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Fabrication and mechanical property prediction of carbon nanotube reinforced Aluminum nanocomposites

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ABSTRACT

The use of carbon nanotubes (CNTs) in nanotechnology and leading industries is of extreme importance due to its various applications. One such application is producing Aluminum reinforced nanocomposites which may find applications in the aerospace and automobile industries. Scientists and engineers have, recently, concentrated increasing attention on the manufacturing and modeling of such materials. This paper deals with preparing Carbon Nanotube Reinforced Aluminum Nanocomposite (CNRAN) and predicting its mechanical and surface properties using the finite element method (FEM). To prepare the reinforced nanocomposite, a pre-alloyed powder was milled in a planetary ball mill under the argon atmosphere. Multi-wall carbon nanotubes (MWCNTs) were then added to the powder in a particular procedure. Next, a finite element model consisting of MWCNTs as the fibers and Aluminum as the matrix was constructed. A series of nano-indentation tests were carried out to obtain the mechanical and surface properties of the constructed material. The finite element models were then used to predict the results obtained from real indentation tests. The predicted hardness and elastic modulus from the FE model show good agreement with experimental findings.

1. Introduction

Recently, a lot of effort has been directed toward the development of nanoindentation equipment and techniques for measuring the mechanical properties of nano-scale materials [1–4]. The most extensively used nanoindentation method for evaluating the elastic modulus and hardness of materials was proposed by Oliver and Pharr [5], according to which the slope of the unloading curve which is usually nonlinear is used to calculate the elastic modulus. Hardness is determined by the marked projected area of the indenter and the peak load applied during the test.

Hardness being a considerable property of materials, its measurement has of long been a preoccupation and concern for metallurgists. Measurement of hardness of a material consists of applying a high static load on an indenter of known geometry and an optical microscope to measure the print area left in the material.

With advances made in miniaturization, different methods have been developed to measure this property in nanoscales. With the publication of Oliver and Pharr in the 90s, one of the most popular methods, namely the Instrumented Indentation Testing (IIT) also known as Depth Sensing Indentation (DSI), appeared. This quasi-static indentation method is achieved by pressing an indenter, usually a diamond of known geometry, into the test surface. During this indentation, the penetration depth and the applied load are monitored both during the insertion and withdrawal of the indenter, resulting in a loading and unloading curve of the applied load as a function of the penetration depth, each performed in 30 s. An important advantage of IIT is that an instrumented hardness H and an instrumented elastic modulus E are assessed by mean of a series of mathematical equations.

Atomic-scale indentation of thin films and nanostructured materials is an effective experimental technique for the analysis of material properties. This technique consists of pushing a sharp tip made of a hard material, usually diamond, into a matrix/substrate material under investigation and measuring the loading force as a function of indentation depth. Material properties of the matrix are then evaluated from the analysis of a resultant load-indentation curve and the properties of the tip as well as the plastic behavior of the substrate material.

By numerical calculation of the load–displacement curves, the mechanical properties, Young's modulus and hardness can be obtained from nano-indentation test [5,6]. Today; scientists are also using molecular dynamic (MD) models for finding mechanical properties of such materials [7]. However, molecular models are usually time-consuming and expensive, especially for large models of several micrometers. Also, surface-based properties such as

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hardness are difficult to calculate using these techniques. It is the aim of this study to find a less expensive but still accurate way to obtain the elastic and surface properties of reinforced nanocomposites. Many studies have been already conducted to simulate the nano-indentation test using the finite element method [8], some of them will be addressed in the next paragraphs.

A computer aided engineering (CAE) assisted nano-indentation measurement system has been developed and applied for quantitative evaluation of the elastic properties of anisotropic thin films by Sasaki and his coworkers [9]. The measurement system is based on a nano-indentation test with a spherical indenter and the optimal process is simulated using the finite element method. The anisotropic mechanical properties of thin films were measured by the proposed CAE-assisted nano-indentation measurement system. The results indicate that the method is very effective for evaluating the anisotropic mechanical properties of thin film materials.

In a separate study by Toparli and Koksal [10], the FEM was applied for studying the hardness (H) and yield strength (Y) of dentin subjected to a nano-indentation process. The nanoindentation experiments were then simulated using the ABAQUS finite element software package. The test was performed using a spherical indenter and the simulation was accomplished using the axisymmetric finite element analysis. The load versus displacement was calculated during the loading–unloading sequence for different elastic moduli (E) and yield strengths. Hardness and maximum principal compressive and tensile stresses were plotted for different elastic moduli depending on the yield strength. The dentin was assumed to be isotropic, homogenous, and elasto-plastic. The theoretical results outlined in their study were compared with the experimental results reported in the literature to estimate the hardness and yield strength of the dentin. A similar study was conducted by Gun [11] using boundary element method.

Swaddiwudhipong et al. [12] investigated the strong size effects of materials on modeling of the nanoindentation test which can be used to predict mechanical properties of materials different from their bulk characteristics. They showed that classical plasticity theory was unable to account for this phenomenon. It has been shown that introducing the strain gradient plasticity theory in the analysis makes it capable of capturing successfully the size effects of various materials. A constitutive model for glassy polymers is adopted and implemented as user subroutines in the finite element package, ABAQUS. Numerical analyses of indentations at the micron and submicron levels are carried out to verify the applicability of the model in describing the viscoelastic–plastic behavior of polymers. Substantial discrepancies between the obtained numerical results and experimental data are observed for indentations at the submicron level when the strain gradient effects are not accounted for in the former. However, the discrepancies diminish when the strain gradient effects are included in the constitutive model.

The size effects on nano-indentation were also investigated in a separate study by Huang et al. [13]. The finite element analysis for the strain gradient plasticity theory based on the Taylor dislocation model and the maximum allowable geometrically necessary dislocations (GND) density are used and the results are found to agree very well with the experimental data. Without accounting for the maximum allowable GND density, the indenter tip radius effect alone cannot explain the nano-indentation size effect. It is important to note that their model has a lower limit because once the indentation depth reaches the order of nanometers, discrete dislocation events dominate and the indentation hardness results are scattered. It was shown that the model is not suitable for nano-regimes.

A simple model of the nano-indentation behavior in single crystal materials was proposed by Lin et al. [14]. Their proposed model is based on results obtained using various specimens. They claimed it can be used to elucidate the behavior of bulk materials under nanoindentation. In [15,16] investigations were carried out on single crystals and alloys by nano-indentation respectively.

The indentation response of Aluminum–matrix SiC particle-reinforced metal matrix composites (PR-MMC) impressed by a circular indenter has been numerically analyzed under the two-dimensional discrete dislocation plasticity combined with the ANSYS finite element software [17]. The authors addressed in detail the dependence of nominal hardness on certain factors, including particle size, particle area fraction, matrix thickness between the indenter and the particle, indentation location and particle shape. They showed that the nano-indentation response of PR-MMCs is strongly associated with the particle area fraction of PR-MMCs as well as the blocking of dislocation free gliding within the matrix.

In this paper, first, CNT reinforced Aluminum matrix composite was prepared from multiwall nanotubes (MWCNTs) and Aluminum powder. Next, indentation tests were carried out using diamond Berkovich indenter, and the results were used to find the hardness and Young's modulus of the nanocomposite experimentally. Two finite element models with different degrees of freedom and nanotube distributions were then constructed and used to predict numerically the mechanical properties of the nanocomposite.

2. Materials and methods for the production of CNT reinforced Aluminum matrix nanocomposites

Al2024 is one of the most widely used Aluminum alloys in aerospace and automobile industries due to their high strength and specific stiffness. To prepare nanostructured Al2024 matrix, Al–4.1 wt.%Cu–1.9 wt.%Mg–0.5%Si (Al2024) pre-alloyed powder was milled in a planetary ball mill (Fritsch P7 type) under argon atmosphere [18]. The milling media consisted of five 20 mm diameter balls confined in a 120 ml volume vial. Ball milling was carried out with a ball-powder mass ratio of 10:1 and a rotation speed of 500 rpm for 30 h. Stearic acid 0.5 wt.%, [$CH_3(CH_2)_{16}COOH$] was used as the process control agent (PCA). Scanning electron microscopy (SEM-Philips XL30) was used in order to evaluate the morphology changes of Al2024 powder particles through ball milling for 30 h.

Multi-wall carbon nanotubes (provided by Research Institute of Petroleum Industry) which produced using the catalytic chemical vapor deposition (CCVD) technique with a purity of ~90% were used as reinforcement. To eliminate the catalyst particles and to disperse MWCNTs, they were immersed in concentrated nitric acid for 12 h. MWCNTs were then washed with distilled water and dried at 120 °C. MWCNT samples were characterized using a transmission electronic microscope (TEM) (Philips CM12). They were, subsequently, added to the ethanol and dispersed using an ultrasonic shaker for 1 h in order to obtain a uniform distribution. Then, as-milled Al2024 powder was added to the MWCNTs–ethanol solution and the mixture was dispersed using an ultrasonic shaker for 30 min. Subsequently, the mixed powders were dried at 120 °C in vacuum (~10–2 Pa). In order to improve the dispersion of MWCNTs in the nanocomposite powders, ball milling was executed on nanocomposite powders for 4 h. In this study, 2 vol% of MWCNTs were mixed with milled-Al2024 powder.

Finally, Al2024-MWCNT nanocomposite powder was compacted at 500 °C under 250 MPa in a uniaxial die and cooled in the air to produce disks with a diameter of 50 mm and a thickness of 10 mm. The duration of hot pressing was about 30 min.

Fig. 1a and b shows the SEM images of bundles of carbon nanotubes. According to Fig. 1a, MWCNTs have outer diameters of 20–40 nm and a large aspect ratio. It is evident that most MWCNTs enwind with each other, which apparently has a negative effect on