accordingly, we have improved the analysis in 3-D model to analyze life of parts in complicated structures.

Moreover, recently, we are addressing a more challenging prediction that is to predict the development of a crack from its start to end through the intermediate with increasing demand of pin assignment based on the prediction of the order in which balls of the BGA will break and the prediction of life expectancy of a part with a crack from its reliability test results to improve the package.

4 Proven Cases

We explained our effort to improve life prediction technology. From here, we will introduce some cases where our technology was applied to actual products.

4.1 Efficient Design in FEM

The life of solder joints of SMD parts mainly depends on soldered shape and amount. The shape and amount is specified based on land design values which are determined according to the SMD land and metal mask shape. In order to verify the validity of the land design values, a long reliability test is required. Therefore, various evaluations of the land and metal mask were conducted in parallel. As a result, the evaluations took a very long time because many samples had to be evaluated. Given this fact, we narrowed down the samples to be evaluated in advance by employing the FEM to improve the efficiency of the land design. **Fig. 7** shows an example of the process.

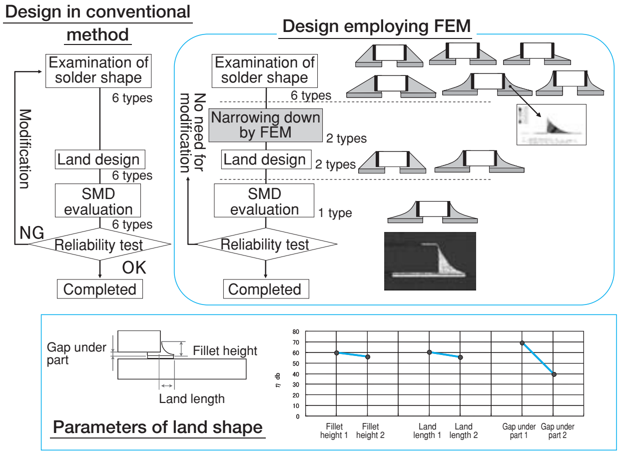

Fig.7 Example of Efficient Land Design of Chip Resistor

Conventionally, we examined six solder shapes with different angle, length and amount of solder fillet, created prototype samples of all the six types, and conducted their SMD evaluation and reliability test that required a long time. Some of the samples were not approved, and in the worst case, all the samples were not approved. In such a case, we had to start the process all over again. On the other hand, by employing the FEM, we can select a few solder shapes that are predicted that their life should be longer than that of others. That enables not only reduction in the number of samples but also elimination of the possibility to have to start the process all over again after the evaluation is completed.

4.2 Part Select Map Employing Quality Engineering and FEM

The life of solder joints became a problem, too, for the QFP due to miniaturization of packages (hereinafter referred to as PKG) and narrow pitches (**Fig. 8**). Moreover, we found that, in the case of chip resistors, parts soldered with lead-free solder crack and break earlier than parts with eutectic solder when the size of them are the same (**Fig. 9**).

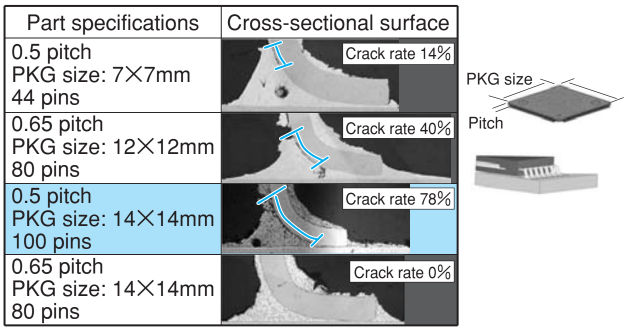

Fig.8 Examples of Cracks of QFP Solder Joints

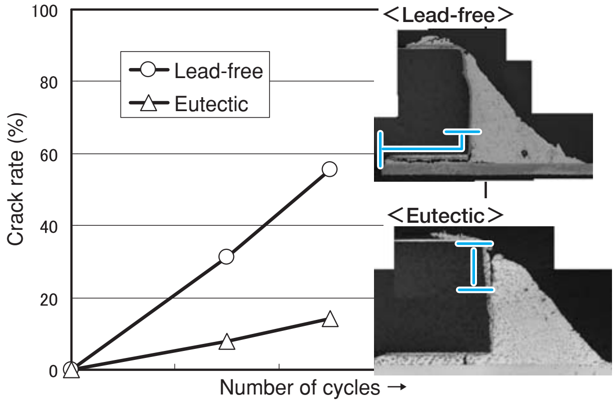

Fig.9 Comparison of Cracks

As mentioned above, solder joint reliability emerged as a problem with the parts soldered with lead-free solder although the same parts had never had a problem when soldered with eutectic solder. As a result, it became necessary to conduct reliability test for solder joints of all parts that we decided to adopt. However, if we had done that, it would have required huge man-hours and work. Therefore, we improved evaluation efficiency by creating a QFP selection criteria map, through simulation, based on which engineering designers can select parts which meet the reliability of solder joints according to the part shape. **Fig. 10** shows the outline of the process of how we created the selection map.

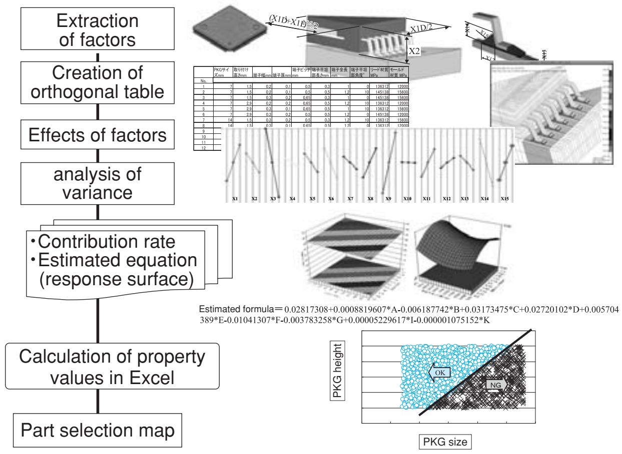

Fig.10 Process of Creating Part Selection Map

The life of solder joints of the QFP is affected by various design factors such as package materials and dimensions of each part. In the process shown in **Fig. 10**, we determined, through simulation, the level of the effect that those factors had on the life of solder joints based on a quality engineering orthogonal table and extracted the effect parameters. Next, we found an estimated equation for life of a joint from multiple regression analysis so that the life can be calculated simply by entering values of factors from the orthogonal table even without simulation.

Using the estimated equation, we conducted Monte Carlo simulation, where calculation is done several times, to find acceptable size and height of the PKG, effect parameters and plotted the part selection map. In **Fig. 11**, the process of the Monte Carlo simulation in Excel is shown.

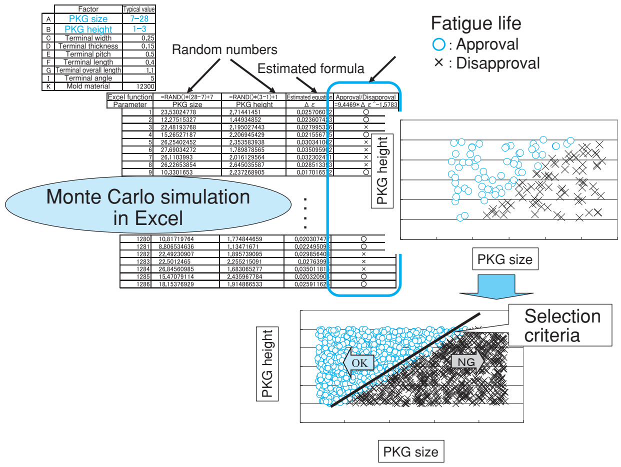

Fig.11 Monte Carlo Simulation in Excel

Fig. 11 shows the results calculated in the estimated equation of solder joint reliability with "○" for approval and "×" for disapproval. The dividing line shows the selection criteria. The QFP selection criteria gained from the process mentioned above serves as a design guideline for engineering designers to design products.

4.3 Use of Crack Development Analysis

As mentioned above, we found that the life of parts soldered with lead-free solder is, in some cases, shorter than the one of parts with eutectic solder. That required us to estimate the allowance of the life of a part from the reliability test results in order to improve accuracy of life prediction with little test data. Moreover, for adopting the BGA, we wanted to narrow down the items to be evaluated for validity that is conducted due to unobservable solder joints located inside. For that reason, we developed a method for crack development analysis in which solder cracks are visualized and their start, intermediate, and end can be estimated. This section explains the methods used by other companies and the application of our method.

4.3.1 Trend of Crack Development Analysis Technology

Conventionally life of a part was predicted by accumulating correlation, as respective database, between the final breaking cycle found in test per shape of solder joints, package type, and soldered area and their simulation results, and then predicting the end of life from the accumulated results of a part in relatively-similar shape and conditions. Therefore, it was difficult to predict the process of cracking because solder joints of various parts crack; the shapes of those solder joints changes in the course where the cracks develop; and accordingly stress distribution continuously changes.

In order to render crack development in the finite element method, the initial finite element model needs to be changed dynamically as the crack develops. For example, finite elements are deleted or connection between elements is cancelled because the joint has lost its rigidity and the elements are not connected any longer.

Among the methods where a finite element model is dynamically changed as a crack develops, there are the element deletion method and the damage path simulation method where elements are not deleted but its rigidity is decreased. **Fig. 12** shows those methods, taking development of a crack on a chip as an example.

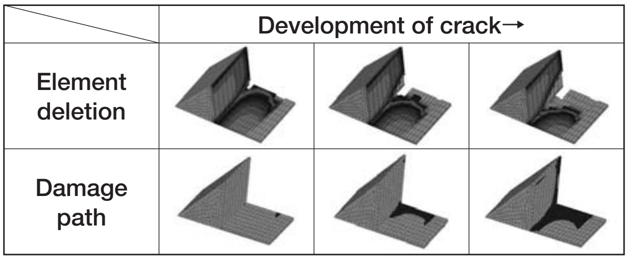

Fig.12 Development of Cracks Shown in Both Methods

In the element deletion method, the elements shown in red are deleted, and in the damage path method, the area in black loses its rigidity. The areas shown in black in both methods render cracks.

We will explain characteristics of those analysis methods, the element deletion method and the damage path simulation (**Fig. 13**).

①Dynamic element deletion method

Mr. Terasaki and others tried a method[5] with solder pumps, using VOXEL elements and micrifying the element mesh size to the actual crack size level. When a strain or stress of an element reaches a predetermined value, the element is deleted, which represents the development of an actual crack. The following two points are considered as the advantage of this method.

(1) Accurate prediction of development of a crack without special preconditions
(2) Good convergence compared to the damage path method (discussed later)

On the other hand, these two points are the disadvantages of the method.

(1) Strong dependency on mesh size and even and minute mesh being required
(2) Huge model size and much time for calculation required for minute and even mesh

②Static element deletion method

Mr. Igarashi and others propose the method[6] where elements are deleted like the method ① for life prediction for chip resistors. What makes this method different from the method ① is that multiple models where elements have been already deleted by engineers are prepared in advance. The Coffin-Manson Law, which is used to predict start of a crack, predicts accurately the cycle where a crack starts with a certain length (for example, 50 μm). The length of a joint is divided by the standard length (50 μm) to find how many models are necessary. The models are prepared as many as the obtained number from the division, and the life of the joint can be calculated from inelastic amplitude of each model, using the Coffin-Manson Law.

For example, in the case of a joint with the length of 500 μm, it is necessary to prepare ten models each of which has a crack with the length of 50 μm. To calculate the life of the joint, the life of crack initiation of those ten models is totaled.

However, if a joint is long, this method is inefficient. Therefore, Mr. Igarashi and others propose a method where only some models are analyzed, instead of analyzing all, and approximation is used for the unanalyzed models based on the analysis results of the analyzed models.

The following three are the advantages of this method.

(1) No need for large computational resource
(2) Convergence better than other methods (① and ③)
(3) Settable calculation time because the number of models to be calculated is limited.

③Damage path method

In the methods ① and ②, a crack is rendered by deleting a part of mesh. However, state of stress similar to a crack can be rendered by decreasing rigidity of elements, even without deleting them. Mr. Mukai and others have made public this method of decreasing element rigidity and call it damage path simulation[7,8]. The following three are the advantages of this method.

(1) Relatively independent of mesh size
(2) No need for large computational resource
(3) No need for creating special mesh

On the other hand, we tested this method and found its possible tendency toward less convergence compared to the other methods.

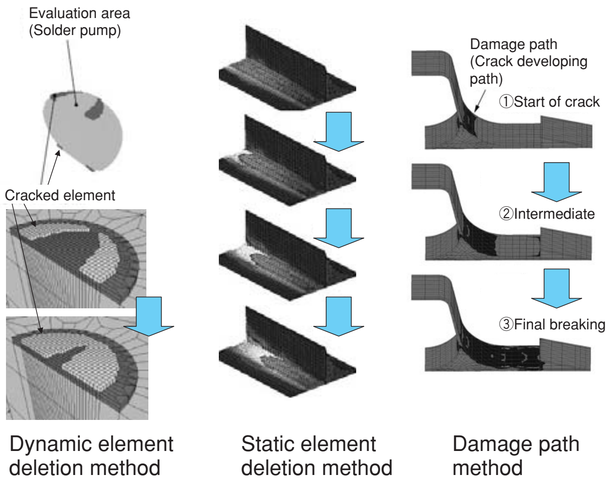

Fig.13 Analysis Examples of Those Methods

Method	Element shape	Model scale Estimation of number of element in the length of 100 μm	Dependency of element size	Number of models	Calculation time	Analysis accuracy	Test results
Dynamic element deletion	VOXEL	100	Yes	1	Longest Changes according to crack length	Good	Not adopted Requires a largescaled equipment
Static element deletion	Tetrahexa	8	Yes	10 or more	Short Changes according to No. of models	Depend on the number of models	Not adopted Requires prediction of development path of cracks
Damage path	Tetrahexa	4	Less	1	Long Changes according to crack length	Depend on mesh size	Adopted Possible to predict development of cracks

Fig.14 Benchmarks of Those Methods

4.3.2 Our Analysis Method of Crack Development

We benchmarked each of those two methods, one of which is the element deletion method where development of a crack is rendered by deleting elements and the other is the damage path method where a virtual crack develops by decreasing rigidity of elements, and decided to adopt the damage path method because model scale less depends on the size of a crack and we can use the conventional model. And then, we developed our own analysis method for our products (**Fig. 14**).

In concrete, we established our analysis program that runs the process from (1) to (3) automatically as user subroutine on ABAQUS, a general structure-analysis software (patent application number 2006-12272). (**Fig. 15** shows its algorithm.)

(1) Adjust the parameters of the Coffin-Manson Law to proper values according to the actual rate of crack development.
(2) Calculate damage state of infinite elements based on the Coffin-Manson Law and decrease rigidity of the elements dynamically based on the calculation.
(3) Regard the elements of which rigidity decreases as an area where a crack develops, and show them graphically. Automatically calculate the length of the elements and crack rate in each cycle.

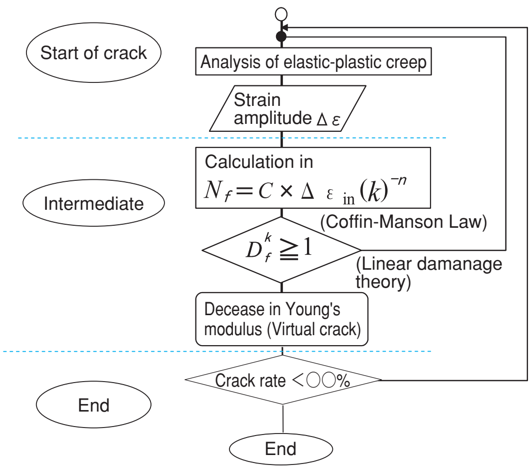

Fig.15 Analysis Algorithm

We gained good correlations as shown in **Fig. 16**, by using the established program.

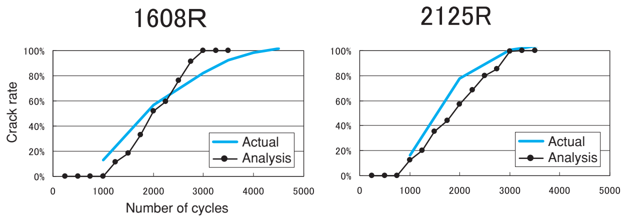

Fig.16 Transition of Crack Rate

4.3.3 Case Examples

We use the analysis of crack development as the evaluation guideline for the BGA or other parts in which a crack cannot be located by appearance. **Fig. 17** shows the simulation of a crack development in a BGA package used for in-vehicle products. Being tolerant to change in temperature environment in vehicles, the terminals outside a package serve as NC to prolong life of terminals inside. With the conventional analysis method, we could predict which solder bump would be broken first, but we could not predict the second bump and later. Therefore, we ground down the package in the sectional area from the outside to evaluate the BGA and other parts. However, the new analysis method of crack development can locate the bump that breaks second or later and help us find problems in the development phase.

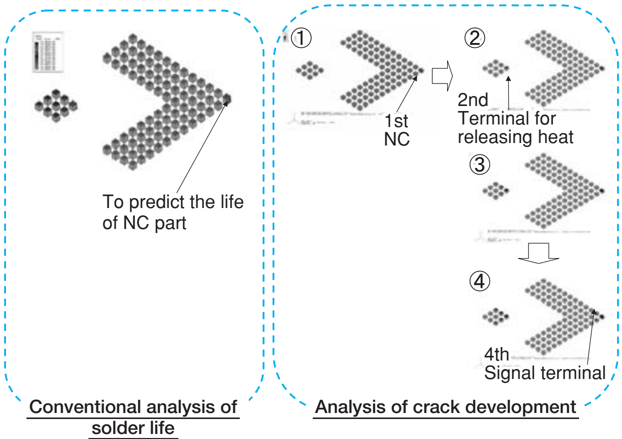

Fig.17 Application Example to BGA

5 Conclusion

This paper explained the history and use of FUJITSU TEN analysis method for life of solder joints, pointing out SMD of electronic part, lead-free solder, high-density of parts as the reasons for our effort.

Here, we would like to extend our sincere appreciation to those who gave kind support for us to gain solder properties and limit of parts' life, and verify simulation results, etc. With these, we contribute to establishment of design guideline and efficient evaluation.

These days, in-vehicle electronic devices are often installed in the engine compartment, which puts those devices in severe conditions in terms of temperature. Among those devices, some handle high current and the number of such devices is increasing. We are now developing another analysis method because we are concerned that reliability of solder joints will become an issue due to transitional self-heating in ECU in the high temperature environment.

We hope to contribute to the development of technology that ensures reliability of miniaturized in-vehicle products by establishing analysis methods employing thermic fluid and stress, and developing analysis methods for joints that will continue to be smaller.

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【Terminology】 (9)(10)(11)

ECU (Electronic Control Unit)

Abbreviation of Electronic Control Unit

Finite Element Method (FEM)

The finite element method is a method to analyze stress and strain by solving the displacement equation for a structure deformed by an external force with the structure modeled in an aggregate of small elements.

SMD

Abbreviation of Surface Mount Device

The SMD is electronic parts that can be mounted on printed wiring boards with surface mounting technology, such as IC, resistors, capacitors.

BGA (Ball grid array)

The BGA is a package with one face covered (or partly covered) with electrode balls (bumps) of solder in a grid pattern. Since electrodes can be provided on the BGA more than the QFP, and leads do not extend outside, the BGA is one of the solutions to producing a miniature package. However, it is difficult to inspect soldering quality by appearance.

SOP (Small Outline Package)

The SOP is a small plastic molded package with "gull wing" leads protruding from the two long sides.

QFP (Quad Flat Package)

The QFP is a small plastic molded package with "gull wing" leads protruding from the all four sides.

Creep

The creep refers to the property where a strain on a material becomes larger with time as a result of exposure to certain stress. The creep is more severe when the material is subjected to heat. The expression "less stretchable" is comparison to this property.

GUI (Graphical User Interface)

The GUI is a user-friendly interface where much information is provided in graphics to users and most basic operation can be done with such a pointing device as a mouse.

Mesh

The mesh refers to an element in FEM.

Tetramesh

The tetramesh refers to the tetrahedral mesh. An automatic mesher can easily show even a complicated shape in tetrahedral mesh. Compared to the hexagonal mesh, the number of elements is larger and accordingly difference is wider.

Hexamesh

The hexamesh refers to the hexagonal mesh. Compared to the tetramesh, it is difficult to automatically show an object in hexagonal mesh. However, the number of elements is smaller and difference is narrower compared to tetramesh.

VOXEL mesh

The voxel mesh refers to the regular hexagonal grid element. An automatic mesher can show an object in the voxel mesh. In the case of a complicated shape, it requires huge equipment. The number of elements of voxel mesh is far bigger than the one of tetramesh or hexamesh. As a result, it is accurate.

Monte Carlo Method

The Monte Carlo Method is a method employing random numbers in simulation or calculation.

As mentioned in the text, we used the RAND function in Excel to calculate variables of characteristic formula in our approach.

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Entered in FUJITSU LIMITED in 1990 and engaged in the simulation related to the mounting technology.
Since 2007 when TECHNOLOGY CENTER was deconglomerated, has been in FUJITSU ADVANCED TECHNOLOGY HPC CENTER. Currently PROJECT MANAGER of FUJITSU ADVANCED TECHNOLOGY HPC CENTER.

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