3D microstructure visualization and modeling of the mechanical behavior of SiC particle reinforced aluminum composites

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Abstract

A serial sectioning process has been developed to visualize and model the behavior of SiC particle reinforced aluminum composite using a reconstructed 3D microstructure. Two-dimensional microstructures were acquired and used to develop 3D solids for visualization and finite-element modeling (FEM). Visualization and modeling of the 3D composite microstructure aided in the understanding of microstructure morphology and provided the means to make the connection between material structure and performance. The approach used here is an improvement over 3D unit cell modeling that uses simplified approximations of the microstructure. The Young’s modulus of the composite predicted by the 3D microstructure model correlated very well with experimental results. Furthermore, the 3D microstructure model prediction was more accurate than 3D unit cell model prediction. The serial sectioning process coupled with finite element modeling is a powerful tool for understanding and accurately predicting the influence of microstructural characteristics on the behavior of materials.

1 Introduction

SiC particle reinforced aluminum composites exhibit high strength and stiffness by combining strong, ceramic reinforcement particles in a soft aluminum matrix [1]. SiC particle size, morphology, and orientation with respect to the loading
axis play a significant role in determining the material’s stiffness, strength, and fatigue resistance [1-4]. Traditional methods of visualizing the microstructure of composites as well as other materials involve simplifying the three-dimensional (3D) structure to a two-dimensional (2D) representation by optical or scanning electron microscopy (SEM). While 2D representation of microstructures is common and gives some idea of the microstructure morphology, it is not fully representative of the 3D structure of the material. Therefore, to visualize and fully understand a material’s microstructure, a technique that can capture the 3D nature of the microstructure is required. Serial sectioning is a technique that allows the quantification of 3D microstructures using classical metallography techniques coupled with computer-aided reconstruction [5]. Recently, computer-aided serial sectioning techniques have been used to study several material systems, including Al-Si [6], proeutectoid iron alloy [7], and SiC/Al composites [8].

While visualization of the 3D microstructure of the material is important, prediction of the behavior and properties of the material is equally important. Thus, a microstructure-based modeling approach is required to link the microstructure with the behavior of the material. Numerical modeling of the behavior of SiC/Al composites has typically been conducted by assuming a single SiC particle of simple geometry in a unit cell model [1, 3, 9]. Unit cell models approximate the highly variable and angular structure of SiC particles using simplified particle geometries such as spheres, ellipsoids, or cubes. This simplification aids in computation but fails to capture the complex morphology, size, and spatial distribution of SiC particles in the Al matrix. It follows that an accurate simulation of the material behavior can only be obtained by incorporating actual 3D microstructure morphologies as inputs to the model.

Here we have used a microstructure-based modeling approach by combining serial sectioning and computer-aided reconstruction with 3D finite element modeling (FEM). Serial sectioning was used to reveal the 3D microstructure of SiC particle reinforced aluminum matrix composites. The reconstructed 3D microstructure obtained was then used as a basis for 3D FEM modeling of uniaxial tensile behavior. The process allowed 3D visualization of SiC particles as well as intrinsic and accurate microstructure-based modeling of the behavior of SiC/Al composites. It will be shown that the 3D microstructure of the composite is more realistic in predicting and visualizing the mechanical behavior of the composite than the simple SiC particle geometry employed in conventional unit cell models.

2 Experimental procedure

In this work a 20 vol.% SiC reinforced 2080 aluminum composite processed by hot-pressing and extrusion (Alcoa Corp.) was examined. The SiC particles in the composite had an average particle size of about 25 μm (F280 designation). The SiC/Al composite samples were cut so that the extrusion axis was parallel to the
cutting plane (longitudinal axis). A serial sectioning method was employed to acquire 2D images of the microstructure as a basis for reconstructing 3D solids for modeling using FEM. The basic steps of the serial sectioning process and modeling were as follows:

1. Sample preparation
2. Fiducial marking by indentation
3. Polishing
4. Imaging and image segmentation
5. Serial section stacking and visualization
6. Finite element modeling

Figure 1 shows a flow chart of the serial sectioning process. The material was sectioned, mounted, and indented by a Vickers micro-hardness indenter to create fiducial marks. Since the geometry of the indenter is known, the amount of material thickness removed can be calculated using the 2D image projection of the indentation. Measurements of changes in the fiducial mark depth were used to determine the thickness between sections from material loss per polishing cycle. Cyclic polishing and imaging of the sample surface were conducted to generate a series of microstructure sections. Using the 2D sections, a 3D solid was reconstructed using imaging software (Surf Driver). The 3D model was exported into a computer-aided drawing (CAD) software and then into the finite element analysis program (Abaqus version 6.3-1 CAE).

Figure 1: Flow chart of serial sectioning process.
3 Results and discussion

3.1 Serial sectioning and visualization

After the SiC/Al samples were cut and mounted for subsequent polishing, a representative region of the microstructure was selected, denoted here as the region of interest, Fig. 2. Selection of the region of interest was important because it defined the volume of microstructure to be analyzed. A “representative” volume is a very subjective assessment that is based on the microstructure feature size, computational capability, and operator judgment. In the composite studied here, it was desirable to obtain a stack of sections such that several SiC particles were included in the analyzed volume. Thus, since the SiC particles were about 25 μm in diameter, it was determined that a 100 μm x 100 μm x 100 μm volume would be suitable for this composite. This volume would yield a reasonable group of particles for reconstruction and modeling. A larger volume (about 200 μm x 200 μm x 100 μm) was imaged so that a smaller, representative volume could be selected.

![Figure 2: Microstructural region of interest, demarcated by four fiducial marks (indentations).](image)

The role of polishing in serial sectioning is very important, for two reasons: (a) to control the amount of material removed and (b) to obtain a high quality surface finish for microstructural characterization. Since the size of the microstructural features dictates the thickness between sections, several SiC particles about 25 μm in diameter, a section thickness of ~1 μm was chosen. This would give about 8 to 10 sections per particle in the analyzed volume. In order to obtain the desired 1 μm per cycle target, a two-sequence routine was used. In order to accelerate the material removal rate the composite was first polished with 15 μm diamond paste. In order to restore the surface quality, while minimizing the material removal rate, the composite was then polished with 1 μm diamond paste. As mentioned above, fiducial marks were used to measure the material thickness loss. Figure 3 shows the decrease in indentation size with increasing polishing time, using data from indentations at the four corners of the region of interest. Figure 4 shows the average cumulative thickness loss of about
1.2 μm per cycle, which was close to the desired 1 μm per cycle thickness loss rate.

Figure 3: Decrease in fiducial mark (indentation) size with increasing polishing depth.

Figure 4: Cumulative material loss rate (in μm/cycle) during serial sectioning process.

After each polishing cycle, optical micrographs of the microstructure were segmented into black-and-white images using conventional image analysis technique, Fig. 5. The sections were then aligned to remove translational and rotational errors. In order to simplify the microstructure for FEM, the objects in the image were simplified using a vectorial format software, as demonstrated in Figure 6. As shown in Figure 6, these simplifications did not significantly change the original morphology of the SiC particles.
To reconstruct the serial section-generated 3D solids, a 3D image analysis and reconstruction software (SURF Driver) was used. In this step, serial sections were stacked, a 3D solid generated, and exported for FEM analysis. Figure 7 shows a multi-particle reconstruction, where several of the particles are clearly aligned along the extrusion axis. The somewhat irregular edges seen on the particles were an artifact of reconstruction caused by slight rotational misalignments in the serial sections. These artifacts were removed upon exporting to the CAD program prior to FEM analysis.
3.2 3D microstructure based finite element modeling

The 3D model of the microstructure with 16 particles was used as a basis for FEM analysis (ABAQUS version 6.3-1 CAE), Fig 8. This model was compared with conventional unit cell models where the SiC particle was perfectly circular (2D plane stress and 2D plane strain) and perfectly spherical (3D). Uniaxial loading was modeled with SiC as a linear-elastic material, because it does not exhibit significant plasticity at room temperature. The aluminum matrix was modeled with both elastic and plastic behavior using experimental stress-strain data of the unreinforced alloy. A 1% uniaxial strain was applied to all models. Table 1 shows the elastic properties used for SiC and aluminum metal matrix.

![Figure 8: (a) Multi-particle model from serial sectioning and (b) corresponding finite element mesh of the model.](image)

Table 1. Elastic properties of SiC and aluminum used in FEM modeling

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Young’s Modulus (GPa)</th>
<th>Poisson’s Ratio</th>
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<tbody>
<tr>
<td>SiC</td>
<td>410</td>
<td>0.19</td>
</tr>
<tr>
<td>Aluminum</td>
<td>72.5</td>
<td>0.33</td>
</tr>
</tbody>
</table>

The 3D microstructure model was compared with spherical unit cell models in 2D (plane strain and plane stress) and 3D, Fig. 9. The highest and lowest simulated moduli and strength were obtained by 2D plane strain and plane stress, respectively. The plane strain condition causes a much higher degree of constraint ($\varepsilon_z = 0$) than the plane stress condition ($\sigma_z = 0$). The 2D behavior is also influenced by the nature of the model. In 2D, the SiC particle is actually modeled as a disk, rather than a particle. Thus, the matrix surrounds only the perimeter of the SiC particle in the 2D models, which will influence the material response. As expected, the 3D models lay between the 2D plane strain and plane stress bounds. The 3D microstructure model exhibited a higher degree of strengthening, since the actual microstructure incorporated the inherent aspect ratio and alignment of the SiC particles along the loading direction. A comparison of all predicted moduli with experimental tensile data on the same composite, from Chawla et al. [10], is shown in Table 2. The 3D microstructure model correlates very well with the experimentally determined Young’s modulus value of 100 GPa. A comparison of the non-elastic portion of the curve, between
the 3D microstructure model and the experiment, shows that the model predicts a higher strength and work hardening rate than the experiment, Fig. 10. This can be attributed to the fact that, experimentally, at this coarse particle size (~ 25 μm), particle fracture takes place at relatively low stresses [1]. Clearly, the FEM model presented here does not take particle fracture into consideration. Better agreement in the plastic portion of the stress-strain curve should be obtained when modeling composites with finer particles that have higher strengths, and fail closer to the ultimate tensile strength of the composite.

![Figure 9: Comparison of stress-strain predictions from various FEM models.](image)

Note that the 3D microstructure model predicts higher strength than the 3D unit cell model, since it considers the true aspect ratio and morphology of the SiC particles.

Table 2. Young’s Modulus Predicted by Various Finite Element Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Young’s Modulus (GPa)</th>
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<tbody>
<tr>
<td>2D Plane Strain</td>
<td>104</td>
</tr>
<tr>
<td>2D Plane Stress</td>
<td>92</td>
</tr>
<tr>
<td>3D Unit Cell</td>
<td>98</td>
</tr>
<tr>
<td>3D Microstructure</td>
<td>100</td>
</tr>
<tr>
<td>Experiment [10]</td>
<td>100.1 ± 0.6</td>
</tr>
</tbody>
</table>

Figure 11 shows the evolution of equivalent plastic strain showing the onset of plastic flow at sharp angular corners of the particles, followed by localization of strain between particles. The plastic deformation became concentrated at the poles of the particles along the loading axis, as predicted by Goodier [11]. It is also interesting to note that within a cluster of particles, there is a lack of plasticity due to the large degree of constraint on the matrix in these regions.
Figure 10: Comparison of experiment and 3D microstructure model prediction. The model predicts slightly higher strength because it does not consider particle fracture, which takes place at relatively low stresses.

Figure 11: Evolution of plastic strain in a 2D section of the 3D microstructure model, showing plasticity at the poles of the reinforcement. Clustered particle regions exhibit lower plasticity due to the higher degree of constraint on the matrix. The SiC particles are outlined in white and the loading axis is horizontal.
4 Conclusions

The following conclusions can be made on this study to develop a serial sectioning methodology for visualization and FEM modeling of SiC particle reinforced Al composites:

- A serial sectioning process was used to reproduce and visualize the 3D microstructure of SiC particle reinforced aluminum composites. The 3D microstructure accurately represented the orientation, aspect ratio, and distribution of the particles.

- FEM simulation of the uniaxial loading behavior of SiC particle reinforced aluminum composite was conducted in 2D (plane stress and plane strain) and 3D (unit cell and microstructure). The 3D microstructure model was the most accurate in predicting the Young’s modulus of the composite.

- The composite studied had a relatively coarse particle size (~ 25 μm), resulting in an early onset of particle fracture at relatively low stress during tensile loading of the actual composite. Thus, the plastic portion of the experimental stress-strain curve was slightly lower compared to the prediction from the 3D microstructure FEM model, where particle fracture was not considered.

- The serial sectioning method, reconstruction, and FEM technique is an improvement over 2D and 3D unit cell models, and can be used to effectively visualize and simulate material behavior.

References