

Reliability of Lead-free solder for Automotive Electronic Devices and Its Applications

Tsunehisu HATA*

Junichi OHMURA*

Masato MORIYAMA*

Tomoo WATANABE*

ABSTRACT

Although an Sn-Pb alloy is generally used for solder at present, environmental considerations have occasioned a search for lead-free solder alloys. The present research evaluated lead-free solder to determine whether it could replace Sn-Pb solder, beginning with the evaluation of the reliability of the solder joint. The evaluation examined reliability under five degradation modes: thermal fatigue, intermetallic compound layer, creep, vibration fatigue, and ionic migration. Lead-free Sn-Ag-Cu solder showed the longest life under thermal fatigue, which is the most crucial element in reliability, and it was confirmed to have reliability superior to Sn-Pb solder in the thermal environments encountered in ordinary use. The Sn-Ag-Cu solder was then put into use as a product in a keyless entry transmitter, where it was demonstrated to satisfy product quality and endurance quality requirements.

1. Introduction

As the global movement for environmental protection continues, restrictions on hazardous substances in vehicles have also been strengthened in recent years. The EU has adopted the WEEE ('08) hazardous substance standards for household electrical appliances and an EU directive ('03) regulating hazardous substances in vehicles and the processing of end-of-life vehicles. In Japan, a household electrical appliance recycling law went into effect in 2001, and a proposed law on vehicle recycling is also presently being studied. The reduction or total elimination of lead and other hazardous substances has come to be unavoidable. Meanwhile, there is resistance to changing the composition of solder in electrical components installed in vehicles because safety considerations demand high reliability in such components. Even if reliability could be assured, however, cost considerations would still be an issue because of anticipated increases in the costs of processing and peripheral materials. At present, therefore, the movement to adopt lead-free materials in automobiles is sluggish compared to the

corresponding movement for household electrical appliances.

The present research evaluated the reliability of lead-free solder using reliability evaluation techniques⁽¹⁾ for examination of joints made with Sn-Pb solder. With the support of those results, the application of lead-free solder to products was studied. This article reports on the resolution of the issues of reliability and cost, and the successful mass production of an electronic device with lead-free solder in the form of a keyless entry transmitter.

2. Reliability of Solder

Electrical components installed in vehicles are subjected to the environmental factors of humidity, vibration, and temperature, as shown in Fig. 1, which cause degradation. There are also internal factors that cause degradation of the components, such as electrolytic dissociation and strain. These factors are summarized in terms of solder characteristics in the diagram of solder joint reliability factors shown in Fig. 2.⁽¹⁾

* Tochigi R&D Center

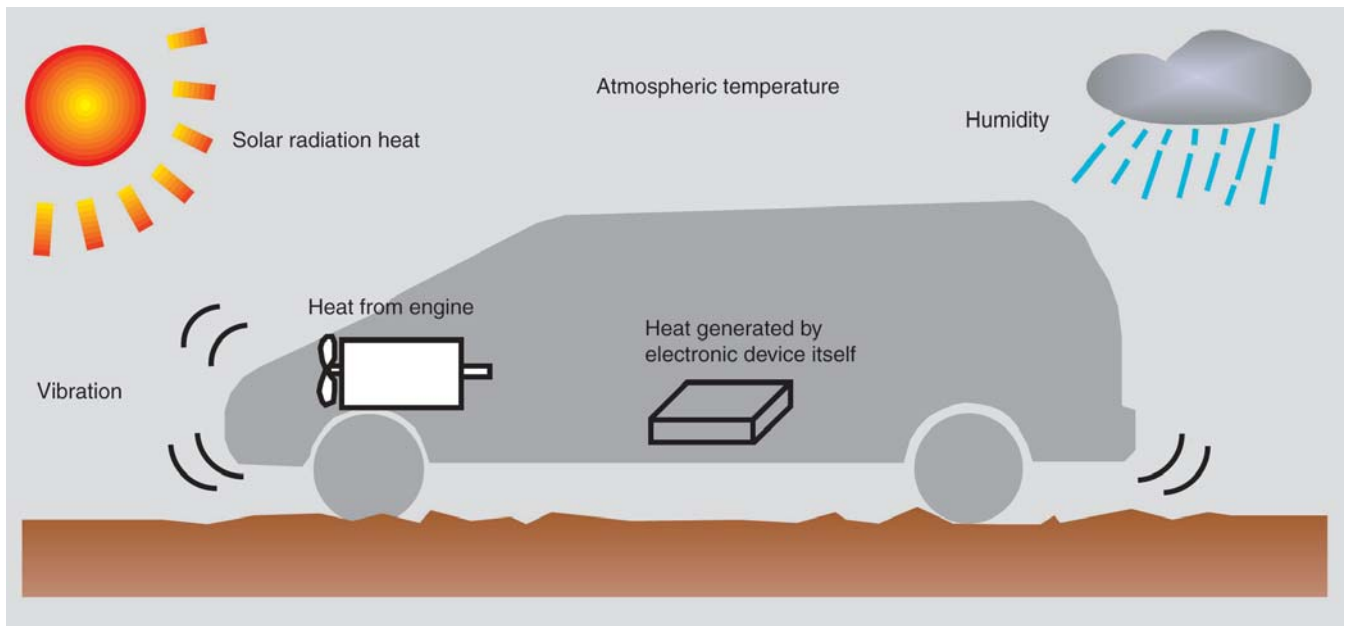


Fig. 1 Stress factors in the automotive environment

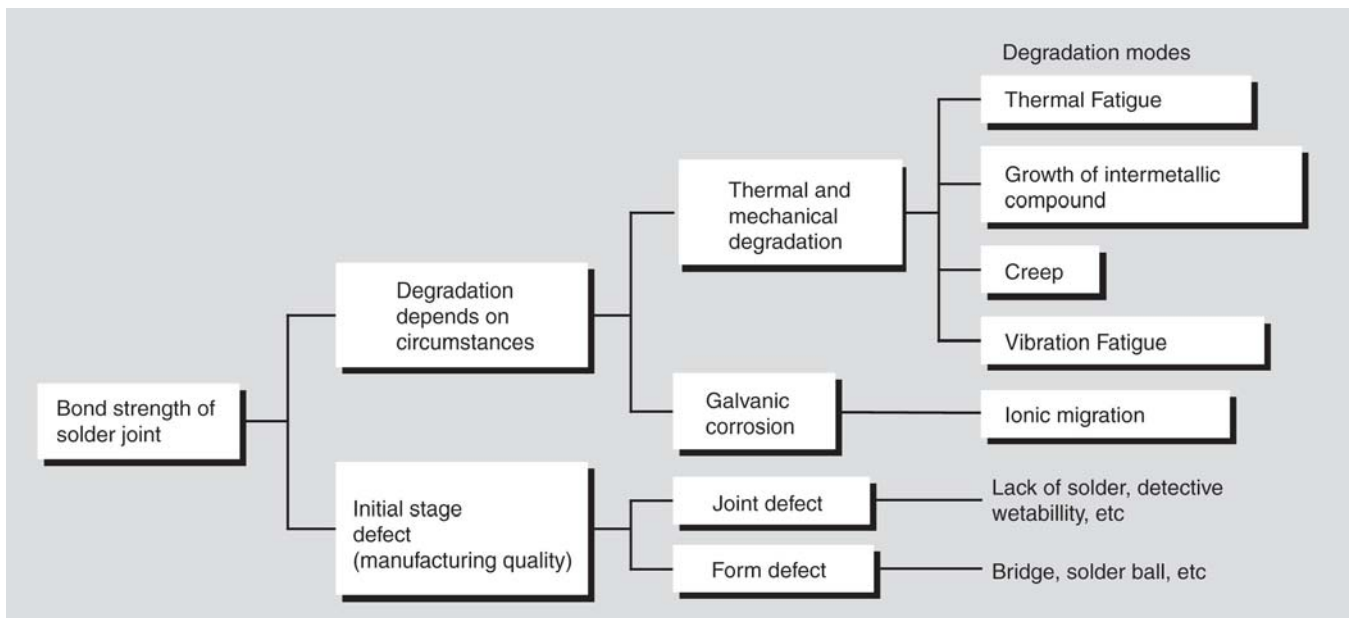


Fig. 2 Solder joint reliability factors

The environmental degradation modes that were considered were: (1) thermal fatigue, (2) growth of intermetallic compounds, (3) creep, (4) vibration fatigue, and (5) ionic migration. Reliability evaluation is the operation of determining whether or not the specified functions can be maintained under given conditions and for a given period of time. In specific terms, this is proving that environmental degradation-type malfunctions will not occur within the period of guaranteed use.^{(3) (4)}

Given these considerations, a reliability evaluation of lead-free solder was conducted by comparing lead-free solder in the form of various types of low melting point Sn-based eutectic alloy with Sn-Pb solder. This will be explained below with reference to the five degradation modes.

2.1. Thermal Fatigue

Fig. 3 shows the mechanism of the occurrence of thermal fatigue.^{(1) (2)}

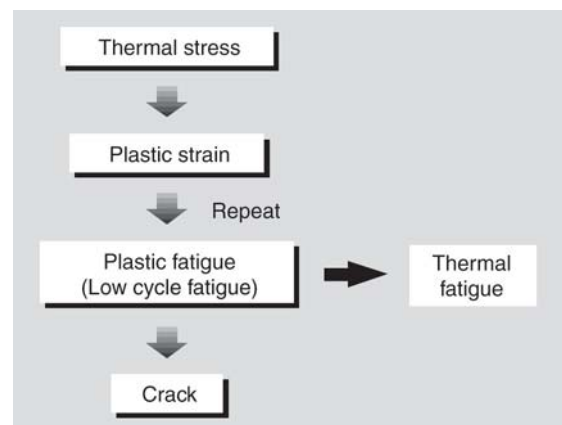


Fig. 3 Mechanism of the occurrence of thermal fatigue

Since the degradation factor is temperature change (ΔT), the most appropriate accelerated test is thermal cycle testing, in which a load is applied by alternating high and low temperatures. Evaluation was conducted using different solder compositions.

Four types of solder were used: (1) Sn-37Pb, (2) Sn-3.5Ag-0.75Cu, (3) Sn-7.5Bi-2Ag-0.5Cu, and (4) Sn-8Zn-3Bi. A ceramic chip resistor (size 2125), which has a coefficient of thermal expansion significantly different from that of the substrate, was mounted on a glass-epoxy substrate using those types of solder. The thermal cycle conditions were temperatures of $-40\text{ }^{\circ}\text{C}$ – $120\text{ }^{\circ}\text{C}$ at 30 minutes each. The results are shown in Fig. 4, Table 1, and Fig. 5. It was determined from the failure mode and internal soundness that Sn-Bi types and Sn-Zn types would be difficult to guarantee, and subsequent evaluation was focused on the Sn-Ag-Cu solder.

Sn-Ag-Cu solder was subjected to thermal cycle testing at three levels of ΔT , between the different temperatures (1) $-40\text{ }^{\circ}\text{C}$ – $125\text{ }^{\circ}\text{C}$, (2) $-40\text{ }^{\circ}\text{C}$ – $100\text{ }^{\circ}\text{C}$, and (3) $-40\text{ }^{\circ}\text{C}$ – $80\text{ }^{\circ}\text{C}$. The results are shown in Fig. 6 and Fig. 7. It is apparent that the Sn-Ag-Cu solder shows longer life than Sn-Pb solder in the low ΔT region ($165\text{ }^{\circ}\text{C}$ and below) that corresponds with the region of ordinary use.

Next, the electrode surface treatment specifications of the chip part were examined for reference purposes. Sn-3.5Ag solder was used together with test pieces mounted with chip resistors with four different types of surface treatment: (1) Sn-10Pb, (2) Sn 100%, (3) Sn-3.5Ag, and (4) Sn-10Bi. These were subjected to thermal cycle testing at $-40\text{ }^{\circ}\text{C}$ – $125\text{ }^{\circ}\text{C}$ for 30 minutes each. The results are shown in Fig. 8. With Sn-10Bi, the crack growth rate was higher on the low cycle, and, as shown in Fig. 9, there were problems such as peeling at the boundary between the component and the solder, and this was judged unacceptable for use.

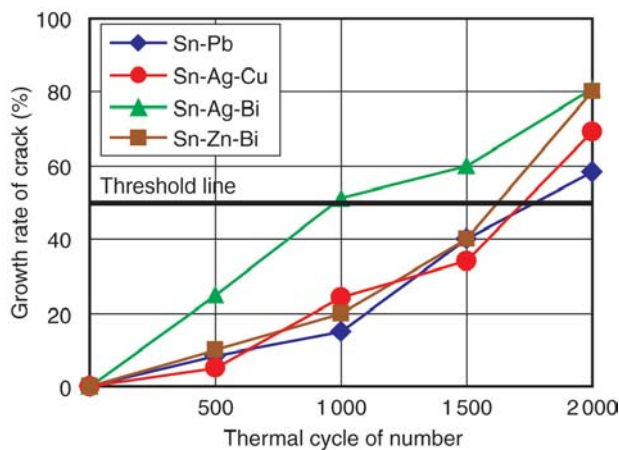


Fig. 4 Tendency of chip resistor degradation classified by solder material

Table 1 Results of thermal cycle test

Solder composition	Mean life-cycle (50% crack)	Internal soundness
Sn-Pb	1 800	OK
Sn-Ag-Cu	1 750	OK
Sn-Bi	1 000	OK
Sn-Zn	1 650	OK

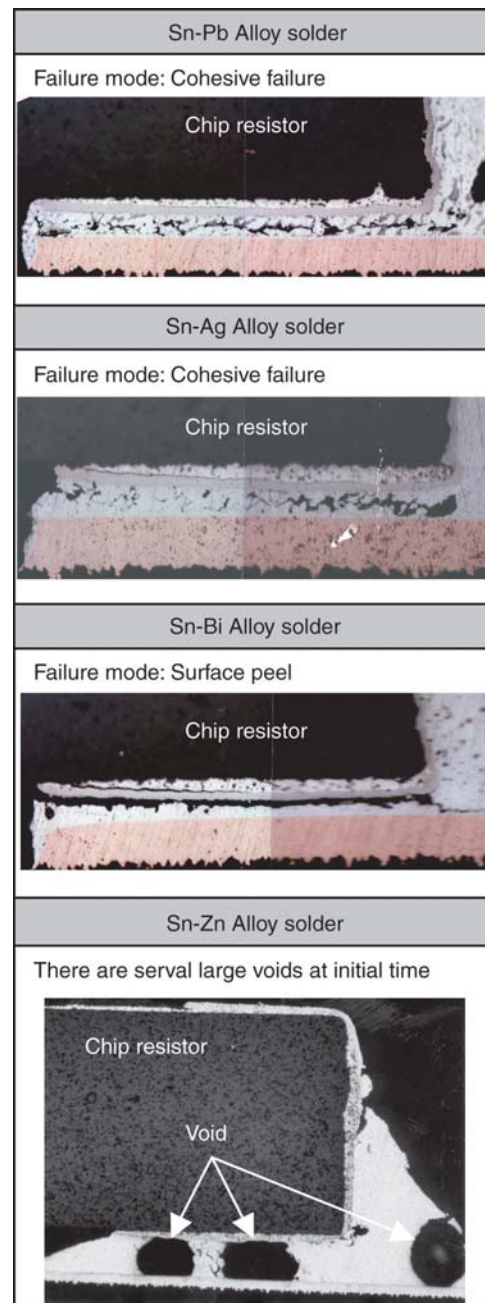


Fig. 5 Cross cut section of solder joint

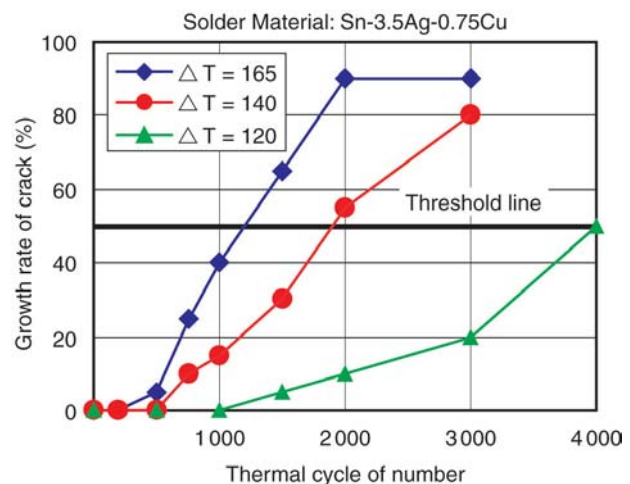


Fig. 6 Tendency of chip resistor degradation classified by ΔT

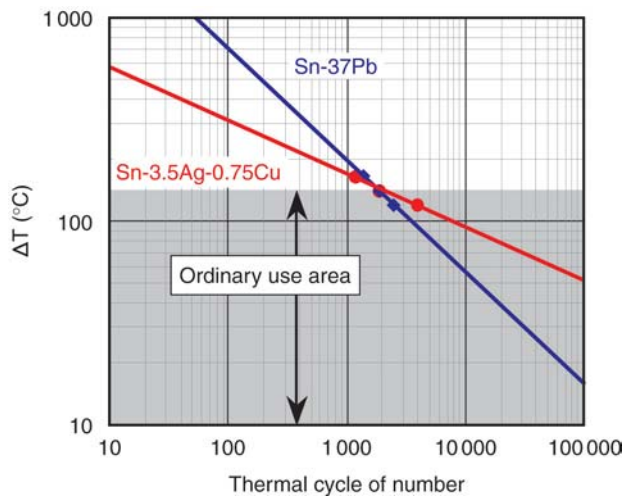


Fig. 7 Limit line of durability of thermal fatigue (chip resistor)

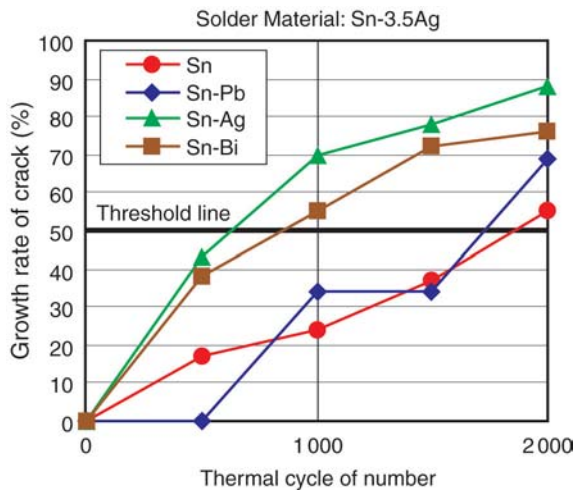


Fig. 8 Tendency of chip resistor degradation classified by electrode material (chip resistor)

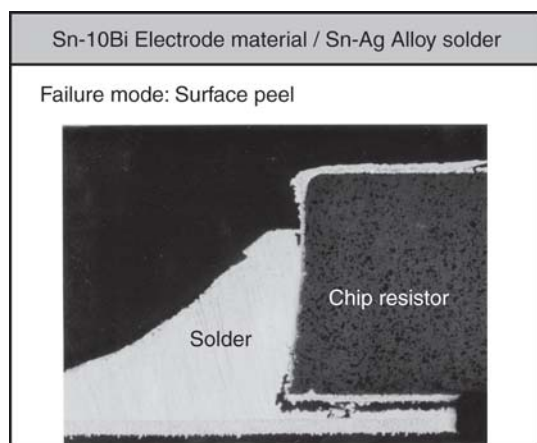


Fig. 9 Cross cut section of solder joint

2.2. Growth of Intermetallic Compounds

When the solder forms a fused junction, the Sn in the solder and the metal (here it is Cu) that forms the substrate pattern form an intermetallic compound layer, as shown in

Fig. 10, by interdiffusion. Upon initial use, the solder and the Cu on the substrate exhibit a strong bond. In the usage environment, however, an intermetallic compound layer grows and enters a stable compound phase. This conversely becomes fragile, causing concern that it will have an influence on the life of the joint.⁽¹⁾

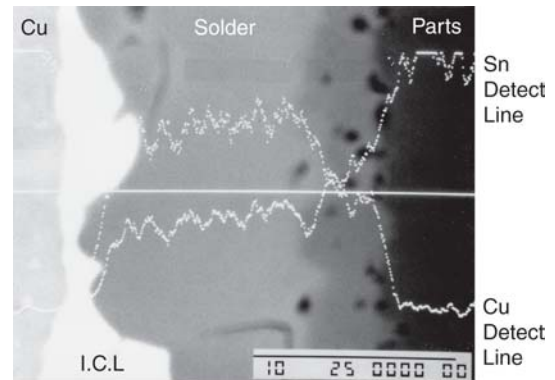


Fig. 10 Micrograph of intermetallic compound layer (I.C.L)

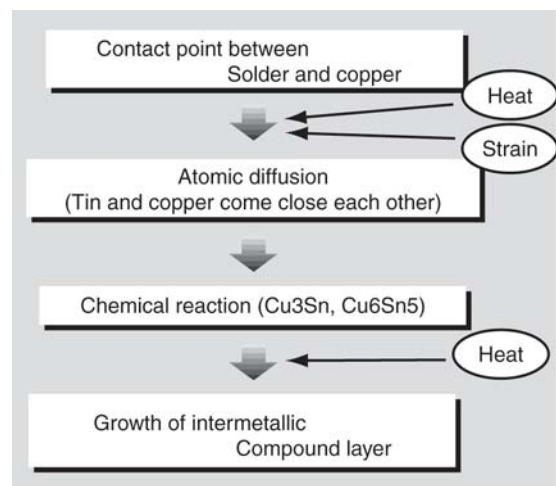


Fig. 11 Mechanism of the growth of an intermetallic compound layer

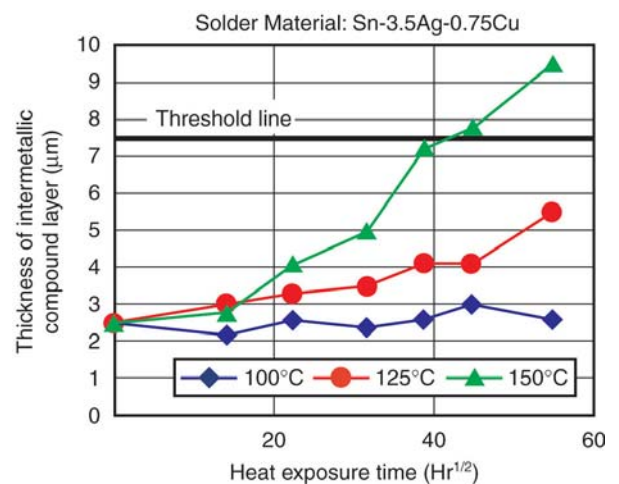


Fig. 12 Growth pattern of the intermetallic compound layer

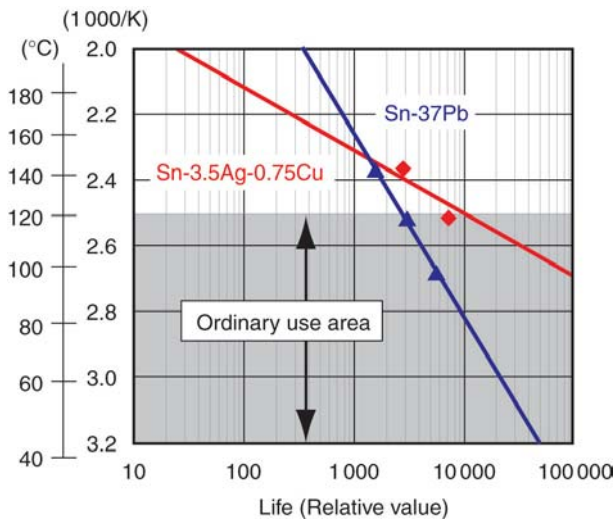


Fig. 13 Limit line of durability of the intermetallic compound layer fracture

Fig. 11 shows the mechanism of the growth of an intermetallic compound layer. It is apparent from this that heat is a factor in degradation, and an isothermal soak test is optimal for the acceleration test. Chip resistors (size 3216) were mounted on a glass-epoxy substrate and allowed to soak under isothermal conditions at the three levels of (1) 150 °C, (2) 125 °C, and (3) 100 °C. The results of this testing are shown in Fig. 12. Fig. 13 is a life chart that has plotted the lifeline point at 7.5 μm . It is apparent from this that Sn-Ag-Cu solder has reliability equal to or better than that of Sn-Pb solder in the ordinary use temperature region.

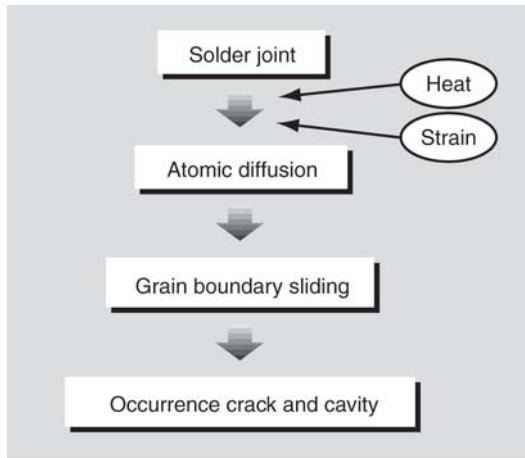


Fig. 14 The creep fracture mechanism

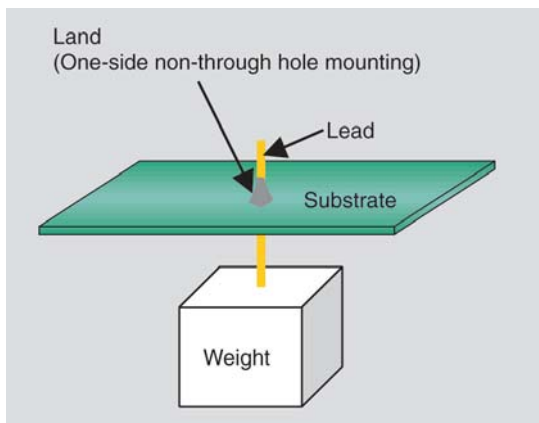


Fig. 15 Creep test method

2.3. Creep

The low melting point of solder means that care must be taken against creep damage even at ordinary temperatures, just as with resin and rubber.⁽¹⁾ Fig. 14 shows the mechanism of creep occurrence, for which the degradation factors are heat and strain. The test piece shown in Fig. 15 was subjected to an isothermal soak test at 125 °C. The results are shown in Fig. 16. It is apparent that the fracture time is superior to that of Sn-Pb solder by two digits of magnitude or more.

2.4. Vibration Damage

A Plastic Leaded Chip Carrier (PLCC), which is capable of high load settings, was used as the test piece and subjected to vibration testing by the method shown in Fig. 17. The environmental temperature was kept at 125 °C, the frequency of the base of the vibrator at 100 Hz, and the acceleration at 25 G, and the weight of the load attached to the back of the PLCC was varied at several levels. Acceleration sensors were attached to the base of the vibrator and to the PLCC to verify that they were vibrating at the same amplitude and phase. The results are shown in Fig. 18.⁽¹⁾⁽²⁾

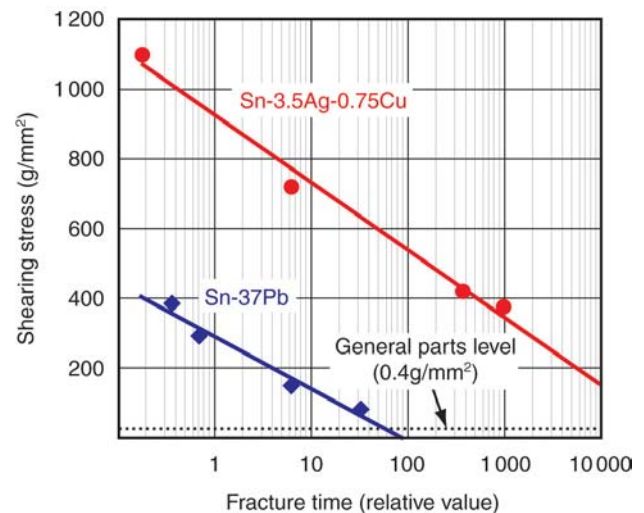


Fig. 16 Creep fracture life chart

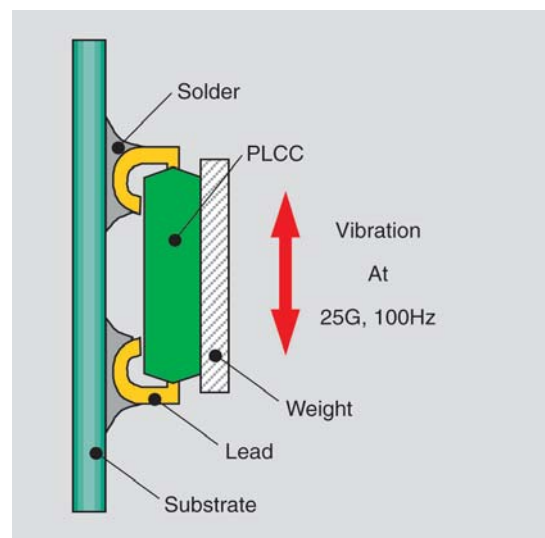


Fig. 17 Vibration test method

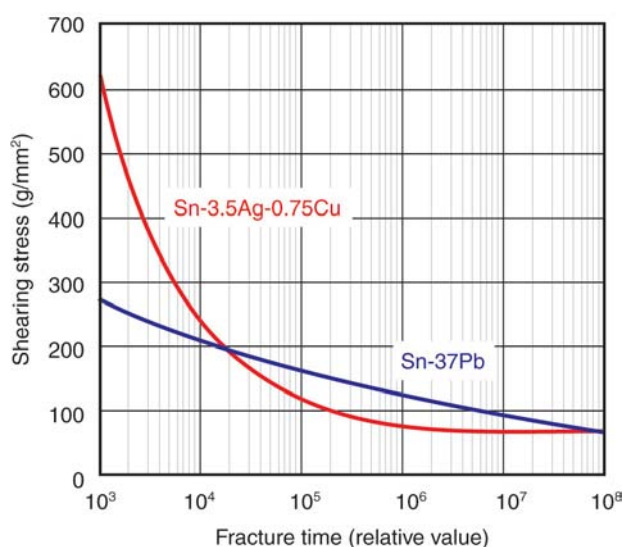


Fig. 18 Breakage probability life curve

The S-N diagram (10% breakage probability life curve) shows the shearing stress applied to the joint on the vertical axis, and the number of cycles to fracture (the life) on the horizontal axis. The shearing stress values converge where the number of cycles is greater. This is the phenomenon of the so-called fatigue limit. It can be determined that, although the Sn-Ag-Cu solder exhibits a different pattern than the Sn-Pb solder, their fatigue limits are at the same level.

2.5. Ionic Migration

Ionic migration is the phenomenon that occurs when voltage applied in an environment of heat and humidity results in the metal between the electrodes on the printed wiring board solving out onto the insulation layer and forming dendrites (also known as whiskers). Repeated

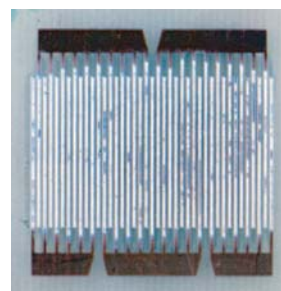


Fig. 19 Sample for ionic migration test

occurrence of this phenomenon can lead to a short circuit. The three degradation factors in ionic migration are humidity (environmental), electrolytic strength (voltage), and temperature. The interaction of these three factors determines the short circuit durability.

The JIS II comb-shaped electrode shown in Fig. 19 was first pre-fluxed, and then cleaned. The soldered specimen was then tested under the following conditions: (1) High-temperature and high-humidity: 85 °C, 85% RH, bias voltage of 50 V applied for 1,000 hours, and then (2) dew cycle: 5 °C – 25 °C, 20 minutes each, bias voltage of 50 V applied for 1,000 cycles. These test conditions are harsher than the conditions of the actual usage environment, and the results showed that no ionic migration occurred in either the Sn-Pb solder and the Sn-Ag-Cu solder.

The reliability of the Sn-Ag-Cu solder was evaluated from the reliability engineering perspective, under the five solder degradation modes: (1) thermal fatigue, (2) growth of intermetallic compounds, (3) creep, (4) vibration fatigue, and (5) ionic migration. Miner's law and other methods were also applied to evaluate market life for all the degradation modes. The results verified that Sn-Ag-Cu solder has reliability equal to or better than Sn-Pb solder.

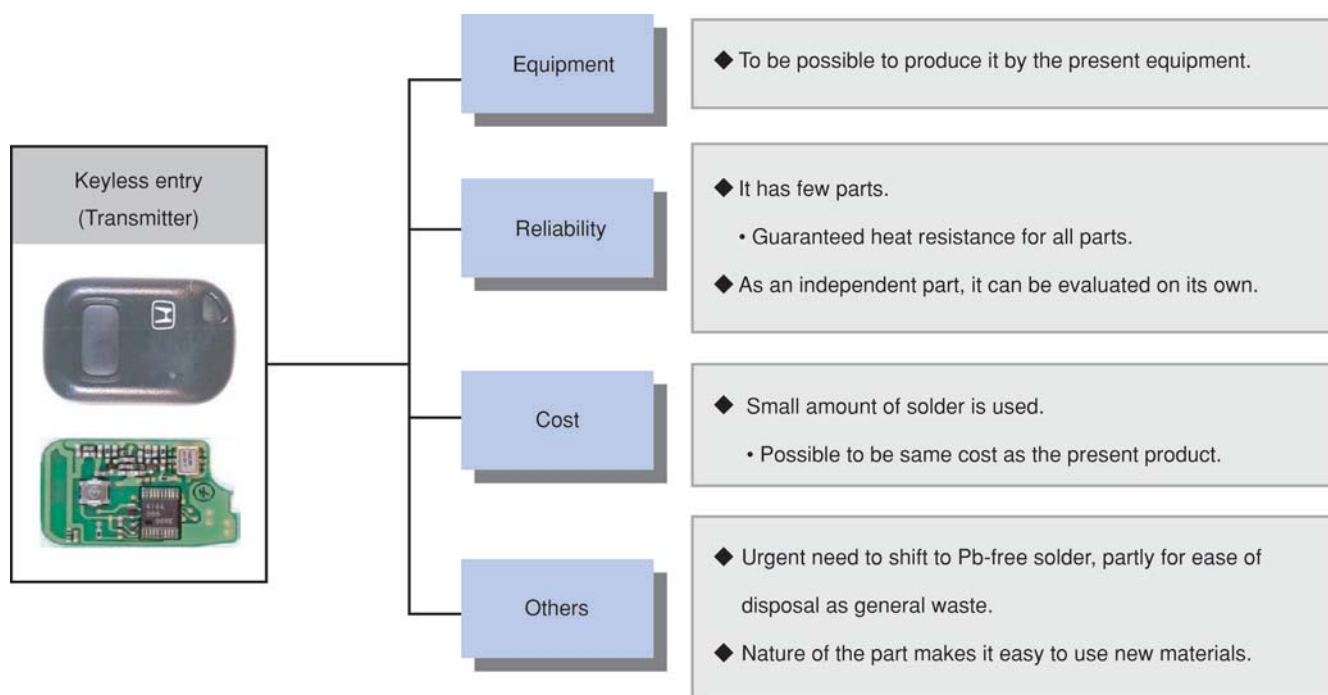


Fig. 20 Reasons for selection of keyless entry (transmitter)

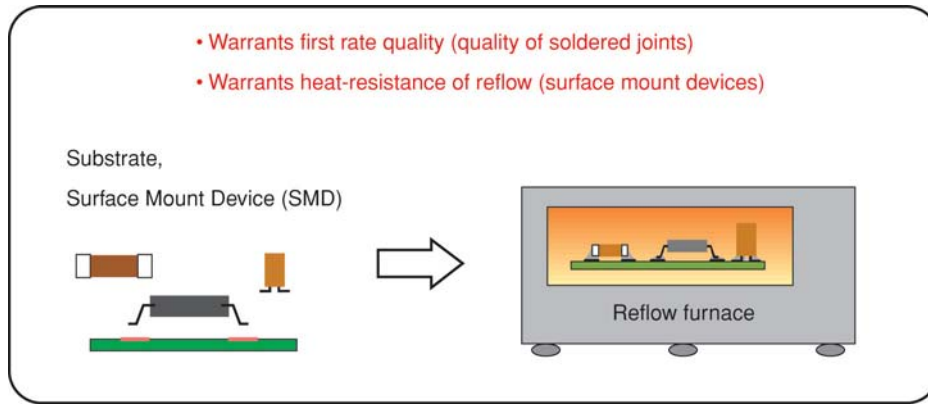


Fig. 21 Reflow soldering process

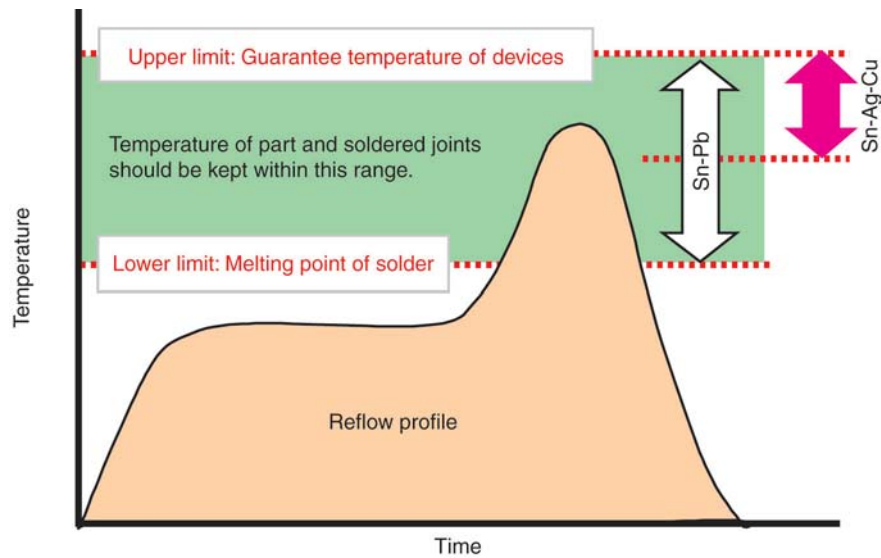


Fig. 22 Temperature profile of reflow soldering

3. Application in Products

Having verified that Sn-Ag-Cu solder has reliability equal to or better than the current mass-produced Sn-Pb solder, the use of lead-free solder applied to products was investigated. The product selected for application was the keyless entry transmitter, for the reasons shown in Fig. 20.

Fig. 21 shows a conceptual view of the reflow soldering process involved.

3.1. Solution of Solder Mounting Issues

The most difficult issue in applying Sn-Ag-Cu solder to a product is that it has a significantly higher melting point (219 °C as opposed to 183 °C) than Sn-Pb solder. In other words, the product must be manufactured within a narrower reflow temperature control range than is required with Sn-Pb solder in order to maintain the quality of the solder joint within the guaranteed heat resistance temperature of the product components. Fig. 22 shows the reflow soldering conditions that resolved this issue for Sn-Ag-Cu solder.

There is only slight variation in component temperatures when reflow soldering on the keyless entry transmitter because of the small number of component parts and the minor differences in the size of those parts. Consequently, it was possible to identify the conditions that would assure

solder quality and component parts quality without making any alteration to the existing reflow equipment used with Sn-Pb solder.

3.2. Results of Product Performance Evaluation

In order to judge whether Sn-Ag-Cu solder provides satisfactory product performance, reliability evaluations were conducted on all specifications of the keyless entry transmitter that require reliability. The results verified that Sn-Ag-Cu solder provides the reliability required for the keyless entry transmitter, and also that it has reliability equal

Table 2 Results of model spec test

Test Item	Result
Thermal cycle	OK
Heat resistance	OK
Switch endurance	OK
Transmission performance	OK
General performance	OK

to or better than the conventional Sn-Pb solder and is suitable for use with the keyless entry transmitter. Table 2 shows selected results from the product performance evaluation. Thermal fatigue is crucial to the reliability of solder, and the evaluation results on this item will be explained in further detail in section 3.2.1.

3.2.1. Thermal fatigue

Thermal fatigue, which is considered to be the most severely demanding criterion in solder reliability evaluation, was evaluated at the lower limit of the solder joint quality obtained under manufacturing conditions that allow mass production. This was also done to predict thermal fatigue life of the joints. The results verified that no cracking occurred due to thermal fatigue in the Sn-Ag-Cu solder joint, and that the thermal fatigue life was sufficient.

Fig. 23 and Fig. 24 show the results of the observation of solder joint cross-cut sections after thermal fatigue testing. Fig. 25 shows a graph of the predicted thermal fatigue life.

4. Conclusion

- (1) The reliability of lead-free soldering was evaluated from the perspective of reliability engineering for the five solder degradation modes of (1) thermal fatigue, (2) growth of intermetallic compounds, (3) creep, (4) vibration fatigue, and (5) ionic migration. The results verified that Sn-Ag-Cu solder has reliability equal to or greater than Sn-Pb solder.

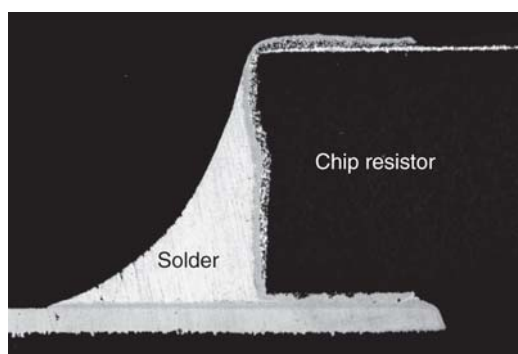


Fig. 23 Sn-Ag-Cu alloy solder cross-cut section (After the thermal cycle test)

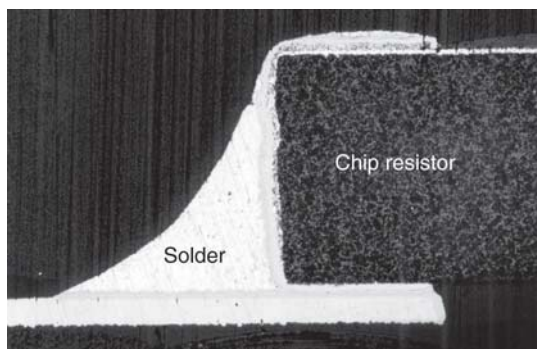


Fig. 24 Sn-Pb alloy solder cross-cut section (After the thermal cycle test)

- (2) With its high reliability verified, Sn-Ag-Cu solder was applied to a keyless entry transmitter. In order to hold down costs when using this solder on a product, it was decided not to alter the equipment or the component designs, and regardless, the results obtained were satisfactory in terms of product quality, product performance, and durability.

5. Postscript

The reliability of lead-free solder has previously been reported in the Technical Review (Vol. 12, No. 1).⁽⁵⁾ Where that research performed evaluation of test pieces with bare-chip die bonding, the present research was conducted on the assumption that ordinary mounting substrate would be used, and reliability evaluation was also conducted. The two research projects yielded wide-ranging information on the reliability of lead-free solder.

At present, the adoption of lead-free household electrical appliances is spreading, and the lead-free movement not only for solder materials but also for treatment of electrode surfaces in component parts is making progress.

The solder material being used is converging on the same Sn-Ag-Cu solder used in the present research. For treatment of the electrode surfaces of component parts, however, there is growing use of Sn-Bi plating with a low Bi concentration (4% or less) for semiconductors and aluminum electrolytic capacitors as a measure to improve the solder wettability and prevent whisker formation between the leads. The present research verified that items plated with Sn-Bi10% showed reduced reliability in thermal fatigue testing. Therefore, care is required when mixing in parts that have Sn-Bi plating.

The change to lead-free automotive electronic devices has progressed with the gradual introduction of lead-free mass-production products starting in August 2000. Meanwhile, Honda has used lead-free solder for the first time in keyless transmitters for models such as the Odyssey and Avancia. Mass production of these products was initiated in August 2001 by Honda Lock MFG. Co., Ltd. With these keyless transmitters having opened the way, the adoption of lead-free automotive electronic devices can be expected to expand steadily.

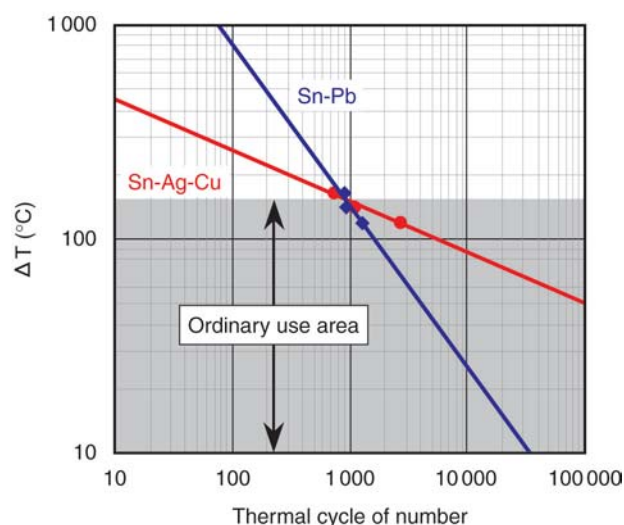


Fig. 25 Limit line of durability of thermal fatigue (chip resistor)

6. Acknowledgements

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References

- (1) Masato MORIYAMA, et al., "Reliability of Solder Joints in Automotive Electronic Devices," Honda R&D Technical Review, Vol. 9, pp. 156 – 166 (1997).
- (2) Junichi OHMURA, et al., "Research in Lead-free Solder Mounting of Automotive Electronic Devices," Japan Welding Society Mate '2000, pp. 307 – 312 (2000).
- (3) Japan Standards Association, ed., *Microelectronics Test Methods and Procedures*, Japan Standards Association, Tokyo (1987).
- (4) Jennie S. HWANG, "Solder Paste for Electronics Packaging," pp. 283 – 309, Kogyo Chosakai, Tokyo (1991)
- (5) Toshihiro OOKAMA, et al., "Reliability Evaluation of Lead-free Solder Joints in the Automotive Environment," Honda R&D Technical Review, Vol. 12, No. 1, pp. 137 – 144

■ Authors ■



Tsunehisa HATA



Junichi OHMURA



Masato MORIYAMA



Tomoo WATANABE