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Effect of Particle Size on the Microstructures and Mechanical Properties of SiC-Reinforced Pure Aluminum Composites

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This article examined the effects of particle size and extrusion on the microstructures and mechanical properties of SiC particle-reinforced pure aluminum composites produced by powder metallurgy method. It has been shown that both particle size and extrusion have important effects on the microstructures and mechanical properties of the composites. The SiC particles distribute more uniformly when the ratio of the matrix powder size and SiC particle size approaches unity, and the smaller-sized SiC particles tend to cluster easily. The voids are found to coexist with the clustered and large-sized SiC particles, and they significantly decrease the density and mechanical properties of the composites. Extrusion can redistribute the SiC particles in the matrix and decrease the number of pores, thus make the SiC particles distribute more uniformly in the matrix, and enhance the interfacial bonding strength. The decrease in the SiC particle size improves the tensile strength and yield strength, but decreases the ductility of the composites.

Keywords mechanical properties, metal matrix composites, microstructures, particle size

1. Introduction

Metal matrix composites reinforced with ceramic particles are of particular interest for a variety of industrial applications due to their high strength, elastic modulus, fatigue resistance and wear resistance, as compared with the corresponding matrix materials (Ref 1-4). Among the different shaped reinforcements, the composites reinforced with particulate-shaped reinforcements offer relatively isotropic properties compared to short fiber- or whisker-reinforced counterparts, and they can also be produced using conventional metal manufacturing process with low cost (Ref 5, 6).

During the last two decades, a large number of the investigations have been carried out to reveal the strengthening mechanisms of metal matrix composites (Ref 7-10). For SiC particle-reinforced aluminum alloy composites, the SiC is the main strengthening factor. One strengthening mechanism is the direct strengthening mechanism resulting from the soft Al matrix transferring the externally applied load to the hard SiC reinforcements. The second strengthening mechanism is the indirect strengthening mechanism resulting from the increase in dislocation density of the Al matrix due to the difference in the coefficient of thermal expansion between the SiC and the Al matrix when subjected to cooling from an elevated processing temperature or heat-treatment temperature. The formation of dislocations can significantly increase the strength of the matrix. It should be noted that the geometrically necessary dislocations generated during initial matrix plastic deformation will also strengthen the composites. When a SiC-reinforced Al composite is loaded, the SiC particles deform less than the matrix. To avoid initiation of the voids, dislocations are generated and stored in the matrix to allow for compatible deformation of the particles and the matrix. These dislocations are called geometrically necessary dislocations (Ref 11).

It is widely accepted that both the particle distribution and particle size have important effects on the mechanical properties of the composites. The voids coexisted with the clustered SiC particles, and the large-sized SiC particles can be treated as pre-existing cracks (Ref 12, 13). The particles along with the voids cannot transfer any load from the soft matrix to the hard reinforcements, resulting in degraded mechanical properties. For a composite with a constant particle volume fraction, there is a close relationship between the particle size and the deformation behavior of the composite. The yield strength and plastic work hardening rate of the composites increase with decreasing the particle size. Large particles are more prone to fracture during extrusion process and tensile testing (Ref 14, 15), and cannot transfer any load from the matrix to the reinforcements.

In this article, the effects of particle size and particle distribution on the microstructures and mechanical properties of SiC-reinforced pure Al composites have been studied before and after extrusion. Scanning electron microscope (SEM) and mechanical testing were used to characterize the microstructures and mechanical properties of the composites.

2. Experimental

In this study, a commercial pure aluminum with 99.5% purity (weight percentage) was used to prepare the aluminum powders by powder metallurgy method. The average size of the

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Al powders is about 44.6 μm after sieving. The SiC reinforcements used in this experiment are in the form of particulate with the average diameters of about 4.7, 16.7, 39.1, and 70.7 μm. The volume fraction of the SiC particles in the composites is 20%. Proper Al and SiC powders were ball-mixed for 7 h using a powder rotator mixer. The ball-to-powder weight ratio was 1:3. The mixed powders were die-pressed at room temperature under a pressure of 200 MPa in a cylindrical steel die. The specimens were then heated in a vacuum furnace (pressure of 7×10^{-3} Pa) with a heating rate of 10 °C/min to 570 °C. At 570 °C, the specimens were sintered for 5 h. After sintering, the specimens were hot extruded to rods at 430 °C with an extrusion ratio of 9:1.

The bulk densities of the composites before and after extrusion were measured by standard Archimedes method. The HB hardness measurements were performed on all the specimens before and after extrusion. The yield strength, tensile strength, and elongation of the composites after extrusion were tested by tensile testing. At room temperature, the dog-bone-shaped tensile specimens, having a gage size of 6 mm in diameter and 40 mm in length, were served in the tensile tests with a constant strain rate of 5×10^{-4} s^{-1} measured on an Instron 8802 testing machine. The yield stress was determined at the 0.2% offset. All the specimens have an axis along the extrusion direction. Each point of the yield strength has been measured on three specimens, and the average value was used. The microstructures of the composites and the fracture surfaces of the tensile specimens before and after extrusion were studied using a JSM-6360LV scanning electron microscope (SEM) and a FEI Nano230 field emission scanning electron microscope (FESEM).

3. Results

3.1 Microstructures of the Composites Before and After Extrusion

Figure 1 shows the microstructures of the composites with different particle sizes before extrusion. It can be seen that the SiC particles distribute more uniformly as the SiC particle size increases. For the composites with small SiC particle size (4.7 and 16.7 μm), segregation of the SiC particles along the surfaces of the Al powders is generally observed, similar to many previous studies (Ref 16-19). As the SiC particle size increases to 39.1 and 70.7 μm, a uniform distribution of the SiC particles can be obtained. It can also be seen that pores are generally observed in all the specimens, and the number of the pores is significantly decreased as the ratio between the Al powder size and the SiC powder size approaches unity. It can be seen from the high magnification images (Fig. 2) that the pores generally coexist with the clustered SiC particles and the large-sized SiC particles.

Figure 3 shows the microstructures of the composites with different particle sizes after extrusion. It can be seen from Fig. 3 that the distributed uniformity of the SiC particles in the composites with small particle size (4.7 and 16.7 μm) has been largely improved after extrusion, compared to the composites before extrusion. Small number of the pores can still be observed in all the composites. However, it should be noted that the number of pores have significantly decreased after extrusion, indicating a better interfacial bonding between the SiC particles and Al matrix after extrusion.

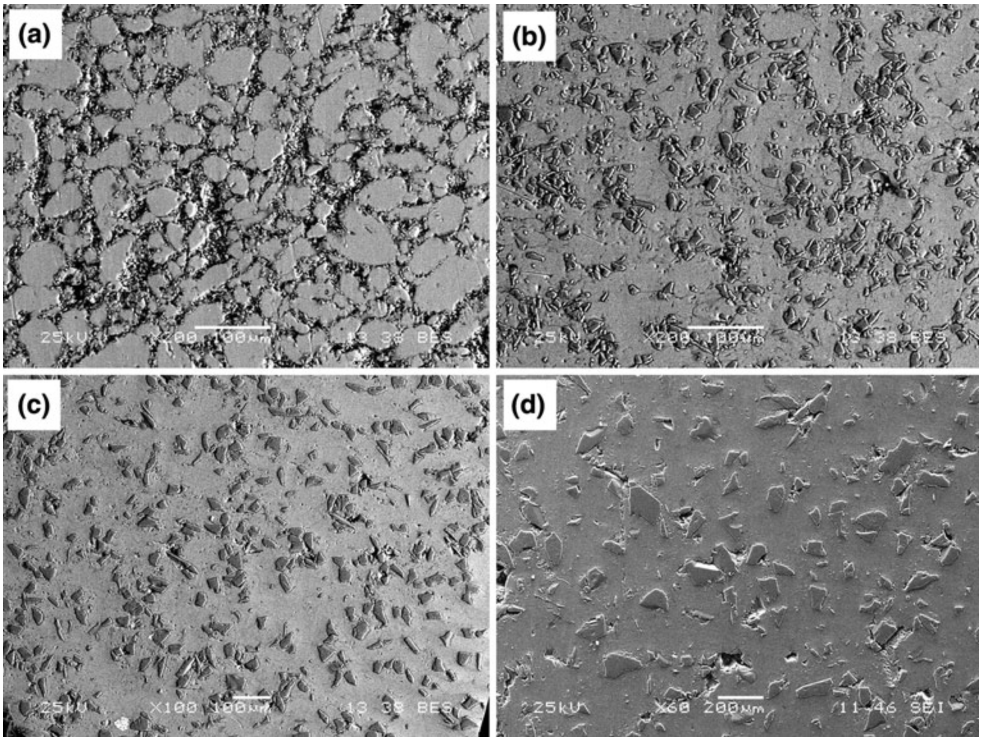

Fig. 1 Microstructures of the composites with different particle sizes before extrusion. The particle sizes are (a) 4.7 μm, (b) 16.7 μm, (c) 39.1 μm, and (d) 70.7 μm

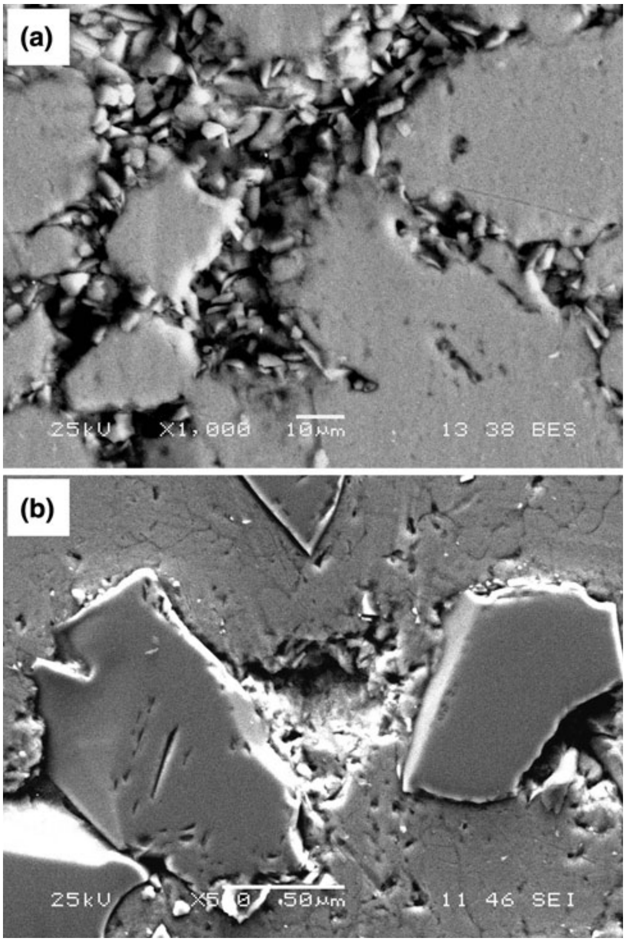

Fig. 2 High-magnification SEM images of the composites before extrusion with the particle sizes of (a) 4.7 µm, and (b) 70.7 µm

3.2 Density Evolution of the Composites Before and After Extrusion

Figure 4 shows the density evolution of the composites as a function of the particle size both before and after extrusion. It can be seen that no matter whether the composites are before or after extrusion, the density increases initially with the particle size up to 39.1 µm, after which the density starts to decrease. The density evolution is consistent with the microstructural observations in Fig. 1 and 3, in which the composite reinforced with 39.1-µm-sized SiC particles has the least number of the pores. It should be noted that extrusion can significantly decrease the number of the pores and thus improve the density of the composites.

3.3 Hardness Evolution of the Composites Before and After Extrusion

Figure 5 shows the HB hardness evolution of the composites as a function of the particle size both before and after extrusion. It can be seen that the hardness of the composites before extrusion increases initially with the particle size up to 39.1 µm, after which the hardness starts to decrease. The hardness evolution is similar to the density evolution of the composites, as shown in Fig. 4. Since the pores will substantially decrease the hardness, the composite reinforced with 39.1-µm-sized SiC particles possesses highest hardness before extrusion. It can also be seen that the hardness of the composites after extrusion decreases with the increase of the SiC particle size. It is widely accepted that for a given particle volume fraction, smaller particle-reinforced composite has higher hardness since it has more reinforcement/matrix interfacial areas to transfer the externally applied load from the matrix to the reinforcements (Ref 1, 6, 10, 20). Previous study (Ref 21) also indicated that the larger SiC particles make the matrix be more ductile but exhibit lower resistance to the indentation deformation. Thus, the hardness of the composites after extrusion decreases with the increase of the SiC particle size. It should be noted that extrusion can substantially improve the hardness of the composites, no matter what particle size is, because of the increased dislocation density and better interfacial bonding after extrusion.

3.4 Tensile Properties of the Composites

Figure 6 illustrates the tensile mechanical properties of the composite after extrusion. It can be seen that both the tensile strength and yield strength of the composites decrease with the increase of the particle size, while the elongation of the composites increases with increasing the particle size after extrusion. One can see that the tensile strength decrease significantly with the increase of the particle size, while the yield strength decrease only slightly with the increase of the particle size, indicating that particle size has significant effect on the work hardening behavior of the composites, instead of the yield phenomenon. It is widely accepted that the composites reinforced by smaller sized SiC particles have larger reinforcement/matrix interfacial area and smaller inter-particle spacing, which can transfer more load from the soft matrix to the hard reinforcements, and thus to improve the work hardening ability and strength of the composites (Ref 10, 20).

3.5 Fracture Surfaces of the Composites After Tensile Testing

Figure 7 shows the SEM fracture surfaces of the composites after tensile testing. It can be seen that the fracture surfaces of all the specimens have similar characteristics, including both ductile and brittle fracture features. All the fracture surfaces consist of numerous dimples in the matrix and fragmentation and decohesion of the SiC particles from the matrix. The dimples should be a result of the void nucleation and subsequent coalescence by strong shear deformation and fracture process on the shear plane, while the fracture and decohesion of the SiC particles can be explained by work-hardening and the fragmentation of the ceramic phase caused by high stress concentration. The main difference of the fracture surfaces is that the decohesion between the SiC particles and Al matrix decreases, and the fragmentation of the SiC particles increases as the SiC particle size increases. For the composite reinforced with 4.7-µm-sized SiC particles, matrix dimples and SiC decohesion from the matrix are the main phenomena observed in the fracture surface, while for the composite reinforced with 70.7-µm-sized SiC particles, matrix dimples, and fragmentation of the SiC particles are the main phenomena observed in the fracture surface.

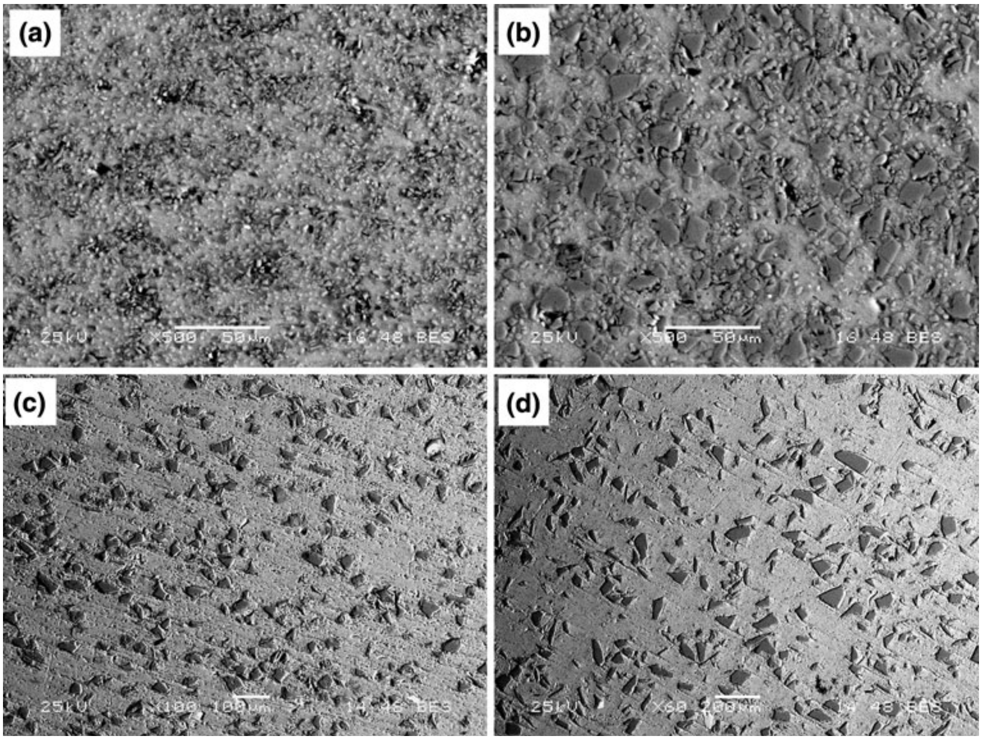

Fig. 3 Microstructures of the composites with different particle sizes after extrusion. The particle sizes are (a) 4.7 µm, (b) 16.7 µm, (c) 39.1 µm, and (d) 70.7 µm

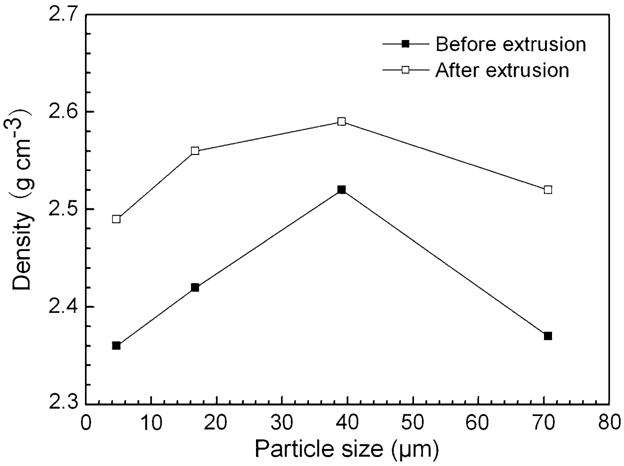

Fig. 4 Density evolution of the composites as a function of the particle size

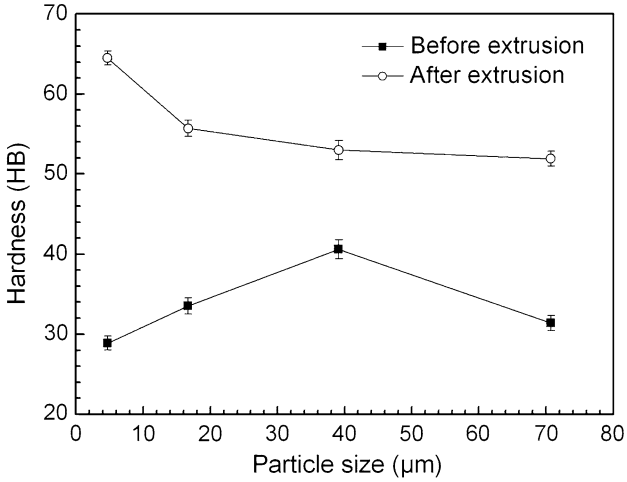

Fig. 5 HB hardness evolution of the composites as a function of the particle size

4. Discussion

4.1 Effect of Particle Size and Extrusion on the Microstructures of the Composites

An important parameter of the metal matrix composites is the distribution of the reinforcements. Among many factors affecting the distribution of the SiC particles, the ratio between the matrix powder size and reinforcement particle size (PRS) is one of the most important factors. Stone and Tsakiropoulos (Ref 22) found that the reinforcements will distribute more uniformly when the PRS approaches unity. Bhanu Prasad et al. (Ref 17) also used the geometrical method to explain the effect of the relative PRS on the distributed uniformity of the reinforcement particles. For the composites with large PRS, the uniform distribution of SiC particles in the composites become impossible because of the inadequate ratio of the surface areas of matrix particles and SiC particles. In that case, the SiC particles were found to be located along the Al powder surfaces in the form of clusters to decrease the surface energy. In this study, the SiC particles distribute more uniformly when the size of the SiC particles is close to the size of the Al powders. The density evolution in Fig. 4 is consistent with the microstructural observations in Fig. 1, in which the composite reinforced with

39.1-μm-sized SiC particles has the fewest number of the pores and the more uniform distribution of the SiC particles.

It should be noted that extrusion can generate severe plastic deformation of the matrix, which leads to the rearrangement of the SiC particles, and thus, to the improvement in the distributed uniformity of the SiC particles. In this study, one-step extrusion is sufficient to eliminate the segregation of the SiC particle and obtain the uniform distribution of the SiC particles, even in the composite with the SiC particle size of 4.7 μm (with the PSR of 9.7). This is due to softness and deformability of the used commercial pure Al in this study. In the study of Slipenyuk (Ref 6), the segregation of the SiC particles in the composites with the PSR of 5.7 and 9.3 still remained even after extrusion due to the high strength of Al-Cu-Mn alloy matrix, which is difficult to be deformed and cannot generate enough plastic flow. On the other hand, the high stress generated during extrusion can also decrease the number of pores and enhance the interfacial bonding between the matrix and SiC particles, as shown in Fig. 3.

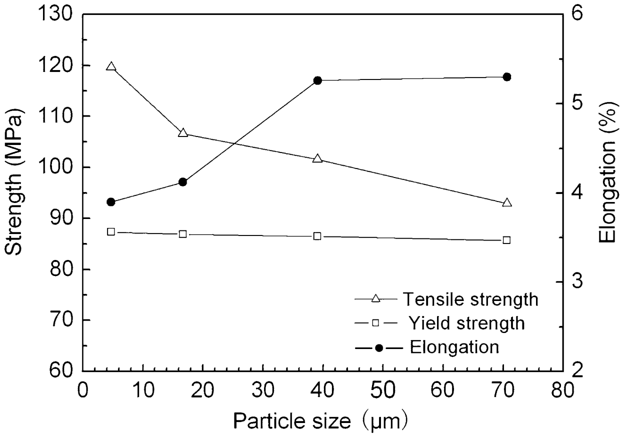

Fig. 6 Yield strength, ultimate tensile strength, and elongation evolutions as a function of the particle size after extrusion

4.2 Effect of Particle Size and Extrusion on the Mechanical Properties of the Composites

Before extrusion, the hardness values of the composites with the particle sizes of 4.7 and 70.7 μm are extremely low, because of the voids and poor interfacial bonding of the composites. During deformation, the clustered SiC particles and voids can be treated as pre-existing cracks, and thus the externally applied stress cannot be transferred from the soft matrix to the hard reinforcements, resulting in the degradation of the mechanical properties, as was also shown in the previous investigations (Ref 12, 13).

It is generally accepted that reducing the reinforcement size can obtain a finer microstructure and improved mechanical

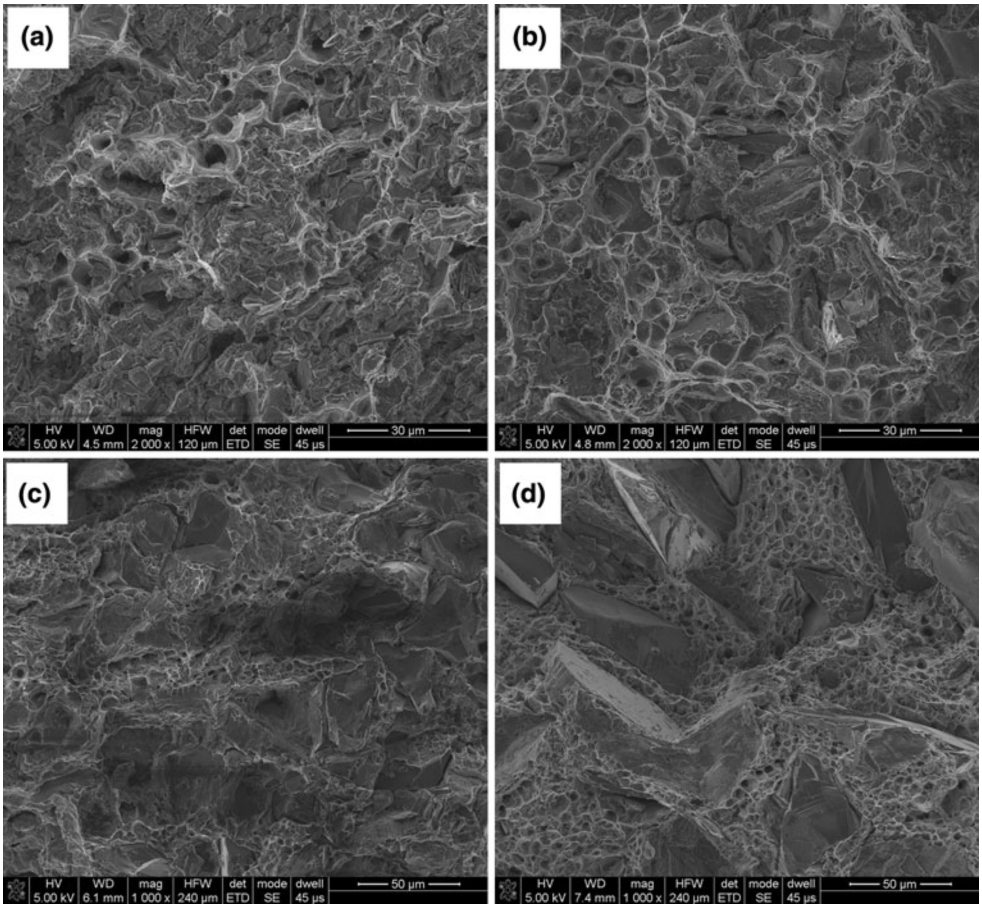

Fig. 7 SEM fracture surfaces of the composites after extrusion and after tensile testing with the particle sizes of (a) 4.7 μm, (b) 16.7 μm, (c) 39.1 μm, and (d) 70.7 μm

properties of the composites for a given particle volume fraction, because of the smaller inter-particle spacing and larger work hardening rate. The decrease in the particle size increases both the effects of direct strengthening and indirect strengthening (Ref 23-25). As the SiC particle size decrease, the interfacial area between the matrix and the SiC particles also increase, and more load can thus be transferred from the matrix to the SiC particles. It should be noted that a large interfacial area can also facilitate the generation of more dislocations in the matrix, thereby improving the mechanical properties of the composites. On the other hand, the larger-sized particles fracture more easily than the smaller ones during extrusion and tensile testing process because of two reasons (Ref 26). First, each larger-sized particle has larger interface area with the matrix, and thus endures higher stress concentration. Second, the particle fracture strength is controlled by the intrinsic flaws within the particle. Since the size of a flaw is limited by the size of the particle, larger particles are more likely to fracture because they have a greater statistical probability of containing a flaw that is greater than the critical size (Ref 27). Since the fractured particles cannot withstand any load, but act as preferential failure sites, the composites with larger SiC particle size show degradation of mechanical properties.

It can be seen from Fig. 6 that the elongation of the composites increases with the particle size, in agreement with some previous studies (Ref 16, 28). This may be attributed to the inter-particle spacing, which decreases with the decrease of the SiC particle size for a given particle volume fraction. Song and Xiao (Ref 28) indicated that the ductility (elongation) is essentially determined by the inter-particle spacing. During deformation, the geometrically necessary dislocations are stored in the matrix, and a large interparticle spacing can accommodate more dislocations during deformation between two neighboring particles to improve the ductility of the composites. However, some other researchers (Ref 1, 6, 23) showed an opposite result, in which the ductility increases with the decrease of the particle size, which might be due to the pre-existing flaws over the critical size in the large-sized SiC particles. In reality, the relationship between ductility (elongation) and particle size may be controlled by a lot of factors, and a further investigation is still required in the future.

5. Conclusion

In this article, SiC particle-reinforced pure Al composites were fabricated by powder metallurgy method. The effects of particle size and extrusion on the microstructures and mechanical properties of the composites have been studied. It has been shown that both particle size and extrusion have important effects on the microstructures and mechanical properties of the composites. The voids coexisting with the clustered and large-sized SiC particles significantly decrease the density and mechanical properties of the composites. Extrusion can redistribute the SiC particles in the matrix and decrease the number of pores, thus make the SiC particles distribute more uniformly in the matrix, and substantially enhance the interfacial bonding strength. The decrease of the SiC particle size will improve the tensile strength and yield strength because of the larger interfacial surface area and larger work hardening rate, but decrease the ductility of the composites because of the smaller inter-particle spacing.

Acknowledgments

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