Finite-Element Modeling of Particle Size Effect on Mechanical Properties of SiCp/Fe Composites

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Abstract: Particle size has a significant effect on mechanical properties of particle reinforced metal matrix composites (PRMMCs). Here, the effect of particle size on mechanical properties of SiCp/Fe composite has been studied using a finite element (FE) model incorporated with the Taylor-based nonlocal theory (TNT) of plasticity, where the tested particle size is 5, 10, 16, 21, 28 and 40 μm, respectively. The results indicate that the TNT-FE model overcomes the shortage of the traditional FE model, which cannot deal with the intrinsic size effect. With the particles of 20 vol.%, the simulated flow stress of the iron matrix composite reinforced by 16 μm SiC particles is the highest and then follows the order of 28 > 5 > 10 > 21 > 40 μm particle reinforced ones, close to the tendency of experimental results. A large area of compressive stress zone is observed in the matrix near the particles in the composites reinforced by 16 and 28 μm particles, which implies that the matrix can be well protected during loading, so that the load-bearing capability is better. The purpose is to optimize mechanical property of SiCp/Fe composite by adjusting particle size and eventually to design PRMMCs from microstructural control.

1. Introduction

Particle reinforced metal matrix composites (PRMMCs) have high modulus, strength, high wear resistance and thermal stability [1, 2]. It is observed that mechanical properties of the PRMMCs depend not only on the type of reinforced particles, but also on the size, content, shape and distribution of particles and the features of the particles/matrix interface [3-5]. In Zhuang’s work [6], mechanical properties of the iron matrix composite reinforced by 13 μm SiC particle was the best with 10 vol.% SiC. Similarly, Zhang et al. observed a peak strength of the 13 μm SiCp/Fe composite when the
particle size increased from 3.5μm to 45μm with 20 vol.% copper-coated SiC reinforcements [7]. Therefore, to understand the relationship between strengthening behavior and microstructure is a critical issue in developing PRMMCs. The continuum models have been used to study mechanical properties of PRMMCs, such as finite element (FE) model [8-10]. However, traditional FE models are based on classical plasticity theory, which lead to a dependence of deformation behavior on volume fraction of reinforcing particles but not on particle size [11]. Recently, dislocation models and Taylor-based nonlocal theory (TNT) of plasticity continuum models have been developed to understand the particle size effect [12-14]. Here, the effect of particle size on mechanical properties of SiCp/Fe composite is studied using a TNT FE model, where the tested particle size is 5, 10, 16, 21, 28 and 40μm, respectively, with 20 vol.% particles.

2. Finite Element Model Setup and Taylor-based nonlocal theory (TNT) of plasticity

In this work, the plane-strain 2D finite element model is employed to simulate a multi-particle composite system during monotonic tensile loading and the model setup for SiCp/Fe composite shows in Figure 1 (a), with spherical particles embedded into the rectangular matrix (ABCD). The volume fraction of SiC particles is 20% and the tested particle size is 5, 10, 16, 21, 28 and 40μm, respectively, corresponding to the particle number from 64 to 1 and particles distributed uniformly, shown in Figure 1 (b).

![Figure 1](image_url)

**Figure 1.** (a) Schematic of the plane-strain 2D finite element model for SiCp/Fe composite and (b) the model setup with different size particles, the tested particle size is from 5 to 40μm, corresponding to the particle number from 64 to 1 and particles distributed uniformly (Pink: SiC particle and blue: iron matrix).

Based on the Taylor nonlocal theory (TNT) of plasticity, the shear flow stress $\tau$ can be given by:

$$\tau = \alpha G_m b (\rho)^{1/2}$$

(1)

where $G_m$ is shear modulus, $b$ is Burgers vector, $\alpha$ is an empirical coefficient and $\rho$ is dislocation density. In this work, the $\rho$ is only composed of geometrically necessary dislocations (GNDs) due to geometrical mismatch (GM) generated in the composite matrix as a result of deformation-induced plastic strain gradient [15, 16]. Some researchers induced particle size effect into various continuum models by incorporating dislocation plasticity to alter the flow stress in the composite matrix ($\sigma_{Flow, Matrix}^{\text{Flow}}$).
which achieved good results [13, 14, 17]. Therefore, the $\sigma_{\text{Matrix}}^{\text{Flow}}$ can be given as

$$
\sigma_{\text{Matrix}}^{\text{Flow}} = \sigma_{\text{Matrix}}^{\text{Ref}}(\varepsilon_p) + M\alpha G_m b(\rho_{\text{GNDs}})^{1/2}
$$

where $\sigma_{\text{Matrix}}^{\text{Ref}}(\varepsilon_p)$ is the stress in unreinforced matrix under plastic strain of $\varepsilon_p$, $M$ is the Taylor factor, acting as an isotropic interpretation of the crystalline anisotropy at the continuum level and $\rho_{\text{GNDs}}$ is the GNDs due to the GM. An enhanced FEM model incorporating the TNT of plasticity has been developed and successfully used in studying the particle size dependent flow strengthening in PRMMCs[14], in which assuming that the particle was pure elastic and the matrix was elastoplastic, the flow stress of the reinforced matrix in Eq.(2) could be adapted as follows,

$$
\sigma_{\text{Matrix}}^{\text{Flow}} = \sigma_{\text{Matrix}}^{\text{Ref}}(\varepsilon_p) + [27 \times (5/2)^{1/2} \alpha^2 G_m^2 \frac{f^{1/3}}{r} b \varepsilon_p]^{1/2}
$$

where $f$ and $r$ was volume fraction and size of particle, respectively.

In this work, the $\sigma_{\text{Matrix}}^{\text{Flow}}$ in Eq.(3) is used as the numerical constitutive input of elastoplastic iron matrix into the TNT-FE model, which considers the effects of intrinsic size and volume fraction of particles on the matrix properties. The SiC reinforcement is treated as pure elastic particle in the FE model. The model setup for the SiCp/Fe composite has already been introduced earlier in Figure.1, and the interface between the Fe and SiC assumes to be connected perfectly. The ANSYS commercial software has been used to implement the FE simulations.

3. Results and Discussion

In this section, particle size effect on mechanical behaviours of the SiCp/Fe composites was studied using the plane-strain 2D finite element (FE) model incorporating with Taylor-based nonlocal theory (TNT) of plasticity.

Firstly, the parameter $\alpha$ in Eq.(3) for the SiCp/Fe composite is determined to 0.4 from experimental data fitting of tensile strength in 21μm SiCp/Fe with 20 vol.% copper-coated particles [18] and the simulated tensile strength is 535MPa, which is only 3MPa lower than the experimental one of 538MPa, shown in Figure.2 (a). Moreover, the tensile strength of 10μm SiCp/Fe has also been tested with 562MPa from our model, compared with the experimental value of 567MPa of 13μm SiCp/Fe. Therefore, this model is valid to use for predicting other-sized SiC reinforced iron matrix composites with $G_m$ of 67GPa and $b$ of $2.5 \times 10^{-10}$ m of pure iron in Eq.(3).
Figure 2. (a) The comparison of experimental and simulated values of tensile strength in 13μm (experiment) via 10μm (simulated) and 21μm SiCp/Fe composites and (b) the simulated stress-strain curves of SiCp/Fe with different particle size.

In Figure 2 (b), the simulated stress-strain curves of the SiCp/Fe composites with different particle size are shown, which depict a size-dependent strengthening phenomenon. The simulated flow stress at the applied strain of 4% from traditional FE and TNT FE models are compared in Figure 3 (a). The simulated stress from traditional model is almost the same in the size of 5, 10, 21 and 40μm cases, and in the size 16 and 28μm cases, respectively, which means that the traditional FE model cannot deal with the intrinsic size effect.

Figure 3. (a) Flow stress at the applied strain of 4% versus the particle size from traditional and TNT FE models and (b) tensile strength versus particle size of SiCp/Fe from experimental results. [7]

In Figure 3 (a), the simulated flow stress at the applied strain of 4% from the TNT FE model is 676, 647, 699, 625, 689 and 617MPa, respectively, associated with particle size of 5, 10, 16, 21, 28 and 40μm. The stress of the composite reinforced by 16μm particles is the highest and then follows the order of 28 > 5 > 10 > 21 > 40μm particles reinforced ones, close to the tendency of tensile strength from experimental observations [7] in Figure 3 (b), where the tested particle was 3.5, 13, 21 and 45μm, respectively.
Figure 4. At the applied strain of 4%, (a) the average normal stress in the particles and matrix in loading direction (y-axis) and (b) the normal stress ($\sigma_{yy}$) contour of the SiCp/Fe composites with different particle sizes.

In Figure 4 (a), the average normal stress in the particles and matrix in the loading direction at the applied strain of 4% has been compared, associated with different particle size. The stress in the matrix decreases with the increasing particle size, which means that the strengthening on the matrix from the particles is better when the particle size is smaller. The stress in the particles for the composite reinforced by 16 and 28μm particles is greater, which means that the load-bearing capability of such particles is better. Furthermore, The normal stress ($\sigma_{yy}$) contours of the SiCp/Fe composites with different particle sizes at 4% strain are plotted in Figure 4 (b). A large area of compressive stress zone exists in the matrix near the particles in the composites reinforced by 16 and 28μm particles, which implies that the matrix can be well protected during loading so that the load-bearing capability is better.

Figure 5. The particle size effect (a) on phase stress partition parameter ($q$) and (b) on strengthening efficiency ($R$) during straining.

The stress relationship between the matrix and the particle can be described by the phase stress partition parameter ($q$) given by the equation of $q = \sigma_p / \sigma_m$ [12], where $\sigma_m$ is stress in matrix and $\sigma_p$ is stress in particles. The relationship between the $q$ and applied strain is plotted in Figure 5 (a). It is shown that for the 16 and 28μm SiCp/Fe composites, the $q$ decreases slightly at first after elastic deformation, then increases dramatically and is over 1.60 at 4% strain, which is greater than the value of 1.40 in 1–55μm SiCp/Al composites with 20 vol.% SiC [12]. While, the $q$ decreases sharply and then becomes relatively stable in 1.20 for the 5, 10, 20 and 40μm SiCp/Fe composites. Moreover, the
strengthening efficiency (R) of a given volume percentage of reinforcement on the matrix can be performed by the equation of $R = (\sigma_c - \sigma_m)/V\sigma_m$ [19], where V is volume fraction of particles, $\sigma_m$ is stress in matrix and $\sigma_c$ is the composite stress. The relationship between the $R$ and applied strain is plotted in Figure.5 (b), where the $R$ can reach about 60% for the 16 and 28 μm SiCp/Fe composites, while it keeps about 20% for the others, comparing with the $R$ of 2.4% in SiCp/Al, 20.3% in carbon nanotube reinforced Cu and 94% in graphene nanosheets reinforced Cu composites [19].

4. Conclusions
Using a plane-strain 2D finite element (FE) model by incorporating Taylor-based nonlocal theory (TNT) of plasticity, the effect of particle size on mechanical properties of SiCp/Fe composite is studied, where the tested particle size is 5, 10, 16, 21, 28 and 40μm, respectively, with 20 vol.% particles.
1. By comparison with experimental results, the TNT FE model overcomes the shortage of the traditional FE model which cannot deal with the intrinsic size effect.
2. The simulated flow stress of the iron matrix composite reinforced by 16μm SiC particles is the highest and then follows the order of 28 > 5 > 10 > 21 > 40μm particle reinforced ones, close to the tendency of experimental observation.
3. A large area of compressive stress zone is observed in the matrix near the particles in the composites reinforced by 16 and 28μm particles, which implies that the matrix can be well protected during loading, so that the load-bearing capability is better.

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