Simulation of the Mechanical Properties of an Aluminum Matrix Composite using X-ray Microtomography

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Aluminum-based particulate-reinforced metal matrix composites (PMMCs) frequently have a heterogeneous distribution of reinforcement particles whether produced by a powder or liquid processing route. The applicability of X-ray microtomography (XMT) for the characterization of this heterogeneity, and its influence on final properties, was investigated for the case of a powder blended and extruded AA2124 matrix with Ni particulate. Three-dimensional image analysis techniques were used to quantify the embedded Ni particle size distribution and the extent and texture of clusters formed. The XMT data were exploited as a rapid method to generate a microstructurally accurate and robust three-dimensional mesh for input for finite-element modeling. Simulation of the elastoplastic response of the material showed excellent correlation with experimental results.

I. INTRODUCTION

TWO-phase systems consisting of discrete entities embedded within a continuous matrix are an important class of material in a number of fields within materials science and engineering. In many cases, the second phase is a deliberate microstructural feature, designed to improve material performance, for example, (1) ceramic reinforcement particles/fibers in a composite material can increase stiffness, (2) a fine dispersion of precipitates in a heat-treatable alloy can improve strength, and (3) a porous network in a polymer material can improve insulation properties. In other cases, the second phase may be an undesirable defect, for example, a pore in a casting, a coarse intermetallic, an inclusion, or a crack. Whether the second phase is a deliberate inclusion or an accidental contamination, understanding the effects of the shape, size, and distribution of second-phase entities on bulk mechanical properties is a challenging task for current simulation techniques. Figure 1 shows some of the common defects found in one class of two-phase materials, particulate-reinforced metal matrix composites (PMMCs).

PMMCs have received considerable attention for use in various engineering applications due to their potentially enhanced mechanical properties compared to monolithic alloys. The degree of property enhancement depends on morphological factors such as volume fraction, size, shape, and spatial distribution of the reinforcement phase, as well as the constituent material properties, load-transfer mechanics, and associated stress/strain profiles and residual stress states arising from heat treatment or prior work hardening.[1,2]

It is worth noting that rapid, accurate, and nondestructive characterization of three-dimensional (3-D) microstructural features is a goal in many areas of materials science, not just composite design. For example, the pore size, shape, and interconnectivity of bioactive glass foams (for tissue scaffold applications[3]) must be carefully controlled to encourage nutrient flow and vascularization while maintaining sufficient mechanical strength and stiffness.[3] Other cellular materials have useful mechanical, thermal, and acoustic properties and are frequently used in fields such as packaging, lightweight sandwich panels, and crashworthiness.[4]

In monolithic alloys, the presence of undesirable intermetallics, inclusions, and porosity can have deleterious effects on mechanical behavior. The extent of property degradation is largely dependent on the size, shape, and distribution of the defect.[5,6,7] The complete removal of undesirable impurities or porosity is often economically unfeasible, and so a quantitative relationship between impurity/pore morphology and bulk mechanical properties is of great interest.

Traditional methods for characterizing and modeling PMMCs have been reviewed by Li *et al*.[8,9] These techniques can be applied to other two-phase materials and can be broken down into two general approaches: (1) those based on two-dimensional (2-D) image analysis of sections through three-dimensional (3-D) microstructural domains of interest[10–13] and (2) those based on 3-D image acquisition.[5,8,9,14–17]

Extrapolation of 3-D microstructural variables from 2-D image analysis is generally limited to nontextured materials containing regularly shaped second-phase particles. However, many real PMMCs contain irregularly shaped reinforcement particles, which result in nonuniform stress distributions in the local matrix, and this region of localized plastic deformation around an embedded particle can be the initiation site of fatigue failure.[9,10,18] Therefore, idealized reinforcement geometry can give misleading results when damage mechanisms are considered. There is a need for fast and accurate generation of models from real microstructures rather than simplified ellipses or ellipsoids.

Serial sectioning is an established technique used to visualize the 3-D distributions of second-phase particles.[5,8,9,14–17] For example, Kral[17] used serial sectioning to characterize the morphology of cementite precipitates. More recently, Chawla *et al*.[19] used serial sectioning and finite-element analysis to model the stress-strain behavior of a representative volume element of Al-SiC$_p$ composite, with good agreement of Young's

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This article is based on a presentation made in the symposium "Computational Aspects of Mechanical Properties of Materials," which occurred at the 2005 TMS Annual Meeting, February 13–17, 2005, in San Francisco, CA, under the auspices of the MPMD–Computational Materials Science & Engineering (Jt. ASM-MSCTS) Committee.