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Strength characterization of Al/Si interfaces: A hybrid method of nanoindentation and finite element analysis

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Abstract

A novel hybrid method of nanoindentation and finite element analysis is used to characterize the silicon particle indentation strength and the mechanical properties of Al/Si interfaces in an aluminum matrix composite. The indentation threshold strength is found to be strongly dependent on the aspect ratio, up to 2, of the buried portion of cylindrically shaped particles. The indentation resistance comes from the plastic-flow strength of the matrix and the slip strength of the interface. The interface slips during loading and opens up during unloading. An element-size-dependent finite element cohesive-zone law is used to extract the interface properties; the results compare well with atomistic estimations.

Keywords: Nanoindentation; Metal–matrix composites (MMC); Finite element analysis (FEA); Interface strength

1. Introduction

In recent years, metal–matrix composites (MMCs) have replaced conventional materials for many structural and tribological components due to their superior mechanical properties, such as light weight, high stiffness and strength, and excellent wear and creep resistance. The performance gain of MMCs is primarily achieved by distributing the load bearing more in the reinforcement phases than in the matrix. The reinforcement/matrix interfaces in such composites play a crucial role as the medium of load transfer in determining the overall mechanical performance of the MMCs. Therefore, it is important to characterize the mechanical properties of the interfaces for tailoring the microstructure of the composites.

The mechanical property characterization of solid interfaces is typically composed of two parts. One is the structural and/or chemical composition characterization. The other is the deformation and failure process characterization, or in other words, strength characterization. While the structural characterization of the interfaces can be readily made with various electron microscopy techniques [1–3], the strength characterization is still a great challenge, especially at a small length scales. It has been widely recognized that the fracture process of an interface is a multiscale phenomenon covering the atomistic scale to the macroscopic laboratory scale [4]. As a consequence, the strength characterization is highly dependent on the length scale of interest. Typical reinforcement sizes of MMCs range from submicron to tens of microns, and quantitative study of interface strength at these length scales has been difficult, both experimentally and computationally. The experimental measurement of interface strength has seldom been carried out at these length scales. Most of the existing computational continuum modeling [5–8] has been just focused on developing simulation techniques for parametric studies which require experimental validations and verifications. Although atomistic simulations of interface failure [9–12] can imitate the fracture process at a small length scales computationally, the time and length scales which they can handle are so small that scale bridging is

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needed for the simulation results to be applied to engineering problems in realistic time and length scales.

The recent development of nano- and micromechanical test instruments, e.g. nanoindenters and atomic force microscopes, makes it possible to measure mechanical properties with fine force and displacement resolutions. In this work, we used a nanoindenter to measure the plastic flow characteristics of the aluminum matrix and the Al-Si interface strength of a hypoeutectic Al-Si alloy by indenting individual silicon particles. The Al-Si alloy is considered as an "in situ" composite, since the hard silicon particles in the aluminum matrix are formed during its casting process. The alloy is one of the primary replacements for steel and cast iron in the automotive industry in the quest to reduce vehicle weight and increase fuel efficiency [13].

Interface strength and/or failure processes are often modeled in a framework of a cohesive zone model (CZM) [5,6,8]. A CZM is typically used to emulate interfacial slip and decohesion processes at various length scales. Cohesive zone modeling assumes that the slip and decohesion processes can be described by the relationship between cohesive traction and separation displacement across the cohesive zone. The relationship is the constitutive relation of the cohesive zone; it depends on the resolution of the deformation kinematics employed in modeling the deformation field which surrounds the cohesive zone. Within the framework of continuum deformation kinematics of linear elasticity, Hong and Kim [14] developed the field projection method (FPM) to extract crack-tip cohesive zone laws of a homogeneous isotropic elastic solid. The method was then extended by Choi and Kim [15] to extract the intrinsic nanoscale CZM laws of an interface between two anisotropic elastic solids.

Modeling of the interface failure processes of MMCs, however, typically requires finite element analysis of the inelastic deformation of the matrix. In this paper, a new framework of a finite element cohesive zone model called the normal-separation induced linear softening cohesive zone model (NILS-CZM) is introduced to simulate the Al/Si interfacial slip and decohesion processes. In the NILS-CZM, the strength of the cohesive zone is scaled from the intrinsic cohesive zone strength to that of the finite element model. The scale bridging is made by forcing the energy release rate of crack growth to be equivalent to the energy consumption rate of the cohesive zone opening, compatible with the admissible finite element deformation (see the Appendix for more details). The NILS-CZM enables us to characterize the interface strength with a newly developed hybrid method of nanoindentation and finite element analysis. In addition, the scale-bridging capability of the NILS-CZM allows us to compare the results with the quantities obtained by molecular dynamics simulations of the failure process at the atomistic scale.

The remainder of this paper is organized as follows. In Section 2, the particle nanoindentation problem is defined, and the approach taken to solve the problem is introduced. In Section 3, we describe the experimental procedures and present the experimental results that are processed with a dimensional analysis. Section 4 covers the finite element analysis and the extraction of interface properties through the comparison between the experimental and finite element modeling (FEM) results. In Section 5, we discuss the comparison between the values of the interface properties measured experimentally and estimated by atomistic simulations. Concluding remarks are given in the last summary section.

2. Problem definition of particle nanoindentation

The most generic configuration of the particle nanoindentation problem is considered, as shown in Fig. 1a. The geometry of the particle is taken to be a round-bottomed cylinder that is vertically embedded in the matrix. The diameter of the particle cross-section is denoted by D, the buried depth H. The particle slightly protrudes out

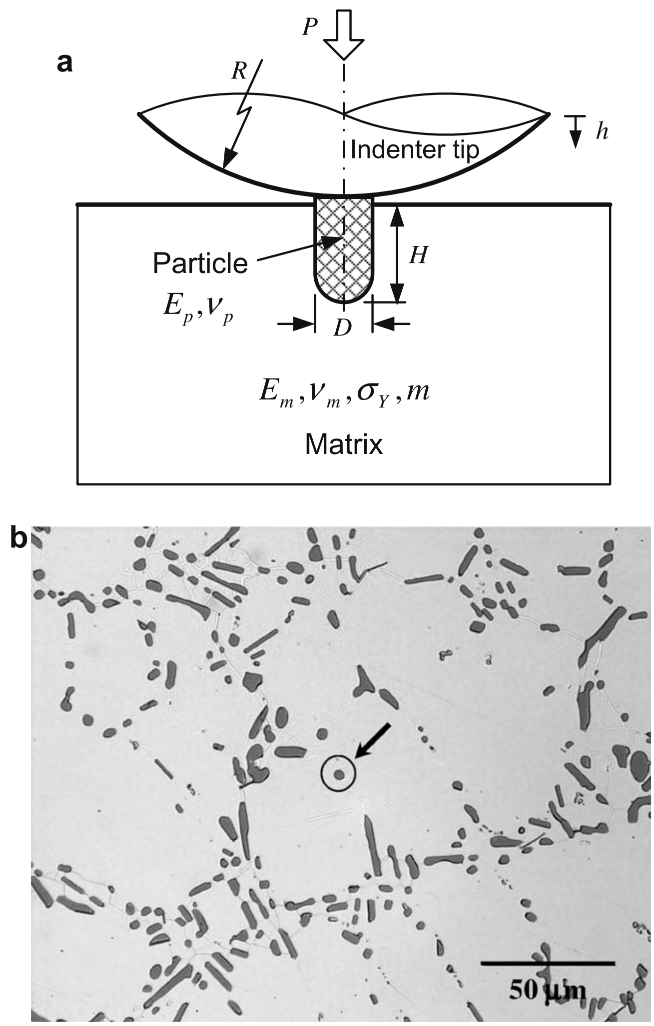

Fig. 1. (a) A schematic of a nanoindentation test of an elastic particle embedded in a ductile metal–matrix. (b) Optical microscopy image of the cross-section microstructure of the hypoeutectic Al-Si alloy. A silicon particle selected for a nanoindentation test is shown inside the circle.