Charpy impact properties of diffusion bonded joints of alumina dispersion strengthened copper to 316 stainless steel

Nishi H.(1), Muto Y.(2), Eto M.(1)
(1) Japan Atomic Energy Research Institute, Japan
(2) Tokai Research Establishment, JAERI, Japan

ABSTRACT Instrumented Charpy impact tests and slow-bend Charpy tests of diffusion bonding joints were performed to compare fracture behavior under the impact and static loads. Moreover elasto-plastic analyses were carried out in order to clarify the fracture behavior for the tensile and V-notch specimens. The bonding strength of joints was smaller than that of DS Cu. The degradation of Charpy strength of joints caused by not only the bonding strength but also the mechanical heterogeneity of bonded zone.

1. Introduction

The development of energy technology, such as gas turbine system and fusion power plants, will require improvements in the performance of materials that can resist high temperatures. Alumina dispersion-strengthened copper (DS Cu) has recently developed[1,2] and is particularly attractive for high temperature components because of its excellent thermal conductivity, strength retention and microstructural stability at elevated temperatures. The DS Cu is therefore a good candidate material for the generative heat exchanger of gas turbine and the first wall of a fusion experimental reactor. These applications require bonding of the DS Cu to austenitic stainless steel.

Hence we have carried out research on the tensile and impact strength of diffusion bonding joints between the DS Cu and 316 stainless steel.[3] In the previous studies, the tensile strength of the joints was as large as that of DS Cu base metal, however, the Charpy impact strength of the joints was considerably lower than that of DS Cu. The Charpy impact test is generally useful for characterizing the transition from ductile to brittle fracture behavior under varying conditions of temperature and loading rate. The brittle fracture, likely to lead the degradation of the Charpy impact strength, might be caused by the dynamic deformation, because the strength of joints were sensitive to the loading rate.[4,5] In this investigation, instrumented Charpy impact tests and slow-bend Charpy tests with V-notch specimens of joints
were performed to compare the fracture behavior under the impact and static loads. Moreover fracture surfaces of the broken specimens were examined by scanning electron microscope. As the results, both tests exhibited almost the same fracture behavior. Then, elasto-plastic analyses of the tensile and the V-notch specimens were carried out using FEM in order to clarify the fracture behavior of the tensile and the slow-bend Charpy specimens.

2. Procedures of experiments and FEM analyses

2.1 Materials

The 316 stainless steel and DS Cu, GlidCop Al-15, were commercial grade materials. Their chemical compositions are listed in Table1. The DS Cu contained about 0.3% of Al₂O₃ dispersoids [1,2] and was 20mm thick plate, which received 60% of reduction by cold rolling.

A uniaxial hot press was used to the solid state diffusion bonding. The bonding environment of the chamber was a vacuum at 5x10⁻³ Pa or lower. Butt bonding were carried out with the bonding surface perpendicular to the rolling direction of DS Cu under three bonding conditions as shown in Table2. The bonding surfaces were polished to roughness of 0.2 µm and degreased in acetone just prior to the bonding. Every test specimen was machined with bonding interface located at the center of specimen. The tensile tests were conducted with specimen 6mm of diameter at room temperature. The results of tensile tests are added to Table2. The tensile specimens except for joint J1 fractured at the DS Cu region about 10mm apart from the interface. Consequently, joint J2 and J3 had sufficient strength as well as DS Cu. Fig.1 shows micrographs near the interface of joint J3 observed by SEM and TEM. Intermetallic compounds and recrystallization, which might be defect and cause degradation of the strength of joints, were observed near the interface in the DS Cu.

2.2 Procedures of instrumented Charpy tests and slow-bend Charpy tests

Instrumented Charpy impact and slow-bend Charpy tests were conducted using standard V-notch Charpy specimen, 10x10x55mm, at room temperature. Notch of 2mm depth were introduced by milling with a 45° double angle cutter at the interface in respect to joint as shown in Fig.2. The instrumented impact tests were done with a conventional Charpy impact machine (capacity 294J). This machine mainly consisted of a strain-gauged striker and a potentiometer with which the angular position of the pendulum was measured. These strain and angular position were transformed to the load and the deflection of specimen. The slow-bend Charpy tests were conducted with MTS testing machine at a crosshead speed of 0.01mm/s measuring the deflection of load point with LVDT.

2.3 FEM analysis model

The finite element mesh of the tensile and Charpy specimens are shown in Fig.3. The
tensile specimen was modeled by only one-half of specimen using an appropriate symmetry boundary and constructed with isoparametric 8-node biquadratic axisymmetric element. The Charpy specimen was assumed to be in a state of plane strain and was modeled with 3-node element. The elasto-plastic analyses were performed with a computer program ABAQUS, using Young's modulus, Poisson's ratios and stress-strain curves of the 316 stainless steel and DS Cu base metals as shown in Table3 and Fig.4 respectively.

3. Results and discussions

3.1 Instrumented Charpy impact tests and slow-bend Charpy tests

Load-deflection curves of the instrumented Charpy impact tests and the slow-bend Charpy tests of the DS Cu and all joints are shown in Fig.5. The curves of the impact tests resembled those of slow-bend tests, while it is evident that yielding had occurred prior to reaching maximum load. The maximum load and ductility of joints were extremely lower than those of DS Cu for both the instrumented Charpy impact and slow-bend Charpy tests. In particular joint J1 was inferior to DS Cu. Table4 shows the results of absorbed energy, which were calculated by the integration of the load-deflection curves. The absorbed energy of the joints were also smaller than those of DS Cu. In addition, the absorbed energy of the Charpy impact tests almost equaled to those of the slow-bend Charpy tests. The ratio of absorbed energy of the joints to DS Cu was about 20%.

Fig.6 shows micrographs of SEM observation of the fractured surface making comparison between the impact and the slow-bend specimens of DS Cu and joints. The DS Cu exhibited ductile fracture even in the case of the impact tests showing dimple pattern (Fig.6(a)). Both the impact and the slow-bend specimens fractured at the DS Cu near the interface. The impact specimen concerned with fractured surface was similar to the slow-bend specimen (Fig.6(b) and (c)), revealing fine dimple failure pattern at higher magnification as shown in Fig.6(d). These results denote that the degradation of the Charpy impact strength of the joints was not caused by high loading rate of the impact tests.

3.2 FEM analyses

According to the slow-bend tests, the maximum load, ductility and absorbed energy of the joints were considerably smaller than those of the DS Cu, however, the tensile strength of joint J2 and J3 obtained that of DS Cu. Hence elasto-plastic FEM analyses were carried out in order to clarify the deformation related to the strength and strain energy for the tensile and slow-bend test specimens. Fig.7 is contours of the equivalent plastic strain distribution at 5% of nominal strain in tensile test. In the state of plastic deformation, the maximum equivalent strain occurred at the DS Cu several millimeter apart from the interface. These results designate that the tensile specimen fractures at the DS Cu region apart from the interface. On the other hand,
the equivalent plastic strain of V-notch specimen concentrated at the DS Cu near the interface as shown in Fig. 8, in which the specimen was bent up to 0.75mm of the deflection corresponded to the maximum load of the test. The maximum equivalent strain was 125% at the notch surface of DS Cu 0.002mm apart from the interface. In addition to the strain, Fig. 9 shows contours of plastic strain energy density, which resembled the contours of equivalent plastic strain. This strain concentration arose from the mechanical properties of bonded zone in which mechanical heterogeneity between 316 stainless steel and DS Cu existed. Moreover the analysis of slow-bend test for the only DS Cu specimen was done up to 1.1mm of the deflection, at which the maximum load developed according to the test. The maximum equivalent plastic strain of this case was 165%, which was greater than that of joint. These suggested the bonding strength near the interface was smaller than that of DS Cu base metal. Therefore the degradation of Charpy strength of joints comparing to DS Cu caused by not only the mechanical properties of bonded zone but also the bonding strength.

4. Conclusions
   (1) The maximum load, ductility and absorbed energy of the joints were considerably smaller than those of the DS Cu for both the impact and slow-bend tests, though joints had sufficient strength as well as DS Cu. The fractured surfaces of impact and the slow-bend specimen exhibited ductile fracture. The degradation of the Charpy impact strength of the joints was not caused by high loading rate of the impact tests.
   (2) As the results of FEM analyses, the maximum equivalent strain occurred at the DS Cu several millimeter apart from the interface in the state of plastic deformation for tensile test. The equivalent plastic strain of V-notch specimen, however, concentrated at the DS Cu near the interface. These strain concentration arose from the mechanical properties of bonded zone.
   (3) The bonding strength of joints was smaller than that of DS Cu base metal. The degradation of Charpy strength of joints caused by not only the strain concentration of bonded zone but also the bonding strength of joint.

References
Table 1  Chemical compositions of DS Cu and 316 stainless steel (mass%).

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<thead>
<tr>
<th></th>
<th>Al</th>
<th>O</th>
<th>Fe</th>
<th>Pb</th>
<th>B</th>
<th>S</th>
<th>Cu</th>
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<tbody>
<tr>
<td>DS Cu</td>
<td>0.14</td>
<td>0.092</td>
<td>0.007</td>
<td>0.001</td>
<td>0.018</td>
<td>&lt;0.001</td>
<td>Bal</td>
</tr>
<tr>
<td>316 stainless steel</td>
<td>C</td>
<td>Ni</td>
<td>Cr</td>
<td>Mo</td>
<td>Mn</td>
<td>Si</td>
<td>P</td>
</tr>
<tr>
<td></td>
<td>0.03</td>
<td>10.25</td>
<td>16.29</td>
<td>2.10</td>
<td>1.19</td>
<td>0.44</td>
<td>0.32</td>
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Table 2  Conditions of diffusion bonding and their tensile strength.

<table>
<thead>
<tr>
<th>Joint ID</th>
<th>Bonding temperature (K)</th>
<th>Pressure (MPa)</th>
<th>Hold time (time under pressure) (ks)</th>
<th>Tensile strength (MPa)</th>
</tr>
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<tbody>
<tr>
<td>J1</td>
<td>1073</td>
<td>9.8</td>
<td>3.6(3.6)</td>
<td>356</td>
</tr>
<tr>
<td>J2</td>
<td>1173</td>
<td>16.7</td>
<td>3.6(1.02)</td>
<td>395</td>
</tr>
<tr>
<td>J3</td>
<td>1273</td>
<td>9.8</td>
<td>7.2(0.06)</td>
<td>380</td>
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Table 3  Young’s modulus and Poisson’s ratio.

<table>
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<tr>
<th></th>
<th>DS Cu</th>
<th>316SS</th>
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</thead>
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<tr>
<td>E (GPa)</td>
<td>120</td>
<td>185</td>
</tr>
<tr>
<td>ν</td>
<td>0.34</td>
<td>0.30</td>
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</table>

Table 4  Absorbed energy for Charpy impact and slow-bend Charpy tests.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Impact (J)</th>
<th>Slow-bend (J)</th>
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<tbody>
<tr>
<td>316SS</td>
<td>348</td>
<td>-</td>
</tr>
<tr>
<td>DS Cu</td>
<td>53</td>
<td>34</td>
</tr>
<tr>
<td>J1</td>
<td>2.7</td>
<td>3.3</td>
</tr>
<tr>
<td>J2</td>
<td>6.7</td>
<td>8.6</td>
</tr>
<tr>
<td>J3</td>
<td>9.0</td>
<td>9.3</td>
</tr>
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Fig. 1 SEM and TEM observation micrographs near interface for joint J3.
Fig. 2 V-notch at bonding interface.

Fig. 4 Stress-strain curves used in analysis.

(a) Tensile specimen (number of elements=2450)

(b) Charpy V-notch specimen (number of elements=1746)

Fig. 3 FEM analysis models.
Fig. 5 Compersion of load-deflection curves of Charpy impact and slow-bend Charpy tests.

Fig. 6 SEM observations of fractured surfaces for Charpy impact and slow-bend Charpy tests.
Fig. 7 Contours of equivalent plastic strain at 5% of nominal strain for tensile specimen of joint.

Fig. 8 Contours of equivalent plastic strain near notch tip of joint specimen at 0.75 mm of deflection of load point.

Fig. 9 Contours of plastic strain energy density (J/mm$^3$) near notch tip of joint specimen at 0.75 mm of deflection of load point.