Available online at www.sciencedirect.com
SCIENCE DIRECT®
Scripta Materialia 54 (2006) 263–268
Scripta MATERIALIA
www.actamat-journals.com

Nanoindentation measurement of surface residual stresses in particle-reinforced metal matrix composites

E.R. Olivas [a,b], J.G. Swadener [b], Y.-L. Shen [a,*]

[a] *Department of Mechanical Engineering, University of New Mexico, Albuquerque, NM 87131, USA*
[b] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*

Received 15 June 2005; received in revised form 8 September 2005; accepted 16 September 2005
Available online 13 October 2005

Abstract

The surface residual stresses in SiC particle-reinforced Al matrix composites are measured using a recently developed nanoindentation technique. The tensile biaxial residual stress in Al is found to increase with the particle concentration. The stress magnitudes are in reasonable agreement with those from numerical modeling.

Keywords: Nanoindentation; Metal matrix composites; Residual stresses; Finite element analysis

1. Introduction

The mechanical performance of composite materials is influenced to a great extent by the internal residual (pre-existing) stresses. In engineering alloys reinforced with ceramic particles, the main residual stress field is generated during cooling from the processing temperature to ambient temperature, caused by the thermal expansion mismatch between the ceramic particles and the surrounding metal matrix. Due to the generally greater magnitudes of coefficient of thermal expansion of metals compared to ceramics, the matrix and the reinforcement particles will be in a state of, respectively, tension and compression. Experimental techniques such as X-ray and neutron diffraction have been developed and applied to the measurement of thermal residual stresses in metal matrix composites [1–12]. In the present study, we employ the nanoindentation technique to probe the surface residual stresses in silicon carbide (SiC) particle-reinforced aluminum (Al) matrix composites.

The utilization of instrumented indentation in measuring the residual stress on metallic surfaces is relatively new. Tsui et al. [13] studied the effects of pre-existing stress in an aluminum alloy on nanoindentation hardness with the sharp Berkovich indenter, and observed that hardness (determined by standard nanoindentation techniques) increases in compression and decreases in tension. However, the extent of hardness variation is small and is influenced by the pileup geometry, as revealed by the finite element analysis by Bolshakov et al. [14]. Suresh and Giannakopoulos [15] proposed a simple method for measuring residual stress with sharp indenters, based on the difference in contact area of stressed and stress-free materials indented to the same depth. Since the effect of residual stress on the contact area is relatively small, it is not apparent if the method can be practically employed in cases where the residual stress is not too close to the yield strength of the material. Swadener et al. [16] presented a new technique based on spherical indentation, which can be more sensitive to residual stress than measurements with sharp indenters in certain deformation regimes. Experiments have verified that this method is accurate to within 10–20% of the specimen yield strength and can be useful for making localized measurements. The present work utilizes the spherical indentation technique developed in Ref. [16] to determine the representative thermal residual stress in the Al matrix of the composites. The composites

* Corresponding author.
E-mail address: shenyl@me.unm.edu (Y.-L. Shen).

1359-6462/$ - see front matter
doi:10.1016/j.scriptamat.2005.09.021

investigated contained SiC particles with volume fractions from 0% to 30%. We attempt to illustrate the feasibility of this technique in measuring the residual stress on a localized scale in materials with heterogeneous constituents.

2. Experiments

2.1. Materials

An Al–Cu–Mg alloy (2080 Al, with composition 3.6 Cu, 1.9 Mg, 0.25 Zr), unreinforced and reinforced with 10, 20 and 30 vol.% SiC particles, was used in this study. They are henceforth designated as 2080, 2080/SiC/10_p, 2080/SiC/20_p and 2080/SiC/30_p, respectively, in this article. All materials were processed by a powder metallurgy route and extruded. The average reinforcement particle size, after extrusion, is about 6 μm for 2080/SiC/10_p and 2080/SiC/30_p and about 23 μm for 2080/SiC/20_p. A representative optical micrograph of 2080/SiC/20_p is shown in Fig. 1. A detailed characterization of the reinforcement size, distribution and morphology can be found in Ref. [17].

The composites and unreinforced alloy were solution treated at 493 °C for 2 h and water quenched. This thermal excursion is intended to be the primary cause of thermal residual stresses generated inside the composites. To suppress precipitate formation at room temperature, the quenched specimens were stored in a freezer until subsequent handling, polishing and testing. An automatic grinder/polisher was used for grinding specimens on 180 through 1200-grit silicon carbide papers. Polishing was performed with diamond pastes from 3 to 0.25 μm particle size and finally with 0.06 μm colloidal silica.

2.2. Nanoindentation procedure

A Nano Indenter XP with a spherical indenter tip was used to probe the Al matrix between SiC particles. The indenter tip was fabricated from a conical ground diamond with a nominal radius of 10 μm. The actual radius of the tip was determined to be 9.5 ± 0.3 at depths of 30–50 nm. Nanoindentation was conducted in load control with displacement and load resolutions being 0.01 nm and 50 nN, respectively. A constant loading rate of 25 μN/s was applied; after a 15 s hold at the prescribed maximum load, unloading took place at the same rate until the load was completely removed. Three maximum load values were used for each specimen: 1, 2 and 3 mN. Eight to 15 indentations were performed at each load on each specimen, although some were not successful due to improper placement of the indenter tip with reference to the preferred matrix location (away from particles). No thermal drift correction was applied to the data due to the relatively low loads. However, the threshold for thermal drift was set to be less than 0.05 nm/s before the experiments commenced.

2.3. Determining the residual stress

The method is predicated upon the extrapolation of spherical indentation data from the post-yield regime to determine the contact radius at the onset of yielding. It requires the yield strength of the material to be known. The biaxial stress can then be calculated based on a closed form analytical solution. The detailed theoretical background and experimental procedures follow those in Ref. [16]. Only the salient aspects are outlined in this section. The geometric parameters involved are shown in the schematic in Fig. 2, where R is the indenter radius, a is the contact radius, h is the total penetration depth when loaded, h_c is the depth at which contact occurs during loading, and h_f is the final (residual) depth of indentation upon unloading. When a is small compared to R during indentation, the classical Hertzian contact theory can be employed up to initial yielding. The relation between the total depth of penetration h and contact radius a is

$$h = \frac{a^2}{R}. \tag{1}$$

The applied load P is related to h by

$$P = \frac{4}{3} E_e R^{1/2} h^{3/2}, \tag{2}$$

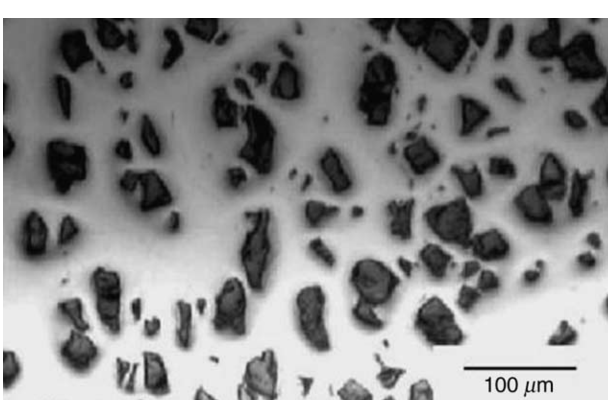

Fig. 1. Optical micrograph of the composite 2080/SiC/20_p.

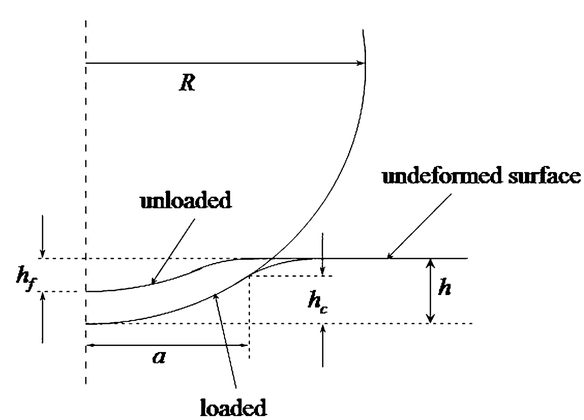

Fig. 2. Schematic showing the indentation geometry and definition of parameters.