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An analytical model for elastic modulus calculation of SiC whisker-reinforced hybrid metal matrix nanocomposite containing SiC nanoparticles

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ABSTRACT

In the present work, elastic modulus of a hybrid aluminum matrix nanocomposite (HAMNC) reinforced with silicon carbide (SiC) whiskers and SiC nanoparticles is analyzed. To this end, a new multi-scale analytical model is developed to calculate the effective elastic modulus of the HAMNC. The SiC nanoparticle aggregation into the HAMNC, frequently encountered in real engineering situations, is simulated. The elastic modulus of HAMNC estimated by the analytical micromechanical model is compared with that directly measured by the experimental method and a good agreement is found between the two sets of results. The effects of volume fraction, aspect ratio and dispersion type of SiC whiskers as well as volume fraction, size and aggregation degree of SiC nanoparticles on the HAMNC elastic modulus are extensively investigated. It is found that the elastic modulus of the SiC whisker-reinforced composite is significantly improved due to the addition of SiC nanoparticles. The results show that the nanoparticle aggregation has a damaging effect on the HAMNC elastic modulus. It is observed that the HAMNC elastic modulus can be enhanced by (i) increasing SiC content, (ii) aligning the SiC whiskers, (iii) increasing the SiC whisker aspect ratio (iv) decreasing the SiC nanoparticle size and (v) uniform dispersion of SiC nanoparticles into the hybrid nanocomposite. The reported results by means of the analytical model can be actually useful to guide design of general hybrid metal matrix nanocomposites with superior effective properties.

1. Introduction

Nowadays, aluminum and its alloys play a critical role in the development of engineering materials [1,2]. This can be due to their capability of forming aluminum matrix composites (AMCs) through a wide variety of reinforcement materials [3,4]. The goal in using reinforcement materials for the fabrication of AMCs is to maximize the mechanical performance of aluminum by improving specific characteristics, such as strength, stiffness, hardness, and wear resistance [5–7]. Among the AMCs, SiC whisker-reinforced AMCs were developed for potential structural applications, especially in the aerospace and automobile industries, owing to the substantial improvements in the mechanical properties of these materials as compared to the monolithic aluminum materials [8–10]. Adding SiC whiskers into aluminum matrix can cause an increase in strength and stiffness, improvement in wear resistance and high-temperature creep resistance, and a decrease in coefficient of thermal expansion [10–12].

Demands on structural materials made of AMCs for better performance in real engineering situations under more severe loads and environmental conditions are increasing. For this purpose, innovative aluminum matrix nanocomposites (AMNCs) achieved by advanced fabrication processes are developed mainly in order to respond to the requirement of new applications [13–15]. AMNC containing SiC nanoparticles is a good example and the growing number of studies emphasizes the interest generated by this AMNC [16–18]. For example, Yao et al. [19] fabricated some specimens of SiC nanoparticle-reinforced AMNCs by the powder metallurgy process. It was shown that by increasing the SiC nanoparticle

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content from 1 to 10 vol%, the yield strength and ultimate tensile strength enhanced from 296 to 343 MPa to 545 and 603 MPa, respectively [19]. In another experimental work, Kollo et al. [20] evaluated the hardness and ultimate tensile strength of AMNCs reinforced with different volume fractions of SiC nanoparticles. The ultimate tensile strength was reported for extruded samples which resulted in 205 MPa for 1 vol% SiC nanoparticle and a strength of 420 MPa for 10 vol% SiC nanoparticle [20]. El-Daly et al. [21] measured the shear modulus, Young's modulus, Poisson's ratio and hardness of AMNC containing different amounts of nano-size SiC particles, including 0, 5 and 10 vol%. Young's modulus of 10 vol% SiC nanoparticle-reinforced AMNC was reported to be 97.1 GPa, which is much higher than that for pure aluminum (72.6 GPa) [21]. Also, Boostani et al. [22] indicated that the addition of 3 vol% SiC nanoparticle into the AMNC leads to 273 and 228% enhancement in yield strength and ultimate tensile strength, respectively, in comparison with that of the pure aluminum matrix. It was reported that strengthening efficiency of SiC nanoparticles is reduced due to their aggregation into the metal matrix [18,22–24]. Thus, the fabrication of SiC nanoparticle-reinforced AMNCs in large scale may be encountered some challenging difficulties.

Another practical use of SiC nanoparticles can be further improvement of the effective properties of existing SiC whisker-reinforced AMCs [25,26]. Aluminum matrix reinforced with SiC whiskers and SiC nanoparticles is called as hybrid aluminum matrix nanocomposites (HAMNCs). This new type of hybrid composite will be an attractive system for high performance materials in service at elevated temperature. Generally, HAMNCs are expected to demonstrate better mechanical properties in comparison with single reinforced composite systems as they combine the advantages of their constituent reinforcements. A literature survey clearly reveals that the effect of adding SiC nanoparticles on the effective mechanical properties of conventional AMCs has been rarely explored. For instance, Zhang et al. [27] fabricated some samples of HAMNCs reinforced with 20 vol% SiC whiskers and 0, 2, 5 and 7 vol% SiC nanoparticles by squeeze casting technique. The experimental tests have shown that the tensile modulus of the HAMNC increases with increasing content of the SiC nanoparticles [27]. There is still a high necessity to study in depth the effect of SiC nanoparticles on the elastic properties of general hybrid metal matrix nanocomposites (HMMNCs). In general, accurate predictions of engineering constants of HMMNCs are necessary for a reliable design of such new systems. However, to the best of our knowledge, no substantial work exists that specifically analyze the mechanical behavior of the hybrid nanocomposite consisting of SiC whisker, SiC nanoparticle and metal matrix. The main novelty of the present work is developing a theoretical approach to predict the elastic modulus of HMMNC reinforced with short fibers and nanoparticles. One of the main features of the proposed approach is considering the effects of size and aggregation of nanoparticles on the elastic behavior of HMMNC.

The evaluation of the HMMNC mechanical properties through experimental tests under different loading conditions can be costly and difficult. Also, the quality of experimental results critically depends on the ability in making homogeneous hybrid nanocomposites with controlled dispersion of nanoparticles. The micromechanical models are an efficient approach to predict the overall behavior of the conventional composite [28–30], nanocomposite [31–33] and hybrid nanocomposite [34–36] systems from the behavior of their constituents. The micromechanical techniques are very cost-effective, especially for various reinforcement/matrix combinations and loading conditions which will provide valuable guidance for analysis and design of HMMNCs.

The objective of the present work is to analyze and calculate the elastic modulus of SiC nanoparticle/SiC whisker-reinforced HAMNC using a physics-based hierarchical approach. The organization of the paper is following: in Section 2, the analytical micromechanical models are presented in details. The outcome is an explicit set of formulae that allows one to determine the effective mechanical properties of the general HMMNCs. Then, the modeling procedure of hybrid nanocomposite is presented in Section 3. In Section 4, the results are presented to quantitatively show the effects of parameters such as volume fraction, diameter and aggregation degree of SiC nanoparticles as well as volume fraction, aspect ratio and dispersion type of SiC whiskers on the elastic modulus of the HAMNC. Also, the comparative studies are conducted with experimental data available in the literature to verify the validity of the proposed model. The concluding remarks are given in Section 5. Such studies could play a significant role from the standpoint of predicting the performance of the HMMNC under service conditions.

2. Micromechanical approaches

First, in this section, the effective elastic modulus of SiC nanoparticle-reinforced AMNC is predicted using an analytical micromechanical approach. Then, the extended simplified unit cell (ESUC) micromechanical approach [37,38] along with a proper representative volume element (RVE) is developed to determine the elastic properties of the SiC whisker-reinforced AMCs.

2.1. Analytical model for AMNCs

The dependence of the elastic modulus of a particulate metal matrix composite (E_c) on the particle volume fraction (V_p) is expressed as [39].

$$E_c = \frac{V_p^{0.67} E_m}{1 - V_p^{0.33}\left(1 - \frac{E_m}{E_p}\right)} + \left(1 - V_p^{0.67}\right)E_m \tag{1}$$

where E_m and E_p denote the elastic modulus of metal matrix and particle, respectively. The introduced model by Eq. (1) can only give Young's modulus of the traditional particulate composite without incorporating the particle size. On the other words, the micromechanical model is not size-dependent. Therefore, the use of a size efficiency factor k_s in Eq. (1) is needed to make an appropriate prediction of the AMNC elastic modulus, as follows

$$E_{nc} = \frac{k_s\, V_p^{0.67}\, E_m}{1 - V_p^{0.33}\left(1 - \frac{E_m}{E_p}\right)} + \left(1 - V_p^{0.67}\right)E_m \tag{2}$$

in which

$$k_s = 1 + \frac{k_0}{\exp\left(\left(\frac{d}{10^{-9}}\right)^a\right)} \tag{3}$$

where k_0 and a are constants. Also, d is the nanoparticle diameter.

Nevertheless, in some cases due to the AMNC fabrication processes, it has been observed an aggregated state for the SiC nanoparticles [18,22–24]. The nanoparticle aggregation is seriously undesirable. Therefore, it is essential to incorporate the nanoparticle aggregation phenomena into the AMNC analysis. To this end, the AMNC system is divided into two fields, the pure aluminum matrix without nanoparticle specified as phase O, and the spherical inclusions that consist of the SiC nanoparticles and rest of the aluminum matrix material signified as phase I [40], as presented in Fig. 1. Therefore,