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Experimental and simulation studies of particle size effects on tensile deformation behavior of iron matrix composites

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SiC particles with four different sizes of 3, 13, 21 and 45 μm were used as reinforcements to prepare iron matrix composite by electric heating dynamic hot-press sintering method. Tensile test at room temperature was carried out to investigate the influence of particle size on mechanical behavior. The results show that iron matrix composites with SiC particle of 13 μm achieve the best tensile strength and elongation. The stress–strain curves of those composites were simulated using a combined model taking into account the dislocation strengthening and particle-cracking probability based on Eshelby's equivalent inclusion method and the microstructures were observed to explain the experimental results. The iron matrix composites with SiC particle of 13 μm with excellent mechanical property can be reasonably attributed to the uniform reinforcement distribution compared with the ones with particle of 3 μm and the relative higher dislocation strengthening effects and lower particle-cracking probability compared with the ones with coarser particles.

Keywords: particle-reinforced metal matrix composites (PR-MMCs); mechanical; microstructure; simulation

1. Introduction

Particle-reinforced metal matrix composites with ferrous matrix have generated great interest for researchers because of their promising strength and wear resistance.[1–4] Kinds of processing routes have been used to fabricate iron matrix composites with ceramic-reinforcing particles, such as hot isotropic processing method,[5,6] powder metallurgy,[7,8] *in situ* reactive synthesis technology [9] and a novel electric heating dynamic hot-processing method which has been developed by our research group, and the iron matrix composite can be produced in a few minutes by use of this method and a near-full density and high strength can be achieved.[10]

As we all known, the design of reinforcing particle size is crucial to achieve excellent performance for particle-reinforced metal matrix composites. Intensive and extensive investigations on the size influence have been conducted in the past decades for the aluminum matrix composites.[11–13] And a common conclusion is that the finer particles show better strengthening effect compared with the coarser ones in these composites.[11,14–16] However, very limited researches on the size influence have

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been reported for the particle-reinforced iron matrix composites. The research conducted by Pagounis [17] showed that tensile strength and final elongation of the steel matrix composite with coarse Al_2O_3 particles (127 μm) were found better than those with the fine particles (59 μm) at the particle volume fraction of 10 and/or 20%, which is different from the result in aluminum matrix composite. Therefore, a more detailed research is needed to get an unambiguous understanding of the particle size influence on iron matrix composites.

In this study, the iron matrix composites with different reinforcing particle sizes are processed by the new electric heating method and the effects of reinforcing particle size on mechanical properties are examined. Modeling by a combined model based on Eshelby's equivalent inclusion method is carried out to provide theoretical guidelines and analysis on the experimental results.

2. Experimental procedure

Commercial pure iron powder with maximum carbon content of 0.015wt.% and average particle size of 26 μm was used as matrix material. Particles of 99.8wt.% α-SiC particles of four kinds with different sizes were chosen as reinforcements. The average size and size distribution of these SiC particles were determined by use of a laser particle size analyzer. Average size (volume mean diameter) of these particles is 3, 13, 21, and 45 μm respectively. And the corresponding standard deviation is 1.2, 4.3, 5.5, and 40.0 μm respectively. The size distributions are shown in Figure 1. It can be found that the particles with small mean diameter show relatively narrow distributions. And with the mean size increased, the distributions become wider.

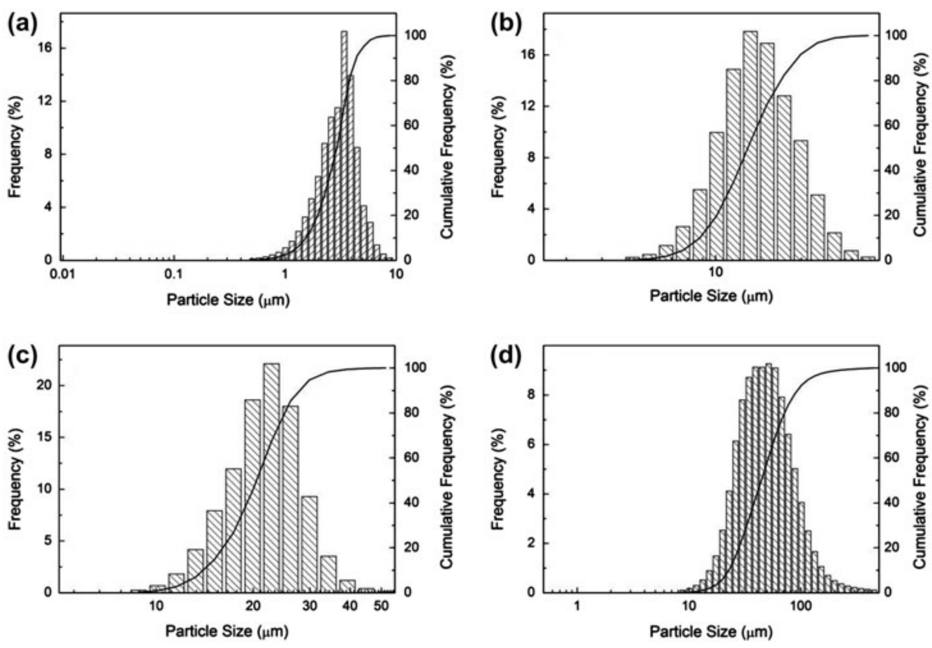

Figure 1. Particle size distribution of SiC with average size of (a) 3 μm, (b) 13 μm, (c) 21 μm, and (d) 45 μm.

The mixture of 10vol.% SiC particle and iron powder was blended in a mixer for 7 h and then was compressed with a pressure of 200 MPa into a compact block by a volume of $60 \times 30 \times 10$ mm. Then, the compact was sintered for 120 s with electric voltage of 5 v and continuing current. A holding stage of 200 s was followed with on (1 s)/off (0.8 s) current cycles. A low compress pressure (8 MPa) was applied on the compact at the beginning of the sintering and then increased to 40 MPa when the temperature was up to 900 °C.

Density of the sample was determined using the immersion method according to Archimede's principle. The hardness was measured by a Vickers hardness tester with 5 kg load and 15 s dwelling time. And the microstructure observations were carried out using optical microscope and scanning electron microscope.

The specimens for tensile test, having a longitudinal direction perpendicular to the pressure applied during fabrication, were cut from the sintered samples and grinded by use of SiC abrasive paper ranging from 600 grit to 1200 grit sizes. The specimen has a gage length of 28 mm and a diameter of 5 mm and has a butt end shoulder, as shown in Figure 2. At least, three tensile specimens were prepared for each kind of composites and the tests were repeated for the samples.

The tensile tests were conducted on an electronic universal tensile tester at room temperature with a crosshead velocity of 0.5 mm min^{-1}. An extensometer was used to measure the strain of the tested sample during loading. In the present study, engineering stress–strain curve is used to illustrate the tensile deformation behavior.

3. Experimental results

Relative density and Vickers Hardness of the SiCp/Fe composites are shown in Figure 3. Obviously, a near-full density of the composites is achieved by the electric heating dynamic hot-pressing sintering. It seems that the reinforcement particle size has no evident effects on the Vickers Hardness of the composites.

A typical microstructure of the composites is shown in Figure 4. It can be seen that a highly dense composite has been achieved, and no visible void can be found. In addition, it can also be seen that SiC particle decomposition has occurred because pearlite has been produced in the pure iron matrix, but the decomposition is not severe since the particles almost keep the original shape and size. Some extent of reactions between the reinforcement and matrix can give rise to the increase of the strength of the composites because of the C dissolution in the iron and the formation of pearlite.[6]

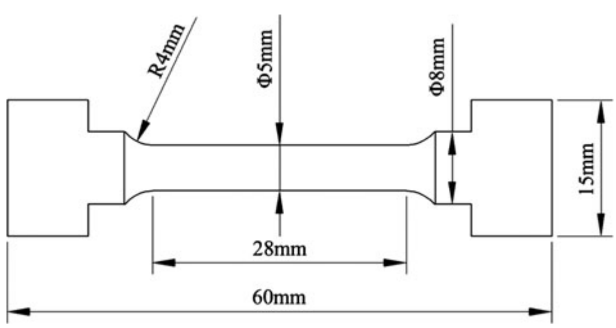

Figure 2. Tensile sample geometry.

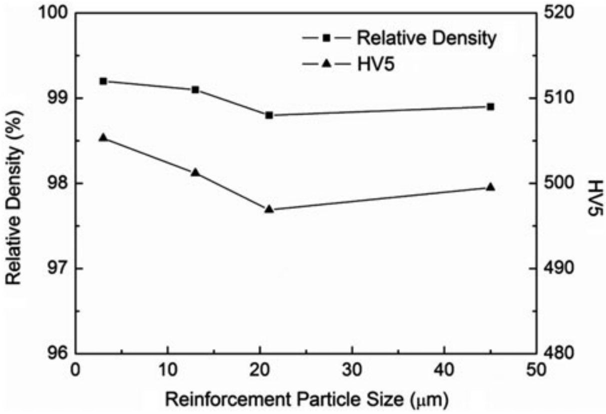

Figure 3. Relative density and Vickers Hardness of the SiCp/Fe composites.

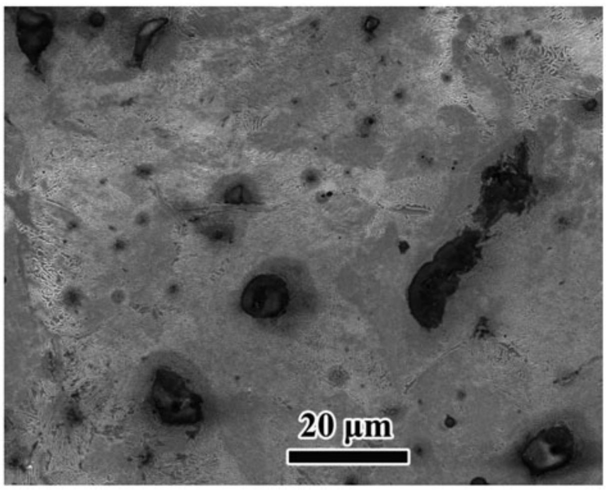

Figure 4. Typical microstructure of the SiCp/Fe composites fabricated by means of the electric heating dynamic hot-pressing method.

Tensile stress–strain curves of the composites with different reinforcing particle sizes are shown in Figure 5. It can be seen that stress–strain relationships of the composites strongly depend on particle size. The composites with particle size of 13 μm exhibit higher stress at the same strain compared with the other ones, while the composites reinforced with the 45 μm particles show an obvious low strength compared with the ones with finer particles. Elongations of the composites also show obvious differences. It is increased with particle size increased from 3 to 13 μm, and reduced with the particle size increased further. Yield stress (0.2% proof stress) and tensile strength of the composites reinforced with particles of different sizes are presented in Figure 6 for comparison. It can be seen that the composites reinforced with SiC particle of 13 μm show higher yield stress and tensile strength compared with those reinforced with particles of 3 and/or 21 μm.

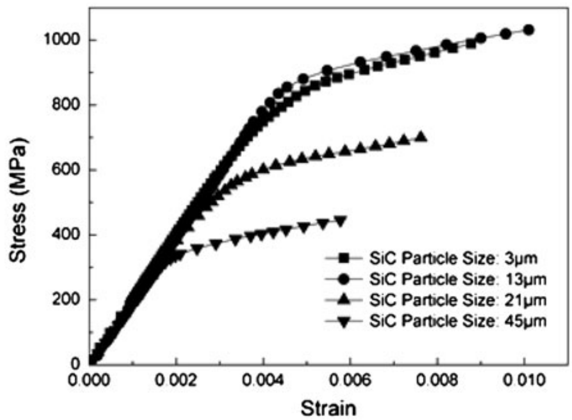

Figure 5. Stress–strain curves of the SiCp/Fe composites with different reinforcement particle sizes.

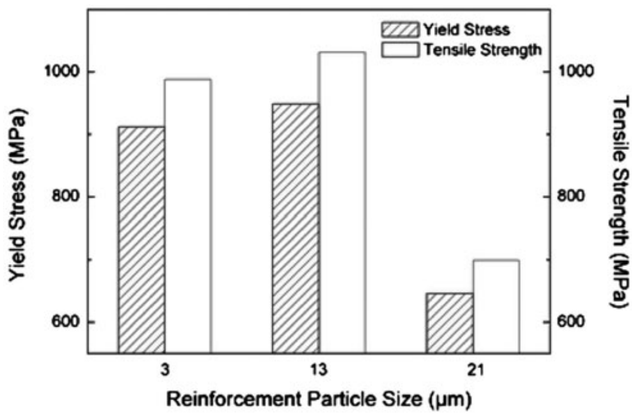

Figure 6. Variation of yield stress and tensile strength with reinforcement particle size.

Clearly, the results indicate that the 10vol.% SiCp/Fe composites show excellent mechanical properties with reinforcement particle size of 13 μm in the range from 3 to 45 μm. Similar results have also been reported in the research conducted by Y. Uematsu in the 9vol.% SiCp/Al composites where the 20 μm particles show better strengthening effect in the range from 5 to 60 μm at room temperature.[18]

It is understood that several types of microstructural damage, including damage of the reinforcement, interfacial debonding, and matrix cavitation, can develop in particle-reinforced metal matrix composites. Figure 7 presents the fractograph taken from the post-test tensile specimens reinforced with 13 μm particles. Cracked particles can be observed on the surface and debonding is hardly found, which indicates that the interface bonding is strong enough. The strength of the interface is so high that the stress of the particle transformed from the matrix during straining can achieve a high level, so some large particles cracked, as Figure 7(b) shown.

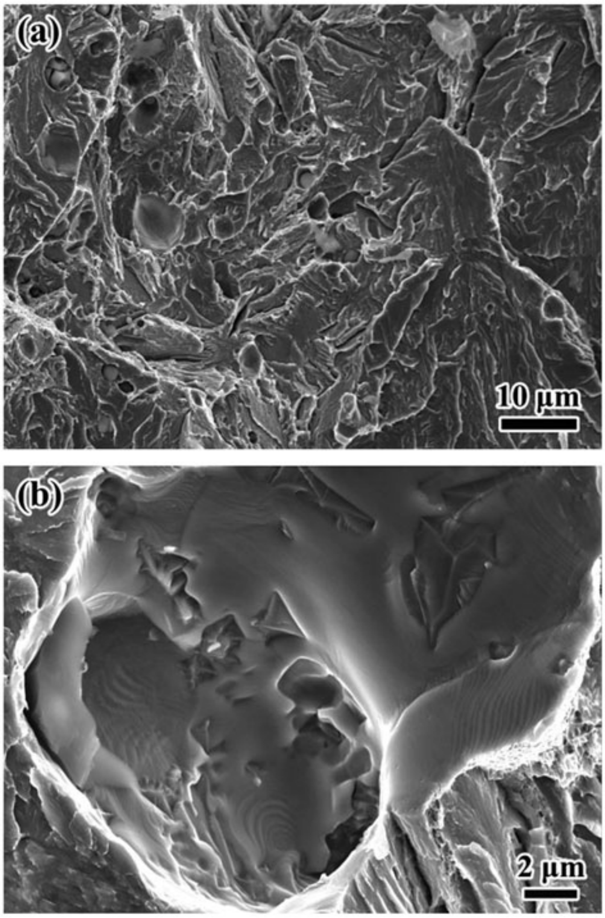

Figure 7. Fractographs of tensile test samples, (a) composites reinforced with 13 μm particles and (b) composites reinforced with 13 μm particles in higher magnification.

4. Modeling and discussion

4.1. Model description

In previous research, an analytical model was developed based on Eshelby's equivalent inclusion method to simulate the mechanical property of particle-reinforced metal matrix composites.[19,20] The stiffness tensor of the composites can be expressed as

$$C_c^{-1} = C_{\mathrm{m}}^{-1}(I + f_1 Q_1(I + L) + f_2 Q_2(I + L)) \tag{1}$$

where $Q_1 = ((C_1 - C_{\mathrm{m}})S_1 + C_{\mathrm{m}})^{-1}(C_{\mathrm{m}} - C_1)$, $Q_2 = ((C_2 - C_{\mathrm{m}})S_2 + C_{\mathrm{m}})^{-1}(C_{\mathrm{m}} - C_2)$, $L = (I + f_1(S_1 - I)Q_1 + f_2(S_2 - I)Q_2)^{-1}(-f_1(S_1 - I)Q_1 - f_2(S_2 - I)Q_2)$, f_1, S_1, C_1 and f_2, S_2, and C_2 are the volume fraction, Eshelby tensor, stiffness tensor of type-1 particle, and of type-2 particle respectively; C_{m} is the stiffness tensor of iron matrix without reinforcement; and I is the identity tensor. In this simulation, type-1 particle represents the intact particle and type-2 represents the damaged particle.

Young's modulus and Poisson's ratio of both the particles and the matrix are constant within elastic range, so that the composite modulus can be calculated by Equation (1). When plastic deformation takes place in composite, the Young's modulus and Poisson's ratio of the matrix should be substituted by secant ones.[21]

Considering that the particle-reinforced composites subjected to a tensile loading, extra dislocation should be produced to ensure the continuity of plastic deformation of the composites because of the elastic modulus mismatch between the matrix and particle. Therefore, the dislocation density of the reinforced matrix is increased compared with the unreinforced matrix. According to the estimation by Dai [22], the increment of dislocation density owing to the difference of modulus is given by

$$\Delta\rho_1 = \frac{6f_p}{bd_p}\varepsilon \tag{2}$$

where b is the Burgers vector, d_p is the diameter of particle, and f_p is the volume fraction.

Thermal mismatch strain generated during composites preparation also contributes to the increment of dislocation density because of the large difference in thermal expansion coefficients (CTE) between metal matrix and ceramic reinforcement. According to [22], the increment of dislocation density is given by

$$\Delta\rho_2 = \frac{12f_p\Delta C_{TE}\Delta T}{bd_p} \tag{3}$$

where $\Delta C_{TE} = C_{TE-m} - C_{TE-p}$, C_{TE-m}, and C_{TE-p} are CTE of the matrix and the particle respectively; and ΔT is the temperature change from processing temperature to ambient temperature.

According to the Taylor dislocation strengthening relation, the increment of flow stress owing to the increment of dislocation density can be expressed as

$$\Delta\sigma = M\alpha\mu b\sqrt{\Delta}\rho \tag{4}$$

where $\Delta\rho = \Delta\rho_1 + \Delta\rho_2$; M is the Taylor factor; α is a coefficient; and μ and b are the shear modulus and Burges vector, respectively. M and α are taken to be 3 and 0.33 respectively in the simulation.

Researchers have demonstrated that composite failure is associated with particle cracking and void formation in the matrix within the clusters of particles, and the fracture probability of particle can be expressed by Weibull statistics [23–25]:

$$P_{cr} = 1 - \exp\left[-\frac{V}{V_0}\left(\frac{\sigma_p}{\sigma_0}\right)^m\right] \tag{5}$$

where σ_p is the fracture strength of the SiC particles; V is the volume of the SiC particles; m is the Weibull modulus; and V_0 is the volume of SiC particles for which the probability of survival is 37% at σ_0.

The dislocation strengthening effect described by Equation (4) and particle-cracking phenomenon described by Equation (5) are incorporated into the Eshelby's equivalent method to account for the size influence on tensile deformation behavior of the SiCp/Fe composites. Parameters used in the simulation are summarized in Table 1.

Table 1. Parameters used in the simulation.

Parameter	Description	Value
E_m (GPa)	Matrix elastic modulus	168
E_p (GPa)	SiC elastic modulus	450
μ (GPa)	Matrix shear modulus	67
v_m	Matrix Poissons's ration	0.25
v_p	SiC Poissons's ration	0.17
V_0 (m^3)	Reference volume of SiC particles	1.78×10^{-14}
σ_0 (MPa)	Reference fracture strength of SiC particles	1550
m	Weibull modulus	2
b (m)	Magnitude of the Burgers vector	2.5×10^{-10}
$C_{TE\text{-}m}$ (°C^{-1})	Thermal expansion coefficient of iron matrix	11.8×10^{-6}
$C_{TE\text{-}p}$ (°C^{-1})	Thermal expansion coefficient of SiC	4.3×10^{-6}

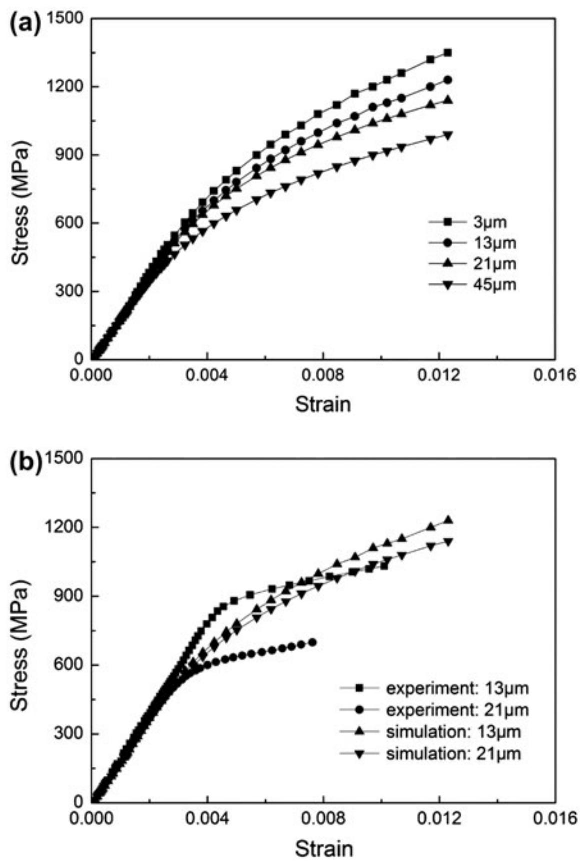

Figure 8. (a) simulated stress-strain curves of the composites reinforced with particles of different sizes and (b) comparison between the simulation and experimental curves.

4.2. Simulation and discussion

As shown in Figure 8(a), the simulated stress–strain curves varied with reinforcement particle sizes. It can be seen that in elastic deformation region, there is no evident difference in stresses among the composites with different particle sizes, which is in good agreement with the experimental results. However, in plastic deformation region, the stresses demonstrate obvious differences. The simulation results show that the composites with finer particle exhibit higher hardening rates and higher stresses compared with the ones with coarser particle at the same strain. This can be attributed to the dislocation strengthening effect and particle cracking. According to Equations (2) and (3), the increment of dislocation density is inversely proportional to the reinforcement particle size, therefore the finer particles show higher dislocation strengthening effect compared to the coarser ones. In addition, the Weibul statistics Equation (5) indicates that coarser particle fracture is more prevalent because the coarser ceramic particles will have a higher probability of containing fracture-initiating defects. And the fractograph observation (Figure 7) also indicates that the particle cracking is a main damage mechanism for the composites reinforced with coarse particles in this study.

The comparison between the experimental and simulation stress–strain curves for the composites reinforced with the 13 and 21 μm particles is shown in Figure 8(b). It can be found that the simulated curves show agreement with the experimental ones within the elastic range. And as the strain increased, the simulation results show some divergences. Perhaps, it is because that the strengthening effects of the *C* dissolution and the formation of pearlite in the iron matrix have not been taken into consideration. In addition, the flow behaviors of the matrix of the composites reinforced with particles of different sizes may be altered because of the inhomogeneous of plastic deformation, but the stress–strain relation of the matrix used in the simulation does not change for this reason. Although the simulation stress–strain curves show some differences with the experimental ones, the model captures the features of the deformation behavior of the composites and gives some clues to analyze the influence of the particle size.

The simulation results indicate that the composites with reinforcement particle of 3 μm achieve better mechanical property than the other ones, which is different from the experimental results. In the experiment, composites with particle of 13 μm offer higher strength and elongation. In order to explain this divergence, particle distribution in composites with different sizes was observed and shown in Figure 9. It can be seen that the composites with particle of 3 μm show an inhomogeneous distribution and particle clusters are easy to be found, as Figure 9(a) and (b) shown. In the regions of particle clusters, the matrix would be subjected to very high-localized stresses during plastic deformation, therefore, composites would fail before being able to reach normal ultimate strength and elongation compared with the ones with uniform particle distribution.[26] In addition, void usually exists in the clustered regions (Figure 9(b)) and therefore the mechanical properties degrade. As the particle size increased to 13 μm, composites attain a uniform particle distribution as Figure 9(c) shown. Thus, the mechanical properties improved as experimental results shown. Though the composites with reinforcement particle size of 21 μm also get a uniform particle distribution (Figure 9(d)), the ultimate strength declines. And this can be attributed to the decrease of dislocation strengthening and increase of particle-cracking probability. Therefore, the iron matrix composites with 10% SiC particle of 13 μm in this experiment attain the best mechanical property.

Reinforcement size is closely related with the mechanical property of particle-reinforced metal matrix composites as the experimental and simulation results indicated in this study and other researches.[11–18] On the one hand, finer particles in the composites show higher dislocation strengthening effects and lower cracking probability compared with the coarser ones, on the other hand, the finer particles tend to agglomerate to achieve a poor particle distribution via the powder metallurgy processing routes.

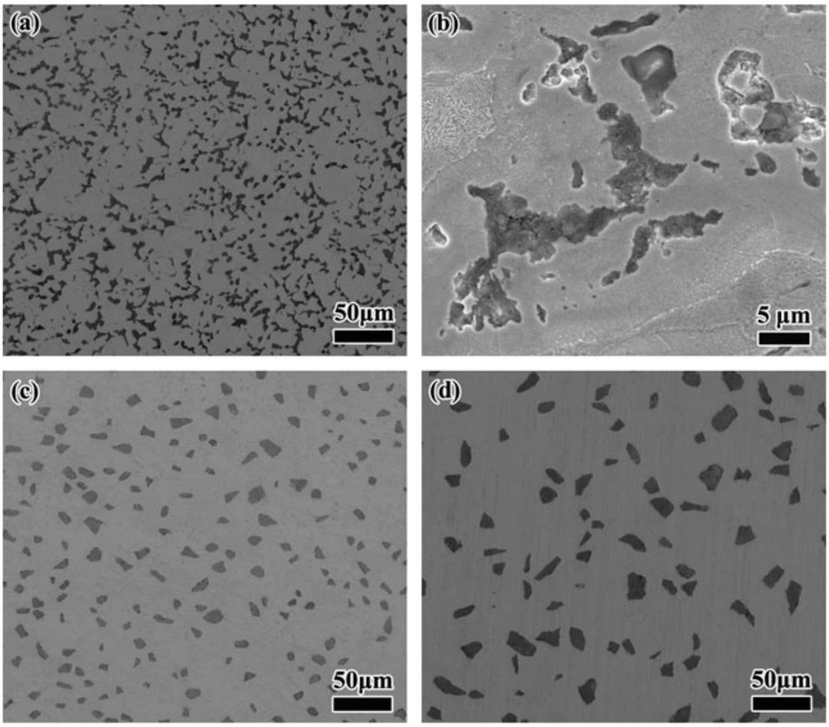

Figure 9. Micrographs showing the reinforcement distributions in composites containing SiC of different sizes: (a) 3 μm (low magnification), (b) 3 μm (high magnification), (c) 13 μm, (d) 21 μm.

Therefore, a critical reinforcement particle size exists which can make the composites achieve the best mechanical properties. In this study, the 10vol.% SiCp/Fe composites show a critical value of 13 μm.

5. Conclusions

In the present study, 10vol.% SiCp/Fe composites with different reinforcement particle sizes were fabricated by electric heating dynamic hot-press sintering method. And the size influence on the tensile deformation behavior was investigated by experimental and modeling methods. The following conclusions can be drawn from the results and discussions.

- The tensile properties of 10vol.% SiCp/Fe composites exhibit complicated dependence on the particle size. On the one hand, a uniform particle distribution in 10vol.% SiCp/Fe composites can be achieved as the particle size increased from 3 to 13 μm. On the other hand, the modeling results demonstrate that the dislocation strengthening effects decrease and particle-cracking probability increases with the particle size increased. Therefore, the composites with reinforcement particle size of 13 μm exhibit higher mechanical properties in the range from 3 to 45 μm.

- Reinforcement particle size should be carefully selected in the particle-reinforced metal matrix composites processed by powder metallurgy routes in order to get a better particle distribution and higher dislocation strengthening effects and lower particle-cracking probability. Composites with a critical particle size can achieve optimum mechanical property.

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