Development of $\text{Al}_2\text{O}_3$/Cu functionally gradient material based on residual stress analysis

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Abstract

In this study, $\text{Al}_2\text{O}_3$/Cu functionally graded material (FGM) was tried to fabricate based on the optimum functionally compositional profile obtained by a numerical analysis. Obtained results in this study are summarized as follows. (1) Residual stress fields arising by the fabrication were analyzed by a finite element analysis based on an actual process. From some analysis results, it was found that the residual stress is reduced by fabricating the functionally graded material with thinner ceramic layer than metal layer. (2) FGM fracture map, which includes crack initiation criterion obtained from the bending strength of $\text{Al}_2\text{O}_3$/Cu composite materials, was proposed. The optimum functionally compositional profile can be found easily by using this map. (3) It was shown that a functionally graded materials with no crack can be fabricated by using the FGM fracture map.
1 Introduction

Structure such as thermal power plant[1] or electric device[2] used in computer have a lot of interface parts. Large stresses may develop at the interface during a fabrication or service, because these interface parts are constituted by connecting together some materials with different properties such as ceramic and metal, and the stresses concentration at the interface can cause cracking[3]. Especially, tremendous efforts for developing a complete FGM including no cracking have been done with trial and error[4].

In this study, ceramic-metal (Al₂O₃/Cu) FGM is tried to fabricate based on the optimum functionally compositional profile, which is obtained by simulating the sintering process.

2 Residual stress analysis by finite element method

2.1 Procedure of stress analysis

Fig.1 Analysis model of functionally graded material and finite element mesh
In the fabrication process of the FGM by a hot press, it is necessary to consider the residual stress field caused during cooling process from sintering temperature to room temperature, for preventing cracking in the sintering material. In this section, the residual stress analysis is performed by using a stack axisymmetric cylindrical model.

Fig. 1 shows the stack cylindrical model used in this study. For considering the actual size fabricated in this study, it was assumed that a radius of the model is 25 [mm], a thickness of the ceramic layer (Cu 0[%]) is H1, the graded layer is h and the metal layer (Cu 100[%]) is H2, where, for example, Cu 20[%] indicates a material with a mixed mass fraction of Cu 20[mass%] and Al2O3 80[mass%]. Effect of each layer thickness on the residual stress was examined here. Linear distribution was assumed in the functionally compositional profile.

Finite element analysis was performed by using MARC, for obtaining the residual stresses. The stack cylindrical model was divided with the four-point axisymmetric node element. Displacements of the divided model were fixed along z axis to x axis direction and at a center-bottom to z direction. Other faces were stress free condition. Coefficient of thermal expansion $\alpha$ [1/K], Young’s modulus $E$ [GPa] and Poisson’s ratio $\nu$ used in this analysis are [5],

\[
\alpha = 7.233 \times 10^{-10} V^2 + 0.683 \times 10^{-8} V + 5.230 \times 10^{-6} \quad (1) \\
E = 2.124 \times 10^{-5} V^2 - 8.788 \times 10^{-1} V + 119.1 \quad (2) \\
\nu = 0.21 + 0.90 \times 10^{-3} V \quad (3)
\]

where $V$ is Cu mass fraction. As the sintering simulation, thermal stress caused between 1403[K] (sintering temperature) and 303[K] (room temperature) was calculated.

### 2.2 Results

Firstly, two kinds of materials were analyzed. One material is the model connected directly Cu layer and Al2O3 layer (Non-FGM), and other is the model with functionally graded compositional layer such as 1, 4 and 9 layers (FGM). Model size for Non-FGM is H1=25[mm], H2=25[mm] and h=0 for Non-FGM and H1=20[mm], H2=20[mm] and h=10[mm] for FGM. Maximum principal stress was taken as
the residual stress, because the maximum principle stress had been used as the fracture criterion for brittle materials like a ceramics[6]. From the analysis results, Non-FGM had the maximum residual stress at the Cu/Al₂O₃ interface on the surface. The maximum residual stress in the all FGM model was reduced considerably in comparison of Non-FGM. Fig.2 shows relationship between the number of divisions of functionally graded layer and maximum residual stress on the model surface. The maximum residual stress is decreasing with the number of divisions, and the maximum stress becomes almost constant from N=4. From this results, N=9 was set in all below analysis.

![Graph](image)

**Fig.2** Relationship between maximum principle stress and the number of layers of FGM

Fig.3 shows relationship between the residual stress (i.e. maximum principle residual stress) and Cu mass fraction, which is transferred from the position taken the maximum residual stress in the functionally graded layer. Solid line in the figure corresponds to the bending strengths of Al₂O₃/Cu composite materials. Here, we can regard the bending strength of the composite materials as tensile strength at a local area in the FGM. Residual stress is decreasing with the thickness of the functionally graded layer h, a residual stress reduces with thinner ceramic layer than metal layer. If it is assumed that residual stress below the tensile strength of the Al₂O₃/Cu composite material provide us what we can fabricate the FGM with no cracking, we can design easily the optimum FGM with no cracking from this diagram. Here, let’s call this figure ”FGM fracture map”. In our case, it is found that H1=2[mm], H2=10[mm] and h=27[mm]...
can be better for the fabrication process.

![Graph showing relationship between residual stress and Cu mass fraction in FGMs]

Fig.3 Relationship between residual stress and Cu mass fraction in FGMs

3 Fabrication of functionally graded material

3.1 Procedure of fabrication

Al$_2$O$_3$ powder (TM-DAR with an average of particle size is 0.22[$\mu$m]) and Cu powder (SF-Cu with 10[$\mu$m]) was used in this study. Material processing equipment used in this study is the hot press with a high frequency induced heating system.

Table 1 Geometries of FGM

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>H1</th>
<th>H2</th>
<th>h</th>
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<tbody>
<tr>
<td>FGM-1</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>FGM-2</td>
<td>9</td>
<td>5</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>FGM-3</td>
<td>9</td>
<td>2</td>
<td>10</td>
<td>27</td>
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Procedure of fabrication is as follows. Al$_2$O$_3$ powder and Cu powder is mixed by using ball mill for 24 hours. These mixed powder
is stacked in the graphite cylindrical container inside the hot press. Mixed powder is sintered under N\textsubscript{2} atmosphere, sintering temperature 1403[K] and pressure 3[MPa]. Table 1 shows three kinds of geometries of FGM which were fabricated in this study. Finally, Cross sections examination of the sintering material were performed by optical microscope, scanning electron microscope and chemical composition analysis.

3.2 Results and discussion

Fig.4 shows observation results of cross section of three kinds of FGMs. Fig.4(a) corresponds to the geometry of N=5, H1=3[mm], H2=3[mm] and h=8[mm]. It is found that crack occurs from surface to center direction. Fig.4(b) is N=9, H1=5[mm], H2=8[mm] and h=25[mm]. In this geometry, the sintering material is broken completely at ceramic-rich side. Fig.4(c) is N=9, H1=2[mm], H2=10[mm] and h=20[mm]. It is found that cracking does not occur.

Fig.5 shows chemical composition analysis results of FGM-3. Cu mass fraction is increasing monotonously with Cu content, and Al and O mass fraction is decreasing.

From these observation results and the chemical analysis, it was found that FGM-3 does not include crack, pore and inclusion, and each chemical composition is changing gradually.

FGM fracture map was compared with fabrication results of three kinds of FGMs. Fig.6 shows the comparison result. Symbol with vertical line in the figure is fabrication results and symbol without the line is analytical results. Stress in the fabrication results was estimated by finite element analysis, and the stress in the analytical results is maximum residual stress. Cu content in the fabrication results was determined from the position of crack initiation. Cu content in the analytical results corresponds to the position of maximum residual stress. In FGM-1, residual stress in the analytical result takes maximum at Cu50[%]. But, crack caused actually at Cu35[%]. In FGM-2, residual stress takes maximum at Cu30[%], but crack initiated at 15[%]. In both materials, crack initiation position which was estimated by FEM was different from the actual crack initiation position. This reason was considered due to a scattering strength of functionally graded layer, microstructure effect due to a wavy interface and so on. Finally, in FGM-3, maximum residual stress in
the analytical result became below fracture criterion completely and cracking did not also initiate in actual.

![Cross section of functionally graded materials](image)

(a) FGM-1  
(b) FGM-2  
(c) FGM-3

Fig.4 Cross section of functionally graded materials
Fig. 5 Relationship between mass fraction of Cu, Al and O and Cu content in FGM

Fig. 6 Comparison between FGM fracture map and experimental results

4 Conclusion

In this study, $\text{Al}_2\text{O}_3/\text{Cu}$ functionally graded materials were tried to fabricated based on the residual stress analysis. Obtained results are summarized as follows.
(1) Residual stress analysis was performed by finite element analysis. It was found that residual stress obtained by the analysis had considerable effect for the compositional profile in the functionally graded layer, and the residual stress was reduced by choosing the thinner ceramic layer.

(2) FGM fracture map was constructed by using bending strength of composite materials. Optimum functionally graded compositional profile was found by combining with the finite element analysis results.

(3) Some functionally graded materials were fabricated by the hot press on comparing with FGM fracture map, and it was shown to be able to get no cracking functionally graded material.

Reference


