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On the role of nano-size SiC on lattice strain and grain size of Al/SiC nanocomposite

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ABSTRACT

In the present study high energy ball mill was implemented to produce aluminum (Al) matrix composite powders reinforced with silicon carbide (SiC). To clarify the role of particle size of SiC on lattice strain and grain size of Al two series of SiC with micron and nano-size were selected. Aluminum and SiC powders were mixed mechanically and milled at different times (2, 5, 10 h) to achieve Al–2.5 vol%SiC and Al–5 vol%SiC composite powders. The produced composites were investigated using X-ray diffraction pattern (XRD) to elucidate the role of particle size, secondary phase content and milling time on grain size and lattice strain of Al matrix. The results showed that an increase in milling time caused to reduce the grain size unlike the lattice strain of Al matrix. At the same condition a faster grain refinement for Al/SiC nanocomposites were observed with respect to Al/SiC composites.

1. Introduction

Metal matrix composites (MMCs) such as Al, Ti and Ni alloys reinforced with Al_2O_3 or SiC particulates or whiskers have the potential to provide desirable mechanical properties including high specific stiffness, high plastic flow strength, creep resistance, good oxidation and corrosion resistance [1,2].

Among aluminum matrix composites, Al/SiC composites have recently received particular interests due to their high specific modulus, high strength and high thermal stability. They can be widely used in the aerospace, automobiles industry such as electronic heat sinks, automotive drive shafts, ground vehicle brake rotors, jet fighter aircraft fins or explosion engine components [3].

Although casting is the cheapest technique for composite fabrication, it is difficult to use for synthesizing Al/SiC composites due to the extreme gap difference in the thermal expansion coefficients between the two constituents and also because of poor wettability between molten Al (or Al alloys) and SiC. In addition it may lead to an undesirable reaction between SiC and molten Al, producing brittle phases of Al_4C_3 and Si. To avoid both making brittle phases and particle agglomerations during fabrication of Al/SiC composite, solid state process such as mechanical alloying (MA) has been suggested. Mechanical alloying of multi-component powders is a solid state process capable to obtain metastable structures as amorphous and nanocrystalline materials with high thermal stability [4]. Powder particles in the ball mill are subjected to high-energy collision, which causes the powder particles to be cold-welded together and fractured. High energy ball milling processes, including attrition mills, SPEX shaker mills and planetary ball mills, have been established as a non-equilibrium mechanical processing technique to achieve solid state reaction of various alloy systems and nanocrystalline materials. The mechanical properties of particle reinforced composites are largely dependent on the reinforcement particle microstructure, distribution and volume fraction [5–9].

The microstructure of nanocrystalline materials can be effectively studied by X-ray diffraction line profile analysis. Crystallite size and strain effects acting concurrently cause the broadening of a profile. In plastically deformed metals and ceramics the lattice distortions are mainly caused by dislocations, so the strain broadening can be expressed by grain size and dislocation parameters such as concentration, arrangement, etc.

According to the literature survey done by the authors there are many articles which have been focused on the production of composite materials using mechanical alloying method [3–5,10–26]. In some of them the effect of various parameters such as milling condition and SiC content on physical and mechanical properties of Al/SiC composite have been studied [20–26]. Due to the importance of role of grain size on mechanical properties of composite such as strength and toughness of Al/SiC composites, the main goal of the current research is concentrated on the role of milling conditions

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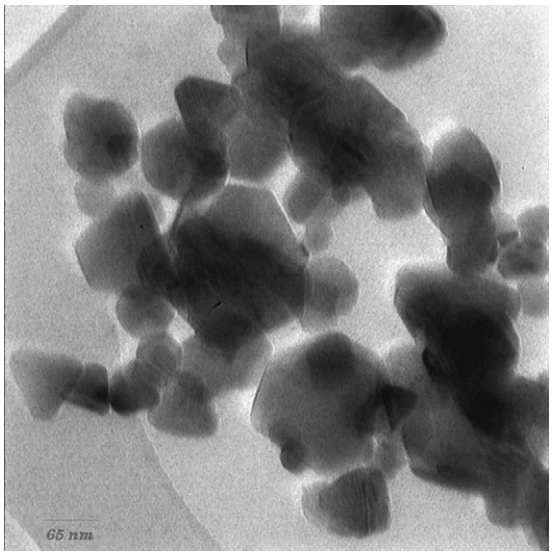

Fig. 1. TEM micrograph of nano-size SiC.

specially reinforcement particle size on X-ray diffraction pattern, grain size and lattice strain of Al in Al/SiC composite powders.

2. Experimental

2.1. Material

To produce Al/SiC composites, SiC powders with average particle size of about 5 μm from Zamin Tavana (Iran-Tehran) company and SiC powders with particle size of 45–55 nm were used. Fig. 1 shows TEM micrograph of nano-size SiC. Al powders with purity of about 99% and average particle size of about 45 μm were obtained from powder metallurgy (Iran-Khorasan) company.

Stearic acid as lubricant or surfactant, was added to the powder mixture to control the particle size of composite powders. In fact it was used to avoid any unwanted and excessive cold welding of the powder particles onto the internal surfaces of the vial and to the surface of the grinding medium during the heavy plastic deformation.

2.2. Ball milling

Both micron and nano-size SiC were mixed with aluminum powders separately to achieve Al–2.5 vol%SiC and Al–5 vol%SiC powder mixtures. 1.1 wt% stearic acid was added to the mixture as surface active agent to control the particle size of composite powders and the suitable amount of this lubricant was obtained with experimental method. The mixtures were milled using a planetary ball mill (M200) at different milling times (2, 5 and 10 h). A ball to powder weight ratio of 10:1 was kept constant in the steel vials. Steel balls with three sizes were used, i.e. 8, 10 and 12 mm. Milling was carried out at air atmosphere condition and with milling intensity of 36.2 Hz. For the purpose of comparison pure Al powders were milled at the same condition. Table 1 shows the specification of used powders and milling conditions.

2.3. X-ray diffraction pattern (XRD)

The diffraction patterns of milled samples were achieved by X-ray diffraction analysis. XRD patterns were obtained using a Philips X'Ppert Diffractometer with Cu Kα radiation ($\lambda = 0.154$ nm) in the range of $2\theta = 110^\circ$ by the step of 0.02°.

Table 1
specification of used powders and milling conditions.

Particle Size of SiC	5 μm, 45–55 nm	Particle size of Al (μm)	45
Stearic acid (%)	1.1	SiC (%)	0, 2.5, 5
Ball size (mm)	8, 10, 12	Milling time (h)	2, 5, 10
Ball/powder weight	10:1	Milling intensity (Hz)	36.2

3. Results and discussion

X-ray diffraction patterns of produced aluminum composite powders reinforced with different SiC content are given in Fig. 2-a–d). Remarkably, in X-ray diffraction pattern the peak of Al and SiC is sensible unlike the peak of other component such as Al_4C_3 and Si. This event is related to this point that in different methods of Al/SiC composite production, the interface of two phases is one essential part of composite. Bonding develops from physical or chemical interactions, interfacial frictional stress and thermal stresses due to mismatch between coefficient of thermal expansion of reinforcement and matrices. In casting of Al/SiC composite, SiC reinforcement particles is not thermodynamically stable in liquid Al and reacts with the matrix, forming aluminum carbide according to reaction (1). It is clear that extension of the reaction depends on the temperature as well as silicon content in the matrix.

$$4Al + 3SiC \rightarrow Al_4C_3 + 3Si \quad (1)$$

Unlike casting, in solid state process such as milling, temperature is very low and leads to avoid formation of undesirable phases [4,27].

Referring to the achieved results it can be concluded that the ball milling method used in the current study is the suitable method to produce Al/SiC composite powders.

Obviously, the starting materials contain coarse polycrystalline grains of Al, suggested by the sharp diffraction peaks of the powder mixture (Fig. 2-a). At the beginning of milling, Al/SiC composite structure has been formed from coarse grains of Al and coarse particles of SiC. On the contrary the Bragg peaks of aluminum matrix powders become broad with increasing the milling time, indicating formation of Al/SiC nanocomposite material (Fig. 2-b). On the other hand, a decrease in the grain size of Al and an increase in lattice strain lead to peaks broadening. This is why the Bragg peaks of both the reinforcement (SiC) and metallic matrix (Al) powders became broad with increasing the milling time. Fig. 2-c shows the diffraction pattern of Al powders reinforced with micron-size SiC at different milling times. The dependency of spectrum on both milling time and SiC content is clear. Also it can also be seen from Fig. 2-d that the diffraction peaks of Al are broaden after 10 h milling, which is due to refining of grain size and increasing of internal strain resulted from severe deformation. The grain size and the internal stress are calculated by Williamson hall's method [28].

$$B\cos\theta = B_d + B_\varepsilon = \frac{k\lambda}{d} + 2\varepsilon\sin\theta \quad (2)$$

where B is the full width at half-maximum (FWHM) of the diffraction peak after instrument correction, B_d and B_ε are FWHM caused by small grain size and internal strain, respectively. K is constant as 0.9, λ is wavelength of X-ray radiation, d and ε are grain size and internal strain, respectively, and θ is the Bragg angle. $\beta_0 = \beta + \beta_s$, where β_0 and β_s are FWHM of broadened Bragg peaks and the standard sample's Bragg peaks, respectively. Figs. 3 and 4 show the dependence of grain size and internal strain of both pure aluminum and aluminum matrix on milling time. As it is clear increasing the milling time, causes to decrease the grain size. The reason of this variation can be referred to this point that with increasing milling time, severe deformation on powder particles applies and leads to increase the crystalline defects such as point defects, dislocations and so on [28–30]. Indeed the presence of defects makes an increase in system energy and the lattice strain. To compensate the mentioned effect dislocations move to form a new orientation with lower energy, the so-called sub-grain boundary [28–30]. For example this result has been observed in nanostructured WC/Co composite powder prepared by high energy ball

Table 2
A comparison of grain size of Al/5%SiC composite reinforced with different particle sizes.

Milling time (h)	Grain size (nm) (nano-size SiC)	Grain size (nm) (micron-size SiC)
2	53	58
10	28	31

milling [29]. The result showed that high energy ball milling can efficiently refine the microstructure of tungsten carbide in a WC/Co composite [29].

Fig. 5 and Table 2 compare the effect of SiC particle size on grain size of Al in composite powders. As it is clear at early stage of milling the grain size of aluminum matrix is almost the same for two series of SiC, i.e. Nano- and micron-size. This is because at the beginning of process the ultrafine particles tend to be agglomerated. To break the mechanical interlocking between them milling time should be increased up to 10 h. In fact after 10 h milling the grain size of aluminum matrix reinforced with nano-size SiC becomes much lower than that of micron-size SiC. The reason of this effect can be attributed to the different mechanisms of interaction between dislocation and nano-size SiC. On the other hand, an increase in milling time leads to raise the amount of plastic deformation as well as dislocation density. With this reason and interaction of dislocations/nano-size SiC, the dislocations pile up and multiplication will be occurred based on Orowan theory. Thus the grain refinement can be happened sooner as particle size of secondary phase approaches toward nano-size. This is why at the same condition the grain size of aluminum matrix reinforced with nano-size

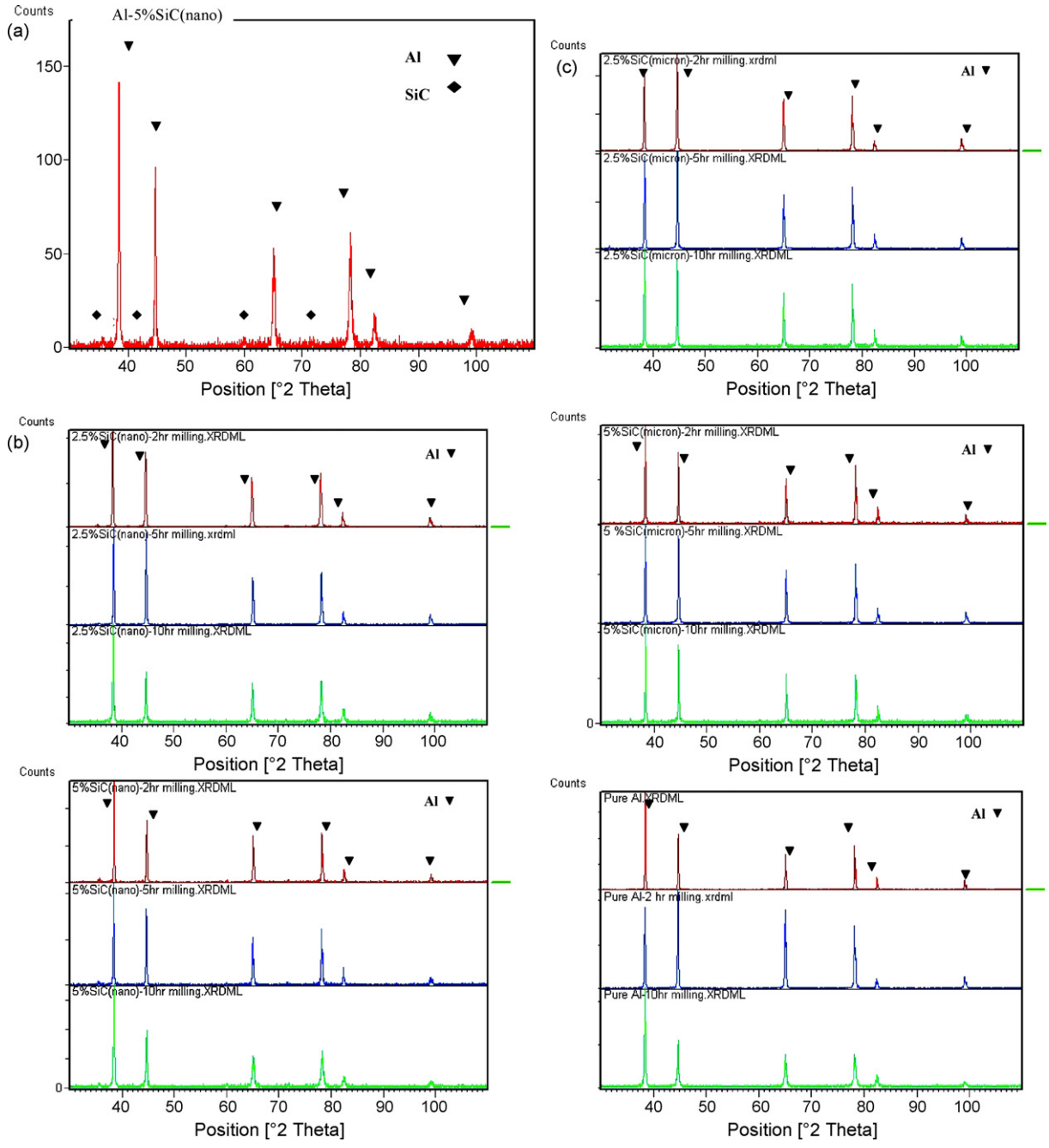

Fig. 2. X-ray pattern of powders, (a) Al and SiC before milling, (b) Al/nano-size SiC, (c) Al/micron-size SiC and (d) pure Al.

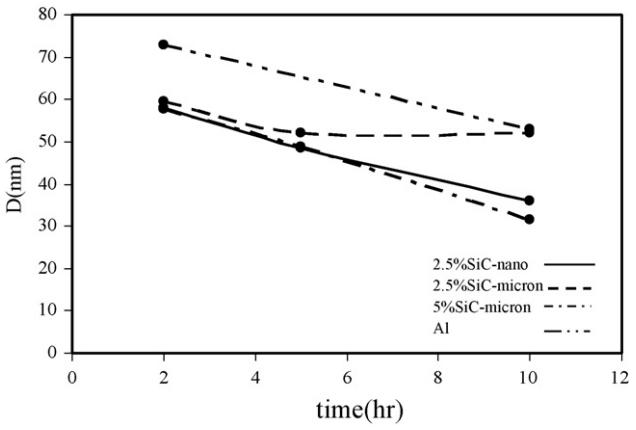

Fig. 3. Dependence of grain size of Al on milling time as a function of secondary phase.

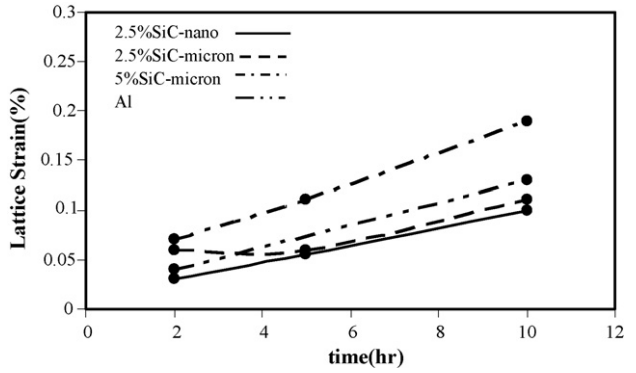

Fig. 4. Variation of lattice strain (%) in Al vs. milling time as a function of secondary phase.

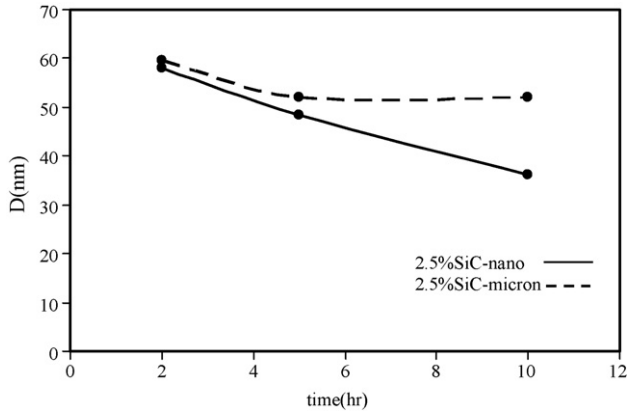

Fig. 5. Dependence of grain size of Al/2.5%SiC composite on SiC particle size.

SiC is much lower than that of micron-size. As a matter of fact this finding suggests that the plastic deformation of the metal matrix is affected by the size of reinforcement particles. But, the aluminum powder containing nanometric SiC particles approaches toward a steady state condition in a longer milling time compared with micrometric particles (Fig. 5).

4. Conclusion

Two series of Al matrix composite reinforced with micron- and nano-size SiC were produced using ball milling method. The role of particle size of SiC on lattice strain and grain size of Al were investigated. The results are remarked as below.

- An increase in milling time causes to reduce the grain size of aluminum unlike the lattice strain.
- Role of nano-size SiC on grain refinement is significant rather than that of micron-size.
- The presence of nano-size SiC leads the system approach to a steady state condition at longer milling time.

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