Tensile Mechanical Properties of Miniature Size Specimen for Sn-3.5Ag Solder at High Temperature

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Citation

Abstract
This study discusses a tensile testing method for a miniature size specimen and specimen size effect on mechanical properties of solders. A miniature size specimen, which has 5mm in diameter of parallel gage part, was proposed in order to reduce the material cost and to investigate specimen size effect on mechanical properties. Since displacement measuring instruments might give unexpected load or unexpected damage to the miniature size specimen, a new type strain measuring method, which uses a non-contact band laser, was also proposed to obtain accurate stress-strain relationship and accurate mechanical properties. Tensile tests were conducted at 313K with 2.0%/s high strain rate to except creep deformation during tensile loading. There was little tensile strength difference between the miniature size specimen and the present bulk type specimen. On the other hand, there was elongation difference between the miniature size specimen and the present bulk type specimen. The reason for smaller elongation in the miniature size specimen is that smaller reductions of area were occurred for the smaller diameter specimen.

1. Introduction
Soldering is an important industrial technique for electronic device mounting. It is well known that Sn-Pb solders are not permit to use because it contains lead, which is a harmful element to environment and human health [1]. There are many kinds of candidate lead-free solder and it is needed to understand their mechanical properties and cyclic fatigue life for using these solders in practice [2-10]. Tensile test is a most popular and important evaluation method for these materials because tensile strength, elongation, proof stress and Young’s modulus are necessary material properties for commercial products design and numerical analysis.

A testing standards for solders also had been published by The Society of Materials Science, Japan in order to unify the testing method such as shape and dimensions of the specimen, heat treatment condition and testing apparatus [11-14]. The specimen for tensile test had been defined as round bar type with 10mm in diameter and the specimen must be machined from huge size casted ingot in order to remove the influence of segregation. Since the casted solder ingot has 40mm in diameter and 200mm in length, it may need huge amount of solder materials for making the specimen.

Size miniaturizing is the most effective for material cost reducing and investigating specimen size effect on mechanical properties, but there are no testing standard and no established testing method. We have developed a newly type tensile testing method at high temperature with a miniature size specimen, which has 5mm in diameter, in order to reduce the amount of material. Tensile testing method and technique with the miniature
size specimen for solders at high temperature was proposed in this study to establish the low cost tensile test. Tensile test with the miniature size specimen also can investigate the specimen size effect on mechanical properties of solders.

2. Experimental Procedure

2.1. Miniature Size Specimen

The new type miniature size specimen, which was designed by numerical analysis, was a solid bar with 5mm in diameter and 30mm in parallel part length as shown in Fig. 1. The 5mm type specimen reduces the material volume for making a casted ingot one-tenth than that of present standard bulk type specimen, which has 10mm in diameter.

Material tested in this study was Sn-3.5Ag lead-free solder of which the chemical compositions and heat treatments are listed in Table 1. Specimens were annealed at 0.87Tm for one hour before tensile tests to stabilize the microstructure of the solder, where Tm is a melting point temperature. Casting of ingot, machining and heat treatment of the specimens were exactly followed to the present testing standard of solders issued by The Society of Materials Science, Japan [11-14].

<table>
<thead>
<tr>
<th>Chemical Composition (mass%)</th>
<th>Sn</th>
<th>Pb</th>
<th>Sb</th>
<th>Cu</th>
<th>Bi</th>
<th>Fe</th>
<th>As</th>
<th>Cd</th>
<th>Ag</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sn-3.5Ag</td>
<td>Bal.</td>
<td>0.0096</td>
<td>0.0077</td>
<td>0.0005</td>
<td>0.012</td>
<td>0.0061</td>
<td>0.001</td>
<td>0.0001</td>
<td>3.51</td>
</tr>
</tbody>
</table>

Heat treatment: 430K×1h air cooling

2.2. Experiment Apparatus

SHIMADZU AGX-250kN with 5kN small capacity load cell unit was used for tensile loading. Displacement and strain of the specimen were measured by two kind of method. One is strain gage method, which uses two pieces of small size strain gages attached to the surface of the specimen. The other is a newly developed non-contact displacement measuring method, which uses band laser. The band laser measures the relative displacement of one pair of small target pins, which were attached to the surface of the specimen with 25mm in gage length. Fig. 2 shows general view of the measuring apparatus with furnace. The furnace can heat the specimen temperature up to 393K by using four 300W cartridge type heaters. Narrow gap between two parts of the furnace was designed for non-contact measuring. The band laser goes pass through the narrow gap of the furnace from the laser projector side to the receiver side and measures relative displacement of the small target pins inside of the furnace.

Tensile tests were conducted at 313K in this study. Temperature of the specimen was measured and controlled by type-K thermocouple attached to the lower pull rod. We had confirmed in advance that temperature distribution and variation of specimen gage part during the test were corresponding with the present testing standards even though specimen might be elongate 200%.

2.0%/s tensile strain rate was used for tensile loading in order to except creep influence or creep damage on stress-strain relationship during the tensile loading at high temperature.

3. Results and Discussion

3.1. Specimen Size Effect on Stress-Strain Curve

Figure 3 shows stress-strain relationship curves of the miniature size specimen for Sn-3.5 lead-free solder at high temperature. A present bulk type specimen data [15], which
has 10mm in diameter, was also plotted with dotted line as a reference. These results curves indicate that displacement of the miniature size specimen could be measured by newly developed non-contact method precisely.

Maximum tensile strength were observed at 3%-5% strain all of three data. The tensile strength of the miniature size specimen was slightly bigger than that of the bulk type specimen. Elongation of specimen (a), (b) and (c) were 19.0%, 25.8% and 42.6%, respectively. As there are no clear elongation data for bulk type specimen, we can guess it may over 50% from Fig. 3. Elongation of the miniature size specimen was shorter than that of the bulk type specimen. Figure 4 is overview of the specimen after the tests. Fig. 4 (a) is results of the test which had 19.0%, the shortest elongation, (b) and (c) are results of the test which had 25.8%, 42.6% elongation, respectively. The reasons for smaller elongation in the miniature size specimen may that some existed defect in the specimen and smaller reductions of area. Elongation difference among the same shape and size miniature specimen imply that some defect, which had been created while casting, might be existed in the specimen. Even though there is no defect in the miniature size specimen, smaller reduction of the area may leads to smaller elongation for the smaller diameter specimen.

As these specimens had ruptured at parallel gage part shown as Fig. 4, the newly designed shape and dimensions of the miniature size specimen are available for tensile test at high temperature. These results imply that tensile testing technique for the miniature size specimen was developed, especially non-contact displacement measuring method at high temperature, but there are still unsolved subjects to establish casting technique for small size soldering ingot without defect.

3.2. Specimen Size Effect on Mechanical Properties

Table 2 and Fig. 5 show the effect of specimen size on mechanical properties. Fig. 5 (a) depicts relationship between specimen size and tensile strength. Tensile strength of the miniature size specimen (φ =5mm) are almost same as that of the bulk type specimen (φ =10mm) for Sn-3.5Ag lead-free solder. This trend indicates that there is no specimen size effect on tensile strengths.

Table 2. Mechanical properties of Sn-3.5Ag lead-free solder at 313K.

<table>
<thead>
<tr>
<th>Specimen size</th>
<th>φ 5mm (a)</th>
<th>φ 5mm (b)</th>
<th>φ 5mm (c)</th>
<th>φ 10mm*1</th>
</tr>
</thead>
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<tr>
<td>Tensile strength B, MPa</td>
<td>44.9</td>
<td>47.0</td>
<td>46.0</td>
<td>42.0</td>
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<tr>
<td>Elongation δ, %</td>
<td>19.0</td>
<td>25.8</td>
<td>42.6</td>
<td>51.2</td>
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<tr>
<td>Proof stress 0.02%, MPa</td>
<td>18.6</td>
<td>45.8</td>
<td>6.8</td>
<td>20.1</td>
</tr>
<tr>
<td>Young’s modulus E, GPa</td>
<td>33.8</td>
<td>69.2</td>
<td>36.7</td>
<td>46.1</td>
</tr>
<tr>
<td>Reduction of area φ %</td>
<td>61.6</td>
<td>87.8</td>
<td>92.2</td>
<td>No data</td>
</tr>
</tbody>
</table>

(*1 Ref. [15])

Fig. 5 (b) depicts relationship between specimen size and elongation. Elongation of the miniature size specimen is smaller than that of the bulk type specimen. The reason for smaller elongation of the miniature size specimen is that small reductions of area were occurred for small diameter specimen. There are also elongation data scatter even though same miniature size specimen. Figures 6 (a), (b) and (c) are photograph of fracture surface after the test for specimen No.(a), (b) and (c), respectively. As some void were observed in the fracture surface of specimen No.(a), shorter elongation of specimen No.(a) might be caused by existed void. These results imply that establishment of casting technique for miniature size ingot is needed.

Fig. 5 (c) shows the effect of specimen size on proof stress, which were measured and calculated by using strain gage data. Solders are so soft material and have so small proof stress that 0.02% proof stress are usually adopted for designing instead of 0.2% proof stress [12]. Fig. 5 (d) shows Young’s modulus measured by using strain gage data. There are data scatter in the miniature size specimen for both proof stress and Young’s modulus even though same specimen size. Figure 7 is enlarged stress-strain relationship, where strain gage data were plotted for strain. Although stress-strain curves of (a) and (c) are almost same, (b) had a larger slope than the other at elastic strain range and ruptured at just over 0.2%. Because of there was also no strain gage trace on the surface of specimen No.(b) after the test, strain gage attached to the surface of
specimen might fell down at early stage of tensile test due to lack of adhesive strength.

Average of proof stress and Young’s modulus for miniature size specimen in Figs. 5 (c) and (d) were calculated as average of specimen No.(a) and No.(c) in order to preclude uncertain strain gage data of No.(b). Average of proof stress and Young’s modulus are 12.7 MPa and 35.5 GPa, respectively. Proof stress of the miniature size specimen was smaller than that of bulk type specimen slightly. Young’s modulus of the miniature size specimen was also smaller than that of bulk type specimen slightly. As the measuring and calculating method for proof stress or Young’s modulus of the miniature size specimen is not established now, more sufficient experiment and data analysis is needed.

**Fig. 5.** Effect of specimen size on mechanical properties for Sn-3.5Ag lead-free solder.

**Fig. 6.** Fracture surface after tensile test.
4. Conclusions

(1) A newly type tensile testing method of the miniature size specimen at high temperature was established. A non-contact band laser measures displacement of the miniature size specimen.

(2) There was little tensile strength difference between the miniature size specimen and the bulk type specimen. These results indicated that tensile test with the miniature size specimen are useful for investigate the tensile strength of solders.

(3) There was specimen size effect on elongation. Elongation of the miniature size specimen was smaller than that of the bulk type specimen.

(4) Proof stress and Young’s modulus of the miniature size specimen were smaller than that of bulk type specimen. But more sufficient experiment and data analysis is needed to confirm specimen size effect on these mechanical properties.

References


