Reliability of Solder Joints Assembled with Lead-Free Solder

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To protect the natural environment, we will introduce the use of lead-free solder instead of the current tin-lead solder in the assembly of printed circuit boards in electronics equipment. During the transition to lead-free soldering, these two types of solders will be used in combination in joints. After the transition, a new element, bismuth, from components will contaminate the lead-free solder joints. We investigated the two types of solder through dynamic mechanical examination and concluded that lead-free solder can be used in combination with the current tin-lead solder and on its own to form sufficiently reliable joints.

1. Introduction

Current tin-lead solders, for example, Sn-37Pb, have a high reliability due to their good mechanical properties and are used for assembling printed circuit boards in electronics equipment. However, they have recently been recognized as a source of lead pollution.

The European Union has adopted a directive to restrict the use of certain hazardous substances in electrical and electronic equipment starting in 2006 to minimize their threat to human health. The lead in current solders is included among the hazardous substances,[1] so to meet the European directive, the solder and components of printed circuit boards must be lead-free. Some representative lead-free solders that are now being used for Surface Mount Technology (SMT) are the tin-silver-copper alloys such as Sn-3Ag-0.5Cu.[2] Also, tin-lead balls are being replaced with tin-silver-copper balls in the Ball Grid Array (BGA) packages in SMT (**Figure 1**). In the case of the Quad Flat-leaded Package (QFP) (**Figure 2**), tin-lead plating of the leads is being replaced with tin-bismuth or tin-copper plating, which has comparable solderability to tin-lead solder.

During the transition to lead-free solders, we can expect to see printed circuit boards that have both types of solders. For example, BGA

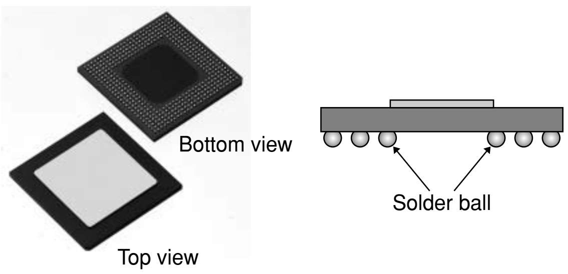

Figure 1
Photograph and schematic of Ball Grid Array (BGA) package.

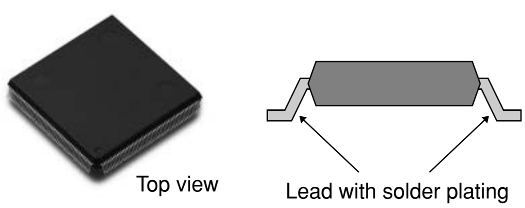

Figure 2
Photograph and schematic of Quad Flat-leaded Package (QFP).

packages with tin-lead balls and QFPs with tin-lead-plated leads could be mounted with tin-silver-copper solder, and conversely, BGA packages with tin-silver-copper balls and QFPs with lead-free-plated leads could be mounted with tin-lead solder. Also, after the transition, the tin-silver-copper solder joints of QFPs will become contaminated with bismuth from tin-bismuth plating on the leads of QFPs.

The differences in the thermal expansion rates of components and printed circuit boards causes solder joints to undergo elastic and plastic deformations, and when these deformations are repeated, the solder can harden, causing solder cracks and eventual joint failure.[3)]

We studied the dynamic mechanical properties of tin-silver-copper and tin-lead solders by subjecting solder samples to twisting cycles.[4),5)] Then, we investigated the fatigue life of these solders and the solder mixtures that would occur in BGA solder joints during the transition to lead-free soldering. Finally, we evaluated the influence of bismuth on the fatigue life of tin-silver-copper joints securing QFPs having tin-bismuth-plated leads. This paper describes this work.

2. Procedure

We measured the dynamic mechanical properties of the solders using the method shown in **Figure 3**. A 30 × 10 × 0.6 mm solder sample was inserted between an electric motor and an axial stress transducer that was fixed with respect to the motor casing. We applied power to the motor to subject the sample to shear stress, and recorded the resulting transducer output. Then, we used the recorded data to determine the dynamic viscoelasticity of the sample during the test.

Solder undergoes both elastic and plastic deformation under stress, and the behavior can be expressed in terms of dynamic viscoelasticity and the shear modulus G', which is similar to Young's modulus for tension, but indicates the ratio of a shear stress to its resulting shear strain. The ratio of plastic deformation and elastic deformation, tanδ, is related to the cumulative fatigue of the solder.

The measurements were performed in a thermal chamber to clarify the temperature dependence (**Figure 4**). The thermal chamber had a heater and a cooler operating on liquid nitrogen. We investigated the temperature dependence of the dynamic mechanical properties from −65 to 125°C.

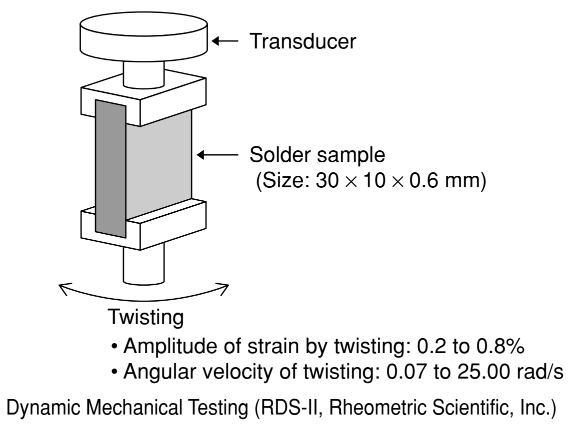

Figure 3
Measurement of dynamic mechanical properties of solder.

3. Results and discussions

3.1 Dynamic mechanical properties at twisting

3.1.1 Temperature dependence of dynamic mechanical properties

Figure 5 shows the temperature dependence of the shear modulus in current tin-lead and tin-

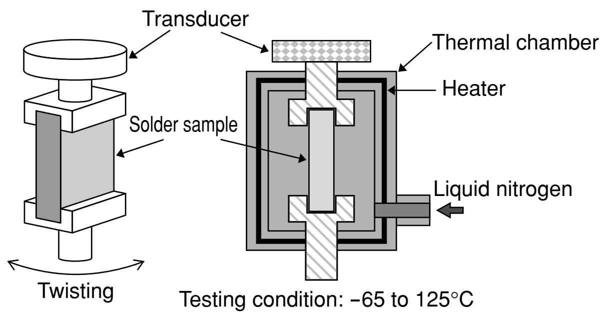

Figure 4
Measurement in the thermal chamber.

silver-copper solders from –65 to 125°C. Although the shear modulus of both solders decreased with rising temperature, there was a large difference in the rate of decrease. The rate of decrease of the tin-lead solder was larger than that of the tin-silver-copper solder, and the G' of tin-lead solder at 125°C was 1/10 that of the tin-silver-copper solder.

This indicates that tin-lead solder softens faster than tin-silver-copper solder when the temperature increases.

Figure 6 shows the temperature dependence of the ratio of plastic deformation to elastic deformation, tanδ. The figure shows that tanδ of the tin-silver-copper solder is four times smaller than that of the tin-lead solder.

This means that the tin-silver-copper solder is harder to deform than the tin-lead solder and therefore less likely to harden.

3.1.2 Influence of twisting velocity on dynamic mechanical properties

Figure 7 shows the shear modulus, G', in current tin-lead and tin-silver-copper solders for twisting velocities from 0.07 to 25 rad/s. In the region above 1 rad/s, the shear modulus of the tin-lead solder increases in parallel with that of the tin-silver-copper solder. Below 1 rad/s, the shear moduli slowly separate.

This indicates that the tin-lead solder deforms easily at twisting velocities below 1 rad/s, which is the range of twisting velocities that solder joints are subjected to in normal equipment

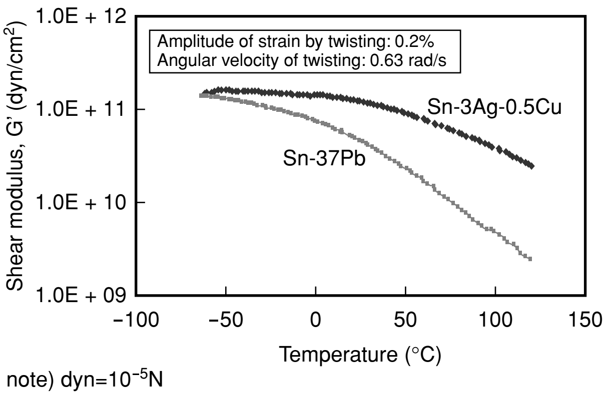

Figure 5
Temperature dependence of shear modulus.

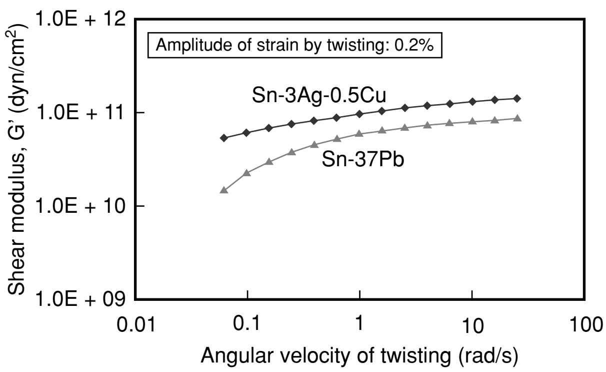

Figure 7
Angular velocity of twisting vs. shear modulus.

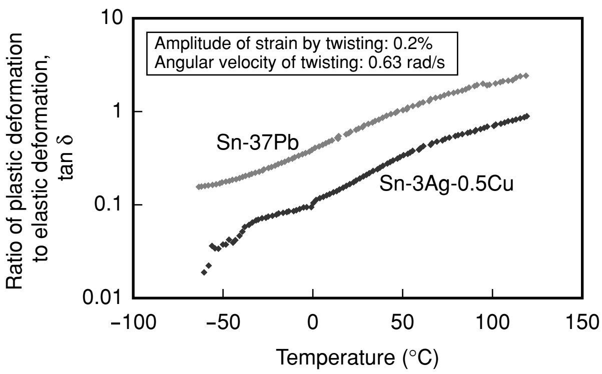

Figure 6
Temperature dependence of tanδ.

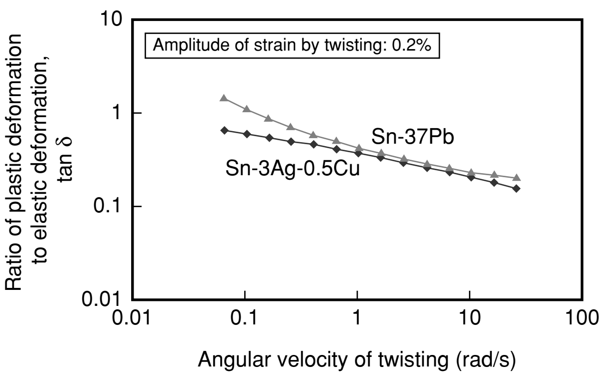

Figure 8
Angular velocity of twisting vs. tanδ.

operation.

Figure 8 shows the ratio of plastic deformation and elastic deformation, tanδ, versus the twisting velocity. In the region above 1 rad/s, tanδ of both solders was the same. However, below 1 rad/s, tanδ of the tin-lead solder increased at a different rate than that of the tin-silver-copper solder. Therefore, the tin-silver-copper solder is difficult to deform plastically and is less likely to harden.

3.2 Fatigue life of solders subjected to twisting cycles

3.2.1 Tin-silver-copper solder and tin-lead solder

Figure 9 shows how the G' of current tin-lead and tin-silver-copper solders changes over cycles of twisting. The rapid drops in the shear moduli indicate the fatigue life; that is, the point where the samples broke. The fatigue life of the tin-silver-copper solder was about 10000 cycles, which is about twice the fatigue life of the tin-lead solder. As in the twisting test, these results suggest that compared to the tin-lead solder, the tin-silver-copper solder is harder to deform plastically and therefore less likely to harden. We therefore concluded that the tin-silver-copper solder has sufficient fatigue resistance for use in electronics assembly.

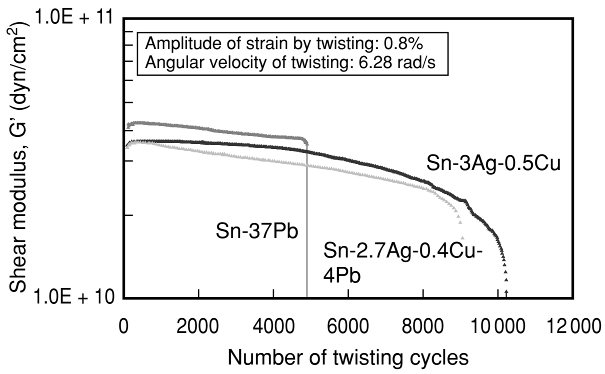

Figure 9
G' of tin-lead and tin-silver-copper solders subjected to twisting cycles.

3.2.2 Solder ball joints of BGA packages during transition to lead-free soldering

The BGA package has solder balls on its bottom surface that function as I/O terminals for connection to a printed circuit board. These balls have a diameter of about 800 µm and a pitch of 1.27 mm. The solder paste printed onto boards using a metal mask is generally 150 µm thick. The ratio of solder in the printed paste to solder in the balls is about 1 to 10 by volume. Therefore, the weight composition of a joint made with Sn-37Pb paste and Sn-3Ag-0.5Cu balls should be about Sn-2.7Ag-0.4Cu-4Pb.

The change in G' of this solder mixture over cycles of twisting is shown in Figure 9. Although mixing tin-silver-copper solder with tin-lead solder reduces the fatigue life, as the figure shows, the fatigue life only fell by 10% and was still superior to that of the tin-lead solder. We therefore considered that the reliability of the mixed solder joint was sufficient.

3.2.3 Solder joints of QFPs after transition to lead-free soldering

QFP leads are solder-plated to a thickness of about 10 µm. After the transition, these leads will be plated with lead-free solder. We determined that when the printed solder paste is 150 µm thick, the joints will be contaminated with 10% by volume of the lead-free solder plating. Therefore, if the composition of the plating is Sn-2Bi, the concentration of bismuth in the solder joint will be about 0.2% by weight.

Figure 10 shows the G' of tin-silver-copper solders containing 0.5% and 1.0% by weight of bismuth over multiple cycles of twisting. We can see that even though a 0.5% addition of bismuth caused an approximate 30% reduction in fatigue life, the fatigue life was still superior to that of the tin-lead solder analyzed in Figure 9.

We therefore concluded that tin-silver-copper solder joints with the expected level of bismuth contamination will have a fatigue life comparable to that of joints made using current tin-lead solders.

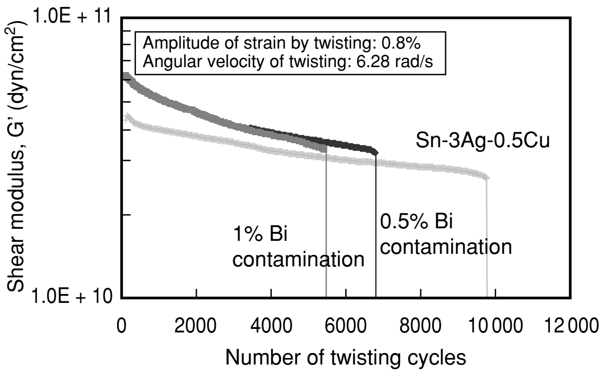

Figure 10
G' of tin-silver-copper solder contaminated with bismuth subjected to twisting cycles.

4. Conclusion

This paper described our approaches to clarifying the dynamic mechanical properties and reliability of tin-silver-copper solder joints both during and after the transition to lead-free soldering of printed circuit boards in electronic equipment.

We found that:

1) Compared to current tin-lead solder, tin-silver-copper solder is harder to deform, is more resistant to hardening, and therefore has a longer fatigue life.
2) During the transfer to lead-free soldering, lead solders and lead-free solders will be used in combination in BGA ball joints. As a result, the fatigue life will be slightly lowered but will still be satisfactory.
3) After the transition, QFP joints will be contaminated with lead-free solder plating from the leads of QFPs. This will slightly reduce the fatigue life, but it will still be comparable to that of joints made using current tin-lead solders.

We will continue by investigating another lead-free solder, tin-zinc solder, which has the advantage of having a lower melting point than tin-silver-copper solder.

References

1) Current Status of Draft EC WEEE Directive, *http://www.lead-free.org/legislation/detail/ec-weee-current-status.html.*
2) Japan Electronics and Information Technology Industries Association (JEITA), Report of Lead-free Solder Project, 2000.
3) R. Satoh et al.: Thermal Fatigue Life of Pb-Sn Alloy Interconnections. *IEEE Trans. on Components, Hybrids, And Manufacturing Technology*, **14**, 1, p.224-232 (1991).
4) H. Yamada et al.: MECHANICAL PROPERTIES OF Sn-Pb SOLDER AND ELASTIC-PLASTIC-CREEP FINITE ELEMENT ANALYSIS OF SOLDER JOINTS. FATIGUE'96, 1996, p.1117-1122.
5) H. Yamada and K. Ogawa: Evaluation for Thermal Fatigue Life of Solder Joints in Electronic Components (in Japanese). Toyota Central R&D Labs. *R&D Review*, **31**, 4, p.43-52, 1996.

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