Computational simulations on the thermal analysis of metal matrix composite (MMC) composed of Al and SiC were performed in extended areas of SiC volume fraction. Due to the experimental limitations, only the narrow range of SiC volume fraction has been examined. Through the simulation, which enables current experimental situation to extend, we attempted to explore the dependencies of thermal and mechanical properties on changing the value of volume fraction (Vf).

To calculate the coefficient of thermal expansion (CTE), variables with temperature and Vf were given in a range from 25°C to 100°C and 0 to 100%, respectively. We obtained quantitative results including CTE as a function of Vf, which are in a good agreement with previous experimental reports. Furthermore, the stress analysis about thermally expanded MMC was performed. At low volume fraction of SiC, the thermal expansion caused the tensile stress at Al near the interface. However, as the volume fraction of SiC was increased, the stress turned to be compressive, it’s because the linked SiC particles contracted the expansion of Al. The MMC of Al matrix face centered cubic site SiC particles has more stress evolutions than the MMC of Al matrix simple cubic site SiC particles at same volume fraction.

Keywords: Coefficient of thermal expansion (CTE); Metal matrix composite (MMC); Al/SiC; FEM.

1. Introduction

Metal matrix composites (MMC) are active field in industrial applications, such as aerospace structure, automotive and so on1-3, due to its enhanced thermal and physical properties. By adding strengthening components into metal matrix, it has been known that the enhanced characteristics are resulted from the reinforcement fraction in a given matrix materials, such as Mg/SiCp, Mg/Nip.4,5 Among the various MMC systems, MMC including aluminum as a matrix has been extensively studied for applying to high strengthening materials system.6,7 Especially, aluminum is well known as a matrix material with a large coefficient of thermal expansion. Thus SiC particles in Al matrix has been considered as a role of CTE reduction in Al/SiCp system.8,9 Understanding the thermal properties, for instance, CTE and thermal stress is required to estimate the
Finite element method (FEM) is a powerful tool for simulating thermal and mechanical behavior of material. That supplies an institutional analysis taking advantages of graphical and numerical post-processes. Moreover, it helps systematic analysis of material behaviors and properties, including investigation of local stress and strain distribution. Nevertheless, there are few reports of FEM study on the thermal properties of Al/SiCp system compared to that of the experimental researches. In this work, we investigated the CTE and thermal stress of Al/SiCp MMC system using computational FEM analysis, which enables experimental information to extend over current Al/SiCp MMC system. Two models are prepared – one is SiC inclusions in Al matrix and, the other is Al in SiC matrix. The dispersion conditions are varied following face-centered-cubic (FCC) and simple cubic (SC) to study the contribution of the geometric arrangement. Empirical equations are obtained from the FEM results. They agree quite well with the experimental results from Zhao and Zhang.\textsuperscript{8,9}

2. Simulation Model

Currently, the control manner of SiCp in Al matrix is not only limited over a large regime due to inter-action between reinforcement material and matrix but also can not show representative nature owing to limited controlled regime over all possible MMC fabrication. In this regard, Computational FEM analysis was carried out for SiCp in Al4032 (a Si-doped aluminum) matrix, which can take into account both thermal and stress enhancers. There have been previous experimental reports, such as the rule of mixture or Kerner’s model\textsuperscript{12} and Turner’s model\textsuperscript{13} estimating the behavior CTE as a function of SiC volume change. To extend experimental information, the computational FEM method on a variety of composite material systems allows MMC fabrication to be fruitful with empirical results and computational manners. In this work, we adopted the simulation model based on Kang et al.\textsuperscript{14} We assumed a perfect simple cubic system, which is negligible on defects such as pores, with particles arranged in simple cubic structure. Structures of FCC models are also taken into concern. The overall stress distribution was readily confirmed by 3-D structure. FEM calculations are used to investigate displacement due to thermal expansion. Generally, MMC is composed of a metal matrix and reinforcing particles. From the previous reports,\textsuperscript{8,9} the arrangement of reinforcement material could play an important role in changing of CTE. In this regard, Three-dimensional simulation was carried out to compute the coefficient of thermal expansion of Al4032/SiCp composite, which was designed to measure line expansion coefficient [Fig.1(a) and (b)]. Fig.1(a) and (b) show that the simulation was carried out for the SiCp with simple cubic(SC and face centered cubic(FCC) arrangement in Al4032, respectively.

For the analysis of metal matrix composite, many researchers suggested the analysis of unit cell of composite.\textsuperscript{10,14} Generally, there are computational difficulties to obtain reasonable results based on a small single unit owing to a lack of interaction between reinforcement particle and matrix, on the contrary, the computation with multiple unit cells allows reliable results due to considerable material interaction. In this study, in order
to obtain more reliable results, CTE was measured by calculating the change in lattice constant considering close neighbor unit cells.

![Fig. 1. FEM models for calculation of the coefficient of thermal expansion. SiC particles were located in simple cubic site (a) and face centered cubic site (b).](image)

To successfully predict experiment data, the finite element structure and necessary boundary conditions should be reasonable. SiC particles were put in an array of simple cubic structure, while its size was neglected. The adopted model is designed with Al matrix and SiC reinforcement, however, for the case where SiC volume is larger than that of the metal, MMC model can be reversed, so that the matrix is SiC and metal becomes the particle. In this case, the 3-D model mesh was converted into a finite element mesh with commercially available ABAQUS 6.5.

To find the effect of volume fraction, the Al matrix with SiC reinforcement was used to achieve 9–50% SiC volume fraction and the opposite case was considered to achieve 60–90% SiC volume fraction.

To analyze the CTE, the temperature of finite element mesh was increased from initial temperature of 25°C to 100°C during simulation.

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>CTE (ppm/°C)</th>
<th>Young's modulus (Gpa)</th>
<th>Yield Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al 4032</td>
<td>25</td>
<td>19.4</td>
<td>79</td>
<td>315</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>20.2</td>
<td>-</td>
<td>62</td>
</tr>
<tr>
<td></td>
<td>300</td>
<td>21.0</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>SiC</td>
<td>-</td>
<td>2.72</td>
<td>20.8</td>
<td>3440</td>
</tr>
</tbody>
</table>

Material properties with pronounced dependence on temperature are used in this simulation. Al4032 and SiC were considered as an isotropic, perfectly elastic material. The material properties are summarized in Table 1.

3. Result and Discussion

3.1. Coefficient of thermal expansion analysis

When SiCp was added in Al matrix with increasing SiCp volume fraction, the CTE value was decreased linearly. The reason that this result is smaller than that of Al, subsequently, SiCp become suppressed state resulting in the difference of their CTE
values. From results in Fig. 2 (b), the model conditions between simple cubic and face centered cubic are considered to have a very similar behavior due to few difference of that CTE results. CTE results in this work are evaluated lower 8~9% than experimental data due to ignore of the defects, such as pores, dislocation in MMC.

As mentioned earlier, the CTE of Al matrix with SiC particles becomes larger than that of the opposite case. Fig. 2(a) reveals that the prototype results varied as a function of temperature. The left image in Fig. 2(a) displays the simulated model with non-deformed condition given at 25°C and the right image shows the deformed model with thermal stress up to 100°C.

\[ CTE = 19.4 - 0.164 \times V_f. \]  

(1)

In order to obtain qualitative CTE results, we extract the fitted equation (1) from previous results dealing with CTE, with unit of ppm/°C, and \( V_f \) the Volume fraction. The designed model is based on the rule of mixture.

For the opposite case of SiC matrix, when the volume fraction of SiCp is above 50%, the CTE decreased linearly. The obtained tendency on computational manner was close to that predicted from Kernal’s model and Turnal’s model. The bulk modulus is thought to be a factor to affect this model and the linearity is not observed any more in SiC matrix of Fig. 2(b). However, SiC volume fraction is, indeed, main factor contributing to the CTE of MMC. In this case, the CTE is a function represented as a 2nd order polynomial, which is written as
Using this equation, we can predict the CTE’s of other regimes as a function of $V_f$.

3.2. Stress analysis

When the MMC was heated, expansion and deformation occurred steadily. Indeed, thermal stress is induced by the difference of lattice constants between the matrix and the particles. Maximum principal stress on each case corresponding to a different cubic arrangement of SiCp is displayed with Al matrix [Fig.3(a)], it shows that the thermal expansion induced the tensile stress at Al near the interface. Fig. 3(b) displays SiC/Al matrix in simple cubic, where the stress turned to compressive stress since the linked SiC particles contracted the expansion of Al at the volume fraction of increased SiC. For Al/SiCp matrix in FCC [Fig.3(c)], the MMC of Al matrix face centered cubic site SiC particles has more tensile stress evolutions than the MMC of Al matrix simple cubic site SiC particles at same volume fraction. Fig.3(d) shows the computed thermal stress results compared with [Fig.3(a)] and [Fig.3(b)], additionally, the measured difference between [Fig.3(a)] and [Fig.3(c)] is also shown in Fig.3(d). The reason on the difference between [Fig.3(a)] and [Fig.3(c)] can be explained with their arrangement including each different CTE. From this viewpoint of structure arrangement, the more packed structure, such as FCC, allows the stress to increase owing to enhanced stress field induced by surrounding atoms.

Additional consideration on the Fig.3(a) and (b) were described as follows: In case of [Fig.3(a)], the smaller CTE of SiC in heated state renders Al matrix expansion so that
plus value of thermal stress were measured. On the other hands, in case of [Fig.3(b)], Al thermal stress in Al/SiC matrix can be obtained with compressed value, (i.e. minus value) because Al particles are isolated in SiC matrix even though Al has larger CTE rather than SiC matrix.

4. Conclusion

In this work, we have demonstrated the thermal properties of Al/SiCp MMC over all mixing composition via FEM analysis manner. To calculate their coefficient of thermal expansion with FEM analysis, we adopted SC and FCC cubic system composed of Al/SiCp, which have the differences of structure having MMC. The obtained results are in a good agreement with previous experimental reports. Additionally, the calculated CTE values also were confirmed with a qualitative extracted equation. We expect that our approach using computational FEM method facilitates prediction to get promising thermal properties on a variety of MMC.

Acknowledgments

This work was supported by the Agency for Defense Development and Defense Acquisition Program Administration, and partially supported by the Korea Science and Engineering Foundation (KOSEF) through the SRC/ERC Program of MOST/KOSEF R11-2005-065 (Chung).

References