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Mechanical properties study of particles reinforced aluminum matrix composites by micro-indentation experiments

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Abstract By using instrumental micro-indentation technique, the microhardness and Young's modulus of SiC particles reinforced aluminum matrix composites were investigated with micro-compression-tester (MCT). The micro-indentation experiments were performed with different maximum loads, and with three loading speeds of 2.231, 4.462 and 19.368 mN/s respectively. During the investigation, matrix, particle and interface were tested by micro-indentation experiments. The results exhibit that the variations of Young's modulus and microhardness at particle, matrix and interface were highly dependent on the loading conditions (maximum load and loading speed) and the locations of indentation. Micro-indentation hardness experiments of matrix show the indentation size effects, i.e. the indentation hardness decreased with the indentation depth increasing. During the analysis, the effect of loading conditions on Young's modulus and microhardness were explained. Besides, the elastic–plastic properties of matrix were analyzed. The validity of calculated results was identified by finite element simulation. And the simulation results had been preliminarily analyzed from statistical aspect.

1. Introduction

The micro-mechanical properties of materials have been a popular and interesting subject nowadays, since the material exhibits different properties from micro scale to macro scale, such as scale effect. Through indentation experiment, it is very effective to explore the mechanical properties in micro scale.[1] Discontinuous particles reinforced metal matrix composites (MMCs) have generated much interest recently due to their promising mechanical properties.[2–9] The mechanical properties of MMCs generally depend on the microstructures of the materials, such as particle size effect.[10,11] The optimization of the mechanical properties of composites is based on the knowledge of the relationship between the microstructure and the macroscopic response of MMCs. Up to now, though a considerable volume of literature regarding the microstructure and macroscopic mechanical behavior exists[12–15]; their micro-mechanical behavior between particles and matrix has not been examined in detail. From the design perspective as well as structure aspect, it is imperative to develop a detailed

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understanding of the micro mechanical and elastic–plastic properties of MMCs.

One of the widely used techniques for the evaluation of the elastic and plastic properties at both microscopic and macroscopic level is the depth-sensing instrumented indentation.[16–20] It has long been recognized that instrumented indentation is a powerful technique for studying resistance of materials against deformation. For this reason, indentation has been widely used as an indirect method to characterize many fundamental mechanical properties of materials including Young's modulus and hardness based on the experimentally determined load-unload curves (*P*–*h*).[1,21–26] The first studies in this field can be traced back to the works of Ternovki et al. followed by the contributions of Nix et al.[27,28] also Oliver and Pharr[23], Lu and Suresh.[29] Nowadays, this subject has been widely studied from theoretical and experimental investigations. For MMCs, scientists have been making preliminary exploration for both indentation experiments and simulations.[30–36] In this paper, a study of instrumented micro-indentation for the characterization of MMCs is reported. The aim of the study is to explore the properties of MMC and to provide a thorough analysis of the deformation during loading/unloading under different conditions.

2. Experiments and theory

2.1. Experimental methods

The specimens investigated (aluminum alloy reinforced by 15% SiC particles) were made by a powder metallurgy route. The raw aluminum was prepared by atomized powder, and then mixed with SiC particle. After hot extrusion (extrusion ratio is 9.8 to 1, at extrusion temperature 773 K), the SiCp/Al composite was obtained. Before testing, the specimens have been annealed at 673 K for 2 h. The content of matrix is shown in Table 1. In this composite, the particle size distributed within the range of 1–12 μm, and the major size is 3–8 μm; the particle aspect ratio lies around 1–2 after statistic analysis by the maximum/minimum axis ratio. The metallographic structure of the study material is shown in Fig. 1. In this figure, the particles (embossed) distributed scatteredly in matrix while assembling in some place and a few of black holes are the positions where particles dropped out during preparing specimens.

Table 1 Chemical composition of matrix in SiC particle reinforced Al matrix composites.

Element	Cu	Mg	Mn	Fe	Si	Zn	Ti	Al
wt.%	4.10	0.64	0.54	0.37	0.34	0.10	0.02	Bal.

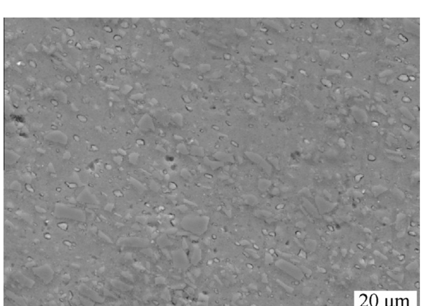

Fig. 1 SEM metallographic structure of MMC.

Instrumented micro-indentation mechanical properties have been measured by using a Shimadzu micro-compression-tester type W501 (MCT) equipped with a Berkovich diamond indenter. And the morphologies of composite were examined by a TESCAN VEGAII-LMH scanning electron microscope (SEM). During the tests, specimens for indentation investigation were performed at different loads (10–25 mN, and 80–400 mN), different micro structures (particle, matrix and interface), and different loading speeds (2.231, 4.462 and 19.368 mN/s). Furthermore, the matrix in MMC has been much more focused in this study to explore the detail micro-mechanical behavior. The indentation load–displacement data obtained during one cycle of loading and unloading was recorded simultaneously. And the micro mechanical properties corresponding to the measuring point were then analyzed from the load–displacement curve.

2.2. Theory

In the indentation field, Oliver and Pharr[22,23] have shown their methods based on the Berkovich indenters. The law relating the applied load, *P*, to the penetration depth, *h*, follows Kick's law:

$$P = Ch^2 \tag{1}$$

where *C* is loading curvature which depends on elastic and plastic material properties, as well as indenter geometry. Similarly, the unloading curve follows a simple power-law relation determined by a least square fitting procedure:

$$P = B \times (h - h_f)^m \tag{2}$$

where *B* and *m* are fitting parameters and h_f is the residual depth after complete unloading. The elastic contact stiffness, *S*, is given by the first derivative at the peak load of unloading curve:

$$S = \left.\frac{dP}{dh}\right|_{h=h_m} \tag{3}$$

where h_m is maximum penetration depth. The depth, along which contact is made between the indenter and the specimen, can be estimated and given by

$$h_c = h_m - \gamma \frac{P_m}{S} \tag{4}$$

where P_m is the peak load at the onset of unloading, and γ is a tip-dependent geometry factor, which is equal to 0.72 for a conical indenter, 0.75 for a Berkovich indenter and 1 for a flat cylindrical indenter.[1,23,37,38] From the knowledge of h_c and taking into account the indenter shape, the developed contact area, *A*, can be given by[39]

$$A = 24.56h_c^2 \tag{5}$$

Then the indentation modulus, E^*, is expressed as[23]

$$E^* = \frac{\sqrt{\pi}}{2\beta} \times \frac{S}{\sqrt{A}} \tag{6}$$

where β is a constant associated with the indenter shape. It has been used to account for deviations in stiffness caused by the