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Effect of Shaping Methods on the Mechanical Properties of Al-SiC Composite

M. Zakeri[a]*, A. Vakili-Ahrari Rudi[b]

[a]*Ceramic Department, Materials and Energy Research Center, P.O. Box 31787/316, Karaj, Iran*
[b]*Materials Science Department, Shiraz University, Shiraz, Iran*

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Al-SiC composites were successfully produced with improved mechanical properties. Effect of SiC content, its particles size and shaping method were investigated. Three shaping methods of conventional powder metallurgy (PM), hot press (HP) and hot extrusion (EX) were used. The hardness of the samples was measured by Vickers method. Tensile and compression tests were performed for the characterization of mechanical properties. Microstructure was monitored by optical microscopy. Maximum relative density (RD) was obtained for hot pressed samples. Higher SiC content with smaller particles size had the best effect on the mechanical properties such as yielding point (YP), ultimate tensile strength (UTS) and hardness. Maximum hardness (6.57 GPa) and UTS (212 MPa) were obtained for Al-20%SiC with SiC mesh size of 1000. Maximum YP was obtained for Al-20%SiC in compression test (143.64 MPa) that is larger than it in tensile test (117.96 MPa). Remarkable difference exists between HP and extrusion methods at higher SiC contents. The YP of EX samples are larger than HP samples. Strains at known stress (562 MPa) of EX samples are smaller than HP samples.

Keywords: *metal matrix composite; extrusion; mechanical properties*

1. Inroduction

Al based composite has been widely used in many fields owing to its excellent properties such as low weight, high special strength and stiffness, high electrical and thermal conductivity, low thermal expansion, good wear resistance and environmental corrosion resistance[1,2]. It is generally prepared by dispersion of ceramic particle like SiC, Si_3N_4, $A1_2O_3$ or TiC in Al matrix and the most commonly used particle is SiC[3-6].

Many methods have been used to prepare Al based composite. In the liquid methods, particles are added to liquid Al by stirring before casting. However, the difference in thermal expansion coefficients of the constituents and the poor wet-ability of molten A1 and SiC particles become an obstacle to the liquid method used for synthesizing Al-SiC composite. In addition, liquid metallurgy may lead to an undesirable reaction between SiC and molten Al, producing brittle phase of $A1_4C_3$ and Si[7]. Solid state method is another way of producing homogenous distribution of these hard particles. In this way, simple mixing of Al and SiC are performed by milling in different type of mills. There is no undesirable reaction and segregation between the components during producing with this method[8].

Al-SiC composite powder can be sintered by several methods such as conventional pressure less sintering, hot pressing, hot extrusion, spark plasma sintering and etc[9-14]. Shaping method has very significant effect on physical and mechanical properties of this composite. Final densities of produced bulk Al-SiC as well as microstructure are two important affecting parameters on the mechanical and physical properties. Paydar showed that Al-SiC composite can be extruded at 400-500 °C with surface area reduction about 80%[15]. Zamani also showed that extruding of this composite at temperatures below 350 °C leads to increasing of extruding pressure and defects in the produced final bulk composite[16]. Hong et al have demonstrated the potential of making high strength Al- SiC composites with reasonable ductility by resistance sintering of mechanically alloyed powders. It was found that the compressive yield stress and ultimate strength increases with increasing SiC volume fraction and decreasing SiC particle size, while the compressive failure strain shows the reverse trend with the variation in SiC particle size and content[17]. Sinter/hot isostatically pressed composites of up to 30 vol.% SiC were produced with a significant improvement in ductility and ultimate tensile strength compared with the other fabrication methods. The measured densities of the fabricated materials indicated that fully dense material was not achieved[18].

In the present work, effect of shaping method and SiC particles size were studied on the mechanical properties of Al-SiC composite. Three different shaping methods of pressure less, hot press and hot extrusion as well as two SiC particles size were used.

2. Experimental Procedures

Al (99%, 25 mm, Khorasan Metallurgy Co.) and SiC (99%, 37 and 15 mm, Merck) were used as starting materials for production of Al-SiC composites. Figure 1 shows the XRD pattern of the as-mixed materials. This pattern includes Al and SiC reflections. Morphology and Particles size of starting materials were also shown in Figure 2. A horizontal low energy ball mill was used for mixing of

*e-mail: M_zakeri@merc.ac.ir

starting materials. Mixture of starting materials and stainless steel balls (20 balls with 8 mm diameter) were charged to stainless steel chamber. Ball milling was only performed for mixing of Al and SiC powders (15 min) with the rotational speed of 100 rpm. Five cylindrical samples (d=19.8 mm, h=30 mm) were produced by cold pressing at the pressure of 573 MPa. All samples were heat treated in atmosphere control furnace (Ar gas) at the temperature of 535 °C for 90 min with the heating rate of 10 $°C.min^{-1}$. One sample were cooled to room temperature and then characterized by the following methods. Two other samples, just hot pressed at the temperature of 535 °C with the pressure of 612 MPa. Two remained samples were hot extruded at the temperature of 535 °C for the surface area reduction of 84.3%. Tensile specimens were fabricated from hot extruded bars on the basis of B557M-84 standard. Tensile and compression tests were performed by an universal testing machine (SANTAM200) with the head speed of 1 mm/min. Hardness of the samples was measured by Vickers method on the load of 10 kg and soaking time of 30 s. Final density of bulk materials was measured by Archimedes method by immersion in distilled water. All samples were etched with 95%H_2O-5%HF solution and then their microstructure was monitored by optical microscopy. Philips X-ray diffractometer with Cu Kα (operating at 25kV and 30 mA) was used for characterizing of starting materials.

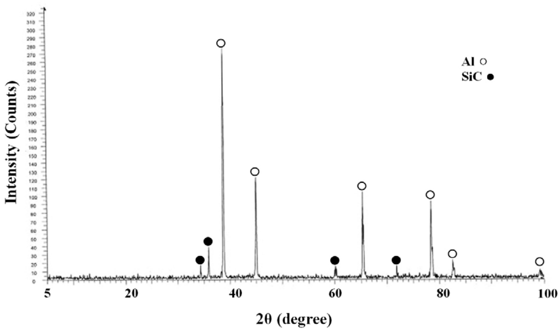

Figure 1. XRD pattern of the mixture of as-received materials.

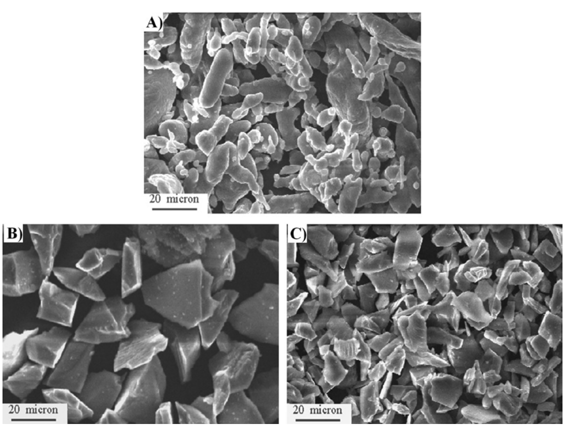

Figure 2. SEM images of as-received materials; A) Al, B) SiC (24 µm, mesh 400) and C) SiC (10 mm, mesh 1000).

3. Results and Discussions

Figure 1 shows the XRD pattern of the as mixed materials. Al-SiC composites with different SiC contents were produced. Morphology of these powders is shown in Figure 2. Al particles have very rounded and regular morphology with the mean particles size of 25 mm. As seen in Figure 2B, C, SiC particles have an irregular and sharp edge that is due to the crushing during their production.

Al-SiC composite powders were hot extruded with different pressure (Table 1). Al had the minimum required pressure for hot extruding at 535 °C. Higher SiC content led to the higher pressure as well as higher temperature. Extrusion pressure increases with decreasing SiC particles size. SiC is a brittle ceramic with no plastic deformation at ambient temperatures[19]. Introducing SiC to Al matrix leads to the decreasing of its plastic deformation. On the other hand, Al viscosity increases due to SiC particles, therefore more pressure and temperature are required for extruding of Al-SiC composite. Higher SiC content and its smaller particles have same effect on the extrusion pressure and temperature as discussed.

Relative density (RD) is the first characterization parameters for any shaping method. Each shaping methods that gives higher RD, it is better for production of bulk composite. RDs of Al-SiC composites with different SiC contents and particle size were shown after shaping with conventional powder metallurgy (PM), hot pressing (HP) and hot extrusion (EX) in Table 2. With comparison of

Table 1. Required pressure for hot extruding at different processing condition.

%SiC (vol.)	SiC particle Size (mesh)	Extrusion		
		Temperature (°C)	Reduction (%)	Pressure (MPa)±5
0	**----**	535	84.31	313.45
5	**400**	535	84.31	358.15
	1000	535	84.31	383.54
10	**400**	535	84.31	408.65
	1000	535	84.31	414.78
15	**400**	570	84.31	382.63
	1000	570	84.31	394.88
20	**400**	570	84.31	414.16
	1000	570	84.31	419.06

Table 2. Al-SiC composite densities measured by Archimedes method.

%SiC (vol.)	SiC particle Size (mesh)	Density %0.2		
		H.P	**P.M.**	**EX.**
0	----	99.86	80.11	99.62
5	400	99.94	84.36	99.21
	1000	99.9	86.68	99.82
10	400	99.97	85.15	99.67
	1000	99.58	88.35	99.39
15	400	99.82	86.25	99.42
	1000	99.62	86.45	99.67
20	400	99.63	86.36	99.34
	1000	99.8	86.4	99.69

these methods, it can be concluded that RD in PM is lower than HP and EX. PM is a pressure less sintering method that there is no pressure during heating, therefore, sintering process cannot be completely performed. The RD of Al-SiC composites that produced with HP were higher than EX. It seems that the static behavior of HP method leads to more plastic deformation and mass transformation. On the other hand, dynamic manner of extrusion method with the shorter process time reduces the plastic deformation and resulted RD. SiC particle size and its contents had no considerable effect on RD.

Microstructure of Al-SiC composites were shown in Figure 3. Figures 3A-C are attributed to PM, EX and HP samples with 10% SiC, respectively. In the PM sample, some pores can be seen in the microstructure due to its

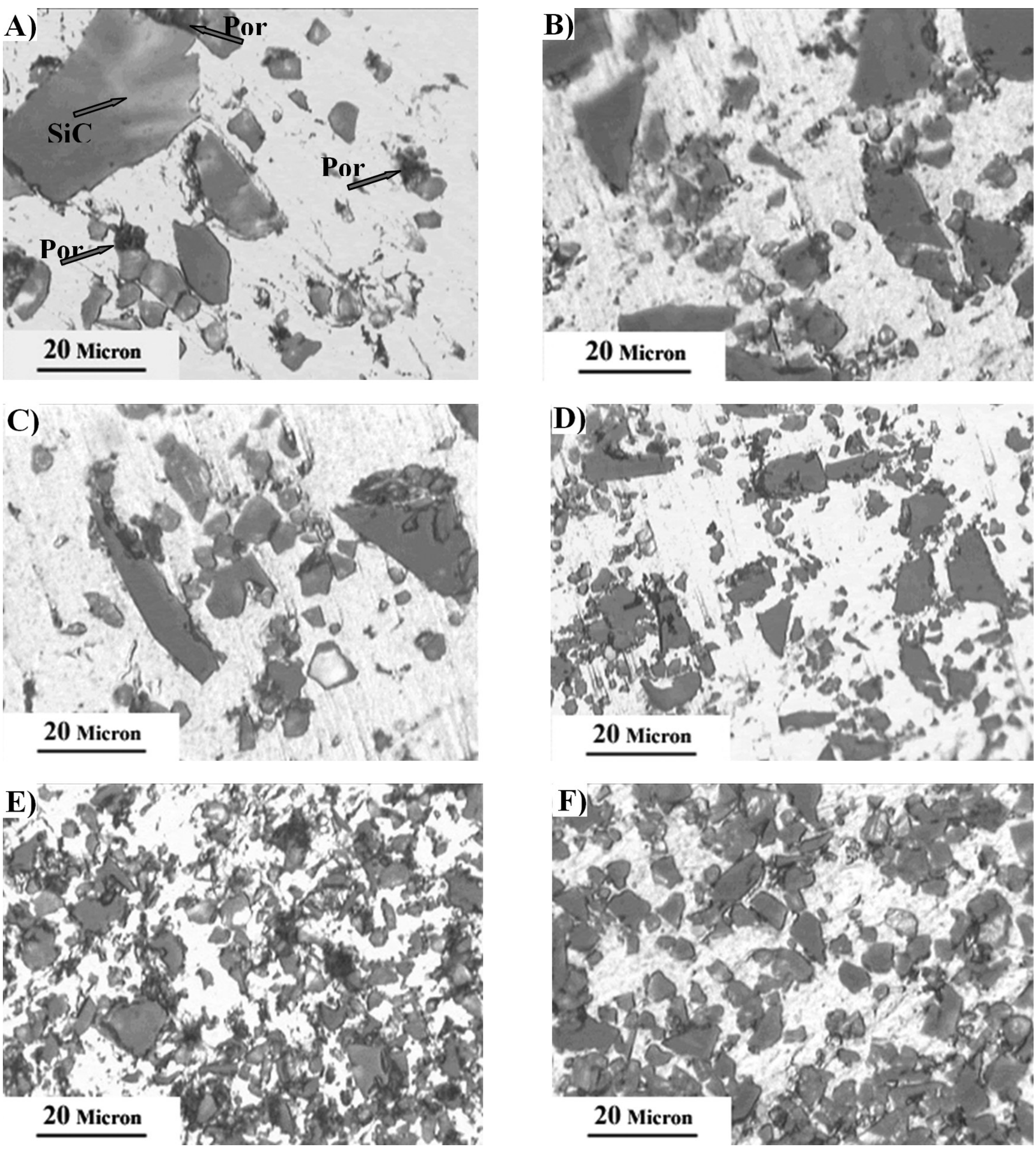

Figure 3. Optical microscopy images of Al-SiC composites; A) 10%SiC mesh 400, P.M., B) 10%SiC mesh 400, EX., C) 10%SiC mesh 400, H.P., D) 10%SiC mesh 1000, EX., E) 15%SiC mesh 1000, EX., and F) 20%SiC mesh 1000, H.P.

low RD. But, approximately, there is no pore in the HP and EX samples microstructures due to their higher RD. Figure 3D shows the microstructure of Al-10%SiC with the SiC mesh size of 1000. Comparison of this image with Figure 2B (SiC size is mesh 400) shows that SiC particles have better distribution in smaller size. Figures 3E, F show the microstructures of Al-15%SiC with EX and Al-20%SiC with HP methods, respectively. Discontinuity of Al matrix increases with increasing SiC content that decreases the ductility and strength of this composite. These effects can be seen in the results of tensile experiments.

Vickers hardness of Al-SiC composites with different SiC contents and particles sizes were presented in Table 3. Pure bulk Al has the minimum hardness in all three methods. As seen, those samples that were produced by PM method have lower hardness in compare with HP and EX methods. As discussed before, sintering process was not completed in PM process and samples have more porosity that leads to the more plastic deformation under indent loading. Higher SiC content with smaller particles size led to the harder composite. High hardness of SiC is the main reason of hardness increasing, but also, low plastic deformation of composite due to existence of SiC reinforcements is another reason for this improvement in hardness. Maximum hardness of 7.45 GPa was obtained for Al-20%SiC that was produced by HP method with SiC mesh size 1000. Comparison of this hardness with pure HP and EX aluminum shows that the hardness increased about 60 and 145%, respectively.

Figure 4 shows the effect of SiC content and its particles size on yielding point (YP), ultimate tensile strength (UTS) and elongation of Al-SiC composite that produced with EX method. As seen, YP and UTS increase with increasing SiC content. Higher SiC content leads to the more SiC particles in the Al matrix and less plastic deformation. On the other hand, SiC particles are a barrier for movement of dislocations in Al matrix; therefore for dislocation gliding between these SiC reinforcements, higher flow stress was required. SiC particles size has a same effect as SiC content. Smaller SiC particle size means more particles in Al matrix with smaller space between them. On the basis of Orown mechanism, the flow stress for dislocation gliding increases with decreasing reinforcements distance[20]. Higher SiC content with smaller particles size led to the lower elongation that is due to the discontinuity of Al matrix. Lower Al content and its discontinuity led to the lower plastic deformation and elongation. In general, Higher SiC content with smaller particle size led to the higher strength with lower ductility Al-SiC composites. UTS of Al-20%SiC with the SiC mesh sizes of 400 and 1000 were increased in compare with pure Al about 18 and 32%, respectively. This effect for YP was 32 and 36% correspondingly. Elongations of Al-20%SiC composite with the SiC mesh size of 400 and 1000 were significantly decreased to 75 and 83%, in that order.

Compression test was performed on the cylindrical hot pressed samples with the same height and diameter (8 mm). Yielding point and strain at known stress (585 MPa) of these samples are shown in Figure 5. SiC content and its particles size had a same effect on YP as tensile tests. But maximum YP of Al-20%SiC in compression test (143.64 MPa) is larger than it in tensile test (117.96 MPa). There is some minor porosity in HP samples (refer to Table 2). These porosities act as crack nucleation in tensile test that leads to lower YP. On the other hands, the applied pressure during compression test leads to closing of these porosities. There is no fracture on compression test of ductile materials; therefore elongation of these materials cannot be measured. There is one approach to measure the elongation by measurement of the sample strain at arbitrary known stress. Measurement

Table 3. Vickers hardness number of Al-SiC composites at different processing condition.

%SiC (vol.)	SiC particle Size (mesh)	Vickers Hardness Number (HV_{10}) (GPa)0.1		
		H.P	P.M.	EX.
0	----	4.67		4.67
5	400			
	1000			
10	400			
	1000			
15	400			
	1000			
20	400			
	1000			

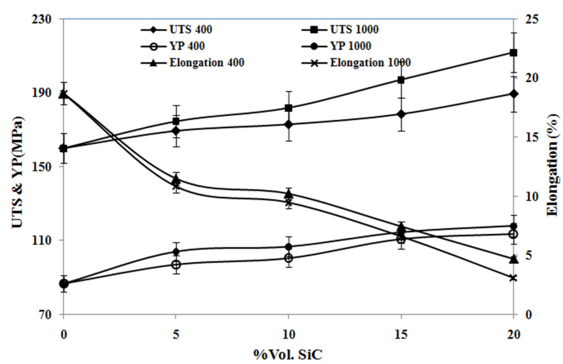

Figure 4. Ultimate tensile strength, yielding point and elongation from tensile experiments of hot extruded Al-SiC composites.

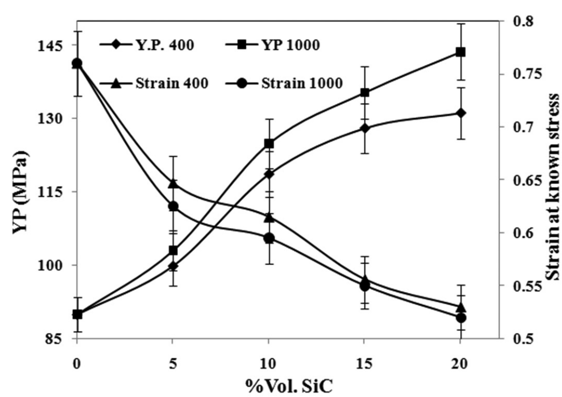

Figure 5. Yield point and strain under known stress (585 MPa) of hot extruded Al-SiC composites from compression experiments.

of strain of the samples at the stress of 585 MPa shows that higher SiC content with smaller particles size decreases this strain. On the other hand, 20%SiC led to the 31.5% decrease of this strain in compare with pure Al that means it's ductility significantly decreased.

HP and EX methods were compared by compression test. As seen in Figure 6, the YP of EX samples are larger than HP samples. Strains at known stress (562 MPa) of

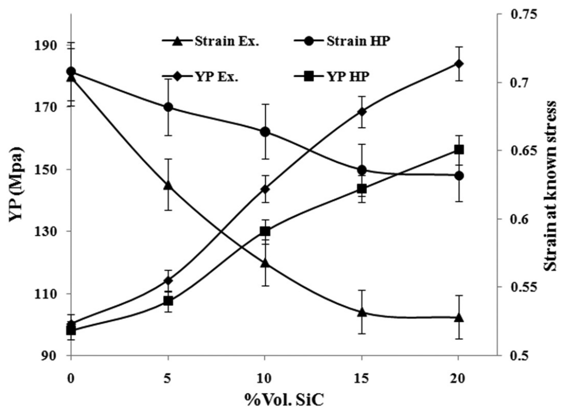

Figure 6. Effect of shaping method on compressive properties of Al-SiC composite.

Table 4. Difference between YP and strain of HP and EX samples.

%SiC	0	5	10	15	20
	0	6.29	10.57	17.40	17.91
	0	9.12	16.90	19.55	19.70

EX samples are smaller than HP samples. Ductility of Al-20%SiC composites was decreased about 25 and 11% for EX and HP samples, respectively in compare with pure Al. On the other hand, the ductility of HP samples is more than EX samples. It seems that this is attributed to dynamic behavior of EX method. On the other hand, static manner of HP method leads to remaining some stress in samples. This stress will decrease the YP and brittleness of HP samples. Difference of YP and strain of HP and EX samples were calculated at different SiC contents (Table 4). As seen, these values increase with increasing SiC content. A remarkable difference exists between HP and EX methods at higher SiC contents.

4. Conclusion

Al-SiC composites with improved mechanical properties were produced by three shaping methods. Effects of SiC content and its particles size were investigated. Results showed that the HP method can produce maximum RD with minimum porosity. Higher SiC content with smaller particles size led to higher strength on the basis of tensile and experiment tests. Brittleness of Al-SiC composite increases at higher SiC content. Maximum hardness of 6.57 GPa was obtained for Al-20%SiC with SiC mesh size of 1000. UTS of Al-20%SiC with the SiC mesh sizes of 400 and 1000 were increased in compare with pure Al about 18 and 32%, respectively. Maximum YP was obtained for Al-20%SiC in compression test (143.64 MPa) that is larger than it in tensile test (117.96 MPa). A remarkable difference exists between HP and EX methods at higher SiC contents. The YP of EX samples are larger than HP samples. Strains at known stress (562 MPa) of EX samples are smaller than HP samples.

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