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Constitutive modeling of elastoplasticity in spark-plasma sintered metal-matrix nanocomposites

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ABSTRACT

A methodology to model the elastoplastic constitutive response of spark plasma sintered metal matrix particulate nanocomposites is presented. The formulated methodology incorporates the effect of Hall-Petch strengthening, Orowan strengthening, dislocation density strengthening, load transfer strengthening and porosity on the elastoplastic response of metal matrix nanocomposite using a mean-field homogenization approach used in conjunction with a plasticity hardening function for metal matrix that is dependent on the metal matrix crystallite size, inclusion particle size and inclusion volume fraction. The effect of sintering process parameters is incorporated into the model using a grain growth model that can estimate the average matrix crystallite size as a function of sintering time, sintering temperature, inclusion size and inclusion volume fraction. The formulated methodology has been validated against experimentally measured crystallite sizes and stress-strain responses of ball-milled and spark plasma sintered Al-Al_2O_3 nanocomposite samples synthesized during the current work. Additional validation of the methodology against the experimental stress-strain response of nanostructured aluminum reported in the literature has also been carried out.

1. Introduction

Metal matrix nanocomposites (MMNCs) are very promising materials that are seeing significant interest from investigators worldwide due to their suitability to a wide range of applications. MMNCs show higher strength and stiffness compared to conventional composites while maintaining the ductility of the metals. The use of a variety of matrix metals having several types of nanoscale inclusions has been reported in the literature. The most commonly reported metals matrices include Aluminum [1–6], Magnesium [7–9], Copper [10] and their alloys. For inclusions, the use of ceramic compounds such as SiC [2,11,12], Al_2O_3 [4–6,10,13], and CNTs [8,14–16] has been extensively reported.

MMNCs show significant enhancement of mechanical properties at very low volume fractions of reinforcements [17]. This is because several new strengthening mechanisms come in play as the reinforcement size is reduced to the nanometer scale. These include the load transfer effect, Hall-Petch strengthening, Orowan strengthening and property mismatch. Because of the load transfer effect, the strength of the soft matrix material is enhanced when the load is transferred to the stiffer and harder reinforcement. Hall-Petch strengthening occurs due to the interaction of dislocations with the grain boundaries. The fact that polycrystalline materials are stronger than single crystals was first reported by Hall [18] and Petch [19] in the early 1950s. Orowan strengthening [7,17,20] occurs due to the interaction of the reinforcement particles with dislocations causing dislocation bowing leading to Orowan loops. Finally, the property mismatch [7,9,17,20] causes the generation of geometrically necessary dislocations (GNDs) during straining. The overall strengthening of the nanocomposites is a combination of the above-mentioned strengthening mechanisms.

Several models to estimate the strength of nanocomposites and nanostructured metals, in general, have been reported in the literature [7,9,20–24]. Dunstan and Bushby [21] have presented a compressive analysis of various equations that can be used to model Hall-Petch effect using several data sets from literature. Khan et al. [22], using experimental results for Al and Fe, showed that as crystallite size is reduced, the parameters of Hall-Petch equation change. They also formulated a crystallite size, strain rate, and temperature dependent hardening law for nano-crystalline metals. An improved version of the model was presented by Farrokh and Khan [24]. For estimating the yield strength of metal matrix nanocomposites, Zhang and Chen [9] formulated a model that incorporated the effects of load transfer strengthening, Orowan strengthening and dislocation density strengthening mechanisms. Sanaty-Zadeh [20] compared Zhang and Chen's model with a modified Clyne model and found out that Zhang and Chen's model under-predicted the yield strength of nanocomposites

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because it did not take into account the Hall-Petch effect. Mirza and Chen [7] presented an improved model that also took into account the Hall-Petch effect.

In the current work, a methodology to model the elastoplastic response of spark plasma sintered metal matrix particulate nanocomposites is presented. The methodology comprises of two main parts: a model for estimation of average matrix crystallite size in spark plasma sintered metal matrix composites and elastoplasticity constitutive model for the composite based on matrix crystallite size and inclusion particle size. The elastoplasticity constitutive model can take into account the effects of matrix crystallite size, inclusion particle size and inclusion and porosity volume fractions on the elastoplastic stress-strain response of metal matrix nanocomposites. The grain growth model can be used to calculate the average crystallite size of the metal-matrix as a function of sintering time, sintering temperature, inclusion volume fraction and inclusion size. The formulated methodology has been validated against experimentally measured crystallite sizes and stress-strain responses of ball-milled and spark plasma sintered Al-Al_2O_3 nanocomposite samples synthesized during the current work. Additional validation of the methodology against the experimental stress-strain response of nanostructured aluminum reported in the literature has also been carried out.

2. Experimental work

2.1. Materials

Aluminum powder, 99.88% purity supplied by Aluminum Powder CO. LTD, and α-Al_2O_3 (with an average particle size of 150 nm), 99.85% purity, supplied by ChemPUR Germany, were used in this investigation. Fig. 1 shows the micrographs of Al and Al_2O_3 powders. More information on the chemical composition and particle size distribution of the aluminum raw powder was reported elsewhere [25].

2.2. Methodology and process parameters

Mechanical alloying was used to synthesize Al-10 vol% Al_2O_3 nanocomposite powder. Pure aluminum, as a reference material, was milled for 24 h. A planetary ball mill (Fritsch Pulverisette, P5, Idar-Oberstein, Germany) was used to perform the milling experiments. The powders were milled in argon inert gas to avoid oxidation. In all experiments, the ball-to-powder weight ratio was maintained at 10:1 and the speed was maintained at 200 rpm. Stainless steel vials (250 mL in volume) and balls (10 mm in diameter) were used. The sticking of the powder to milling balls and vials was minimized using stearic acid (1.5 wt%). Spark plasma sintering machine (FCT system, Germany), model HP D 5, was used to sinter the as-received aluminum powder and the mechanically alloyed pure aluminum and the Al-10 vol% Al_2O_3 powders. Disc-shaped specimens were prepared using a graphite die of 20 mm diameter. A compaction pressure of 50 MPa and a heating rate of 200 °C/min were used in all sintering experiments. Aluminum as-received and milled for 24 h, and Al-10 vol% Al_2O_3 milled for 24 h were sintered at a temperature of 550 °C for holding time of 20 min. More details on the synthesis of Al-Al_2O_3 nanocomposites using mechanical alloying and spark plasma sintering were reported elsewhere [25].

2.3. Microstructure characterization

Microstructural characterization of the ball-milled powder and spark plasma sintered samples was carried out using a field emission scanning electron microscope (FE-SEM) equipped with energy dispersive spectroscopy (EDS). X-ray diffraction analysis with Cu radiation (wavelength λ = 0.15405 nm) was carried out to characterize the crystallite size of the aluminum matrix. The bulk density of the consolidated samples was measured according to the Archimedes principle using Metler Toledo balance density determination KIT model AG285.

2.4. Mechanical characterization

Digital microhardness tester (Buehler, USA) was used to measure the microhardness of the prepared materials. The obtained hardness values were the average of 12 readings. Conditions of a load of 100 gf and a time of 12 s were maintained in all measurements. Compression tests were performed according to ASTM E9-89a standard using Instron universal testing machine model 3367. Multiple standard cylindrical specimens were machined from each sintered sample (25 mm diameter and 12 mm thickness) using wire EDM to final dimensions of diameter = 6 mm (± 0.02 mm) and length =12 mm (± 0.02 mm). Compression tests were carried out using a compression rate of 0.5 mm/min, and the compression load was applied parallel to the direction of the uniaxial spark plasma sintering pressure.

3. Modeling methodology

The elastoplastic response of metal matrix nanocomposites depends on the intrinsic properties of the matrix and inclusions and on the interactions between the metal matrix and inclusions particles. The constitutive behavior of the metal matrix itself is a function of average crystallite size of the matrix and the size and properties of the inclusion

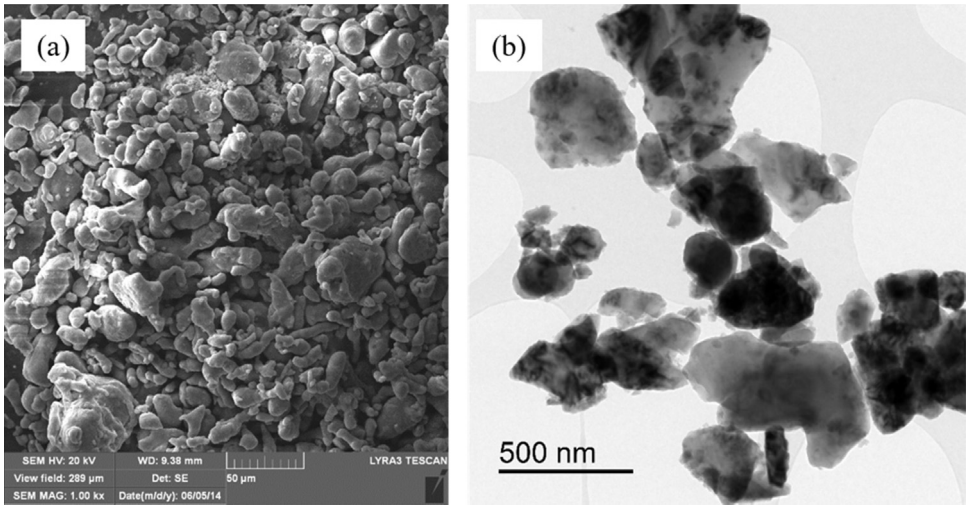

Fig. 1. (a) FE-SEM micrograph of Al powder (b) TEM micrograph of Al_2O_3 powder.