Evaluation of Design Strength and Residual Stress in Ceramic/Metal Joint*

Sun Chul HUH∗∗∗, Won Jo PARK∗∗ and Sung Ho PARK∗∗∗

Since the ceramic has excellent qualities in light weight, abrasion resistance and heat resistance etc., compared with the metal, it has been actively examined in order to apply for the structures such as gas turbine and turbo charger etc., which require high strength and heat resistance. But it is not desirable to be used for the structural material since the ceramic is fragile, so the join with the metal with abundant toughness has been studied. However, during the cooling process, the joint residual stress develops on the ceramic/metal joint by the difference in thermal expansion coefficient between two materials and it affects the bending strength significantly. Also, in order to use the joint material as the structural material, the study about the fatigue of thermal cycle of actual use statement is necessary. Therefore, to ensure security and improvement of the bending strength of joint material, the state of residual stress distribution to the high temperature-thermal cycle, and studied the effects of thermal cycle and state of residual stress distribution on the strength of joint material as well.

Key Words: Residual Stress, Repeat Thermal Cycle, Thermal Expansion Coefficient, X-Ray Stress Measurement

1. Introduction

Recently, it is actively examined to use ceramic material instead of metal material for the structures such as gas turbine, turbo charger, which require light weight, high strength and heat resistance. But, even though the ceramic is excellent in light weight, wear-resistance, and high heat resistance etc., it is very difficult to use the ceramic material for the general structural material because it has the fatal weaknesses in collision resistance, toughness strength and manufacturing process. Therefore, using the ceramics/metal as the joint material with the metal with abundant toughness removing those weaknesses of ceramic it can be used in practical structures as the material complementing good property and weakness(1)–(5). In general, ceramics and metals are joined at a high temperature. The joint residual stress will develop during the cooling process by plastic constraint of both materials due to the difference of thermal expansion different between ceramics and metals and at the same time the tensile residual stress occurring in ceramic lowers the fracture strength of joint material considerably.

For the ceramic/metal bonding material, as far as the bonding technology is concerned, the researches on the method lowering joint residual stress have been performed and especially understanding full information on the magnitude and distribution of joint residual stress. it can be regarded to obtain enough improvement of joint strength and reliance(5), (6).

In addition, in order to use ceramic/metal material as a structural material the problems happening for the long term use such as the fatigue of heat cycle, stress corrosion crack, and creep should be solved prior to the use. In the general structures, the fatigue of heat cycle is the most wide affection on the strength of bonding material. Especially the repetitive heat cycle is considered of significant effect to lower the joint strength. The research for this problem has been rarely performed.

Si3N4/STS304 bonding material is employed for this research. After bonding, when the heat cycle of 1 cycle, 3 cycle, and 10 cycle are loaded at 200°C, 300°C, 400°C and 500°C, the residual stress distribution of joint surface is measured by X-ray stress measuring device to study the variousness of residual stress distribution. By the 4 point
bending, we carried the strength evaluation of the joint material due to repetitive heat cycle at each temperature as well as the complete understanding on the fracture mechanism.

### 2. Experimental Method

#### 2.1 Specimen and joining method

A specimen is produced using the brazing method by joining Nitriding Silicon (Si$_3$N$_4$) and Austenite Stainless steel (STS304) with a Copper thin layer between them. The shape and dimension of the specimen are shown in Fig. 1. The material properties such as elasticity coefficient, poisson’s ratio, and thermal expansion coefficient are shown in Table 1. The joining conditions are shown in Table 2. Figure 2 shows yield strength of Cu according to temperature. Figure 3 shows relation between equivalent stress and equivalent plastic strain of Cu during thermal cycle. As seen in the figure, equivalent stress of before heat cycle (B point) is 28 MPa, but equivalent stress of after heat cycle is 33 MPa. I think that equivalent stress increase by working hardness of Cu on thermal cycle.

#### 2.2 Loading condition of a heat cycle

The heat treatment of bonded material was performed at 200°C, 300°C, 400°C, 500°C using PIB Silicone Knit cylindrical electric furnace. Figure 4 is the configuration of heat cycle. As seen in the picture, the raising temperature-speed to reach each temperature is 1.74°C/mm. After 8 hours, each temperature is cooled down to reach room temperature by furnace cooling and this process establishes one cycle. Repetition of this process provides the maximum 10 heat cycles.

#### 2.3 Measurement of residual stress by x-ray

Figure 5 shows the measuring position to measure the residual stress. As seen in the figure, the residual stress measured along two different directions. Along edge for the ceramic part, the vertical direction of joining surface ($\sigma$) is measured for $x = 0.5, 1, 1.5, 2, 3, 5, 7$ mm along $x$ line about $y = 0.5$ mm like (1). Along center line, the vertical direction of joining surface ($\sigma$) is measured for $x = 0.5, 1, 1.5, 2, 3, 5, 7$ mm along $x$ line about $y = 2$ mm like (2).

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**Table 1** Material properties of specimen

<table>
<thead>
<tr>
<th>Material</th>
<th>Si$_3$N$_4$</th>
<th>Cu</th>
<th>STS304</th>
</tr>
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<tbody>
<tr>
<td>E(GPa)</td>
<td>304</td>
<td>108</td>
<td>193</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.27</td>
<td>0.33</td>
<td>0.3</td>
</tr>
<tr>
<td>$\alpha$(1/K)</td>
<td>$3.06 \times 10^{-6}$</td>
<td>$17.7 \times 10^{-6}$</td>
<td>$16.5 \times 10^{-6}$</td>
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</tbody>
</table>

**Table 2** Conditions of joining

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brazing filler</td>
<td>Ti-Ag-Cu</td>
</tr>
<tr>
<td>Temperature</td>
<td>800°C–850°C</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>$10^3$ torr</td>
</tr>
<tr>
<td>Interlayer</td>
<td>Cu (0.5mm)</td>
</tr>
</tbody>
</table>

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**Fig. 1** Configuration of specimen (unit : mm)

**Fig. 2** Yield strength of Cu according to temperature

**Fig. 3** The relation between equivalent stress and equivalent plastic strain of Cu during the thermal cycle

**Fig. 4** Diagram of heat cycle
2.4 Finite element analysis

Figure 6 shows mesh model used in FEM. FEM analysis is using ANSYS program (Ver.5.7). The joining of ceramics and metal is performed at a high temperature about 1100°C. However, as the blazing material starts to gain rigidity during cooling, the stress is developed since two materials are constrained each other at the joint to the different coefficients.

The FEM model is 8-node isoparametric element, and total of 1749 nodal points. For the boundary condition, symmetry was considered and any kinds of deformation is allowed except a rigid body motion.

3. Results and Discussion

3.1 Residual stress distribution of joint material

Figure 7 shows the measurement of residual stress $\sigma_x$ ($x$ direction) distribution along the edge ((1)). As we can see in the figure, the maximum residual stress develops near the joining interface. After that, the residual stress starts to decrease again and then the residual stress becomes almost 0 constantly.

Figure 8 is the measurement of $\sigma_x$ distribution along the center line ((2)). As seen in the figure, $\sigma_x$ distribution along the center line is almost same with that of the edge. Another word, $\sigma_x$ becomes the maximum tensile stress around the jointing interface and it decreases as the distance becomes far off from the joint. However, $\sigma_x$ of the edge is much larger than that of the center line.

Figure 9 is the results of FEM analysis of residual stresses $\sigma_x$ around an edge and on the center of the bonded material. The residual stresses in ceramics and stainless steel are distributed almost symmetrically corresponding to an origin. The residual stress of center line are compression in ceramics and tension in stainless steel. Those stresses are distributed continuously and smoothly in a whole specimen. The residual stresses of edge line are distributed discontinuously with respect to a joint, which are compressive stress in the stainless steel and tensile stress in the ceramics contrary to the residual stresses on the center line.

Figure 10 is relationship between thermal cycle temperature and residual stress after 1 cycle. As seen in the figure, as thermal cycle temperature increase, maximum tensile residual stress increase. Also, results of X-ray measurement is almost same with that of FEM.

Figure 11 is relationship between maximum tensile residual stress and number of cycle. We see from the figure that residual stress value by the number of loading heat cycle increases as well at every temperature of 200°C, 300°C, 400°C, 500°C for 1 cycle, however, it decreases for 3 cycle, 10 cycle. Also in the variousness of
residual stress by the heat cycle temperature (1, 3 cycle), it shows the maximum tensile residual stress at 400°C while it has the maximum at 200°C by increasing loading number (10 cycle). For the case of 500°C of heat cycle loading, it has the minimum residual stress value regardless of the number of cycle. The study for this point will be carried with brazing filler as well as the arrangement of precipitation and compound by chemical reaction of ceramic.

Figure 12 is the relation between bending strength and various thermal cycle temperature. Fracture strength of bounded material decreases by heat cycle loading. For 1 cycle, as maximum tensile residual stress increases by heat cycle loading, fracture strength decrease. For 3 cycle and more or on high temperature, brazing filler used in stress relaxation produces oxide and precipitation, so strength decreases largely occurs on the joint surface.

### 3.2 The shape of fracture interface

Figure 13 is model of fracture mechanism. As seen in the figure, the shape of fracture has about three different types of A, B, C. (a) is that the fracture starts on the joining surface between copper and ceramic, and it stretches along the joining interface. After it moves 4/5 of total fracture, it turns to the joining part of two material and the final fracture ends there. Which is A type of fracture type. In contrary (b) is that the fracture states on the ceramic part with the maximum tensile residual stress, and it stretches along the side of ceramic. After it stretches 1/3 of total fracture, it turned to the border part and then establishes it’s last fracture surface on the border line between copper and ceramic. Which is B type of fracture shape. And (c) is that the fracture states on the border between copper and ceramic, and it stretches linearly along the joint line. Which is C type of fracture shape.

Figure 14 is photograph where the boundary part of ceramics and copper was observed with SEM to examine the precipitation and the reactive product on the joint interface. Figure 13 (a) (A), As contains a small amount of Cu and N by the principal ingredient. (B) is formed with the
reactive product in the compound form between the metals of CuAg and (C) shows the precipitation of TiN in the particle form. (b) shows the graph which analyzes the element by EDAX.

4. Conclusion

(1) The distribution of tensile residual stress does not change corresponding to a loading of single heat cycle, however the magnitude of maximum tensile residual stress changes. For 200°C, 300°C, 400°C, it increases after 1 cycle, but the residual stress value decreases corresponding to the increase of the number of heat cycle such as 3 and 10 cycle.

(2) The repeated thermal loads decreased the fractures strength of the joints. The dominate factor to the strength decreased at the one thermal load case is the increased residual stress in the vertical direction to the joint interface. But, the factor at the repeated thermal load cycles more than two is regard the TiN precipitation substance produced around the interface.

(3) The fracture patterns without thermal load observed ceramic and interface-ceramic. But, when the repeated thermal load cycles were imposed, three fracture pattern were observed: C type fracture at 200°C, B type fracture at 300°C, 400°C, A type fracture at 500°C. The A type fracture pattern presented the lowest fracture strength.

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References