EFFECT OF EXTRUSION PROCESS ON DUCTILITY AND FRACTURE BEHAVIOR OF SiC_p/ALUMINUM-ALLOY COMPOSITES

Amir PAKDEL, H. FARHANGI and M. EMAMY

University of Tehran, University college of Engineering,
School of Metallurgy and Materials Engineering, Tehran, Iran.

ABSTRACT

The effect of hot extrusion on the microstructure, ductility and fracture behavior of metal-matrix composites (MMCs) of Al6061 alloy reinforced with 10 Vol. % particulate SiC with the average size of 46 µm has been studied. The MMC ingots were fabricated by the stir casting method and were extruded at 450ºC at a ram speed of 1mm/s and at the extrusion ratios of 6:1, 12:1 and 18:1. Various techniques including density measurement, tensile testing, metallography, and SEM fractography were utilized to characterize the microstructure and fracture behavior of the MMCs. The extruded composites exhibited reduced porosity, a more uniform particle distribution and improved ductility in comparison with the as-cast samples. Fracture in the as-cast specimens comprised of cracking of the SiC particle clusters leading to brittle fracture of the MMCs. But after applying the extrusion process, clusters of reinforcement particles were eliminated and some ductility was observed in the MMCs.

Keywords: Al/SiC composites; Fracture; Hot extrusion; Microstructure; Porosity; Stir casting.

1. INTRODUCTION

Over the past two decades metal matrix composites (MMCs) have been transformed from a topic of scientific and intellectual interest to a material of broad technological and commercial significance. Today MMCs are widely used in a variety of applications and the worldwide MMC markets in 1999 accounted for 2500 metric tons valued at over $100M in the ground transportation (auto and rail), thermal management, aerospace and recreational industries [1]. Among the MMCs, discontinuously reinforced aluminum alloy metal matrix composites are a preferred choice for critical applications because they offer a number of advantages such as a 15-40% increase in strength, a 30-100% increase in stiffness and superior wear resistance compared with the unreinforced aluminum alloys [2].

There are several fabrication techniques available to manufacture MMC materials but they can be divided into three types. These are solid phase processes, liquid phase processes and semi-solid fabrication processes. Among the variety of manufacturing processes available for discontinuous MMC production, stir casting is generally accepted, and currently practiced commercially [3]. Stir casting of MMCs generally involves producing a melt of the selected matrix material, followed by the introduction of a reinforcing material into the melt and obtaining a suitable dispersion through stirring. Its advantages lie in its simplicity, flexibility and applicability to large scale production. It also, in principle, allows a conventional casting route to be used [4]. According to Skibo et al. [5], the cost of preparing composite materials using a casting method is about one third to one half that of competing methods, and for high volume production, it is projected that costs will fall to one tenth. However, due to poor wetting of the ceramic particles by molten alloy, the introduction and uniform dispersion of the reinforcement into the liquid matrix is difficult [6]. Moreover, structural defects such as interfacial reactions, formation of porosity and nonhomogeneous particle distribution arise from the unsatisfactory casting techniques [7].

It is known that secondary processing of the discontinuously reinforced composites can lead to break up of particle (or whicker) agglomerates, reduction or elimination of porosity, and improved bonding, all of which contribute to improve the mechanical properties of MMCs [8]. Particulate reinforced aluminum alloys can be formed by conventional plastic deformation processes such as rolling, extrusion or forging, among which extrusion has been used as the most common secondary processing because of its excellent preferential axial alignment of discontinuous fibers as well as large compressive hydrostatic state of stress [9]. However it is necessary to note that the presence of brittle and nearly nondeformable reinforcements such as particulates, whiskers or short fibers as in Al/SiC or Al/Al_2O_3 composites can results in undesirable phenomena such as fracture of reinforcement, debonding of interface or surface cracking in extruded product unless appropriate process design is employed [10].

Particle reinforced metal matrix composites are nearly always far less tough than their unreinforced matrix since the ceramic particles cause a strong acceleration of internal damage build-up, and damage is highly localized in front of the crack tip, leading to fracture. According to the works performed to characterize the tensile constitutive and failure behavior of MMCs under quasistatic loadings, four distinct micromechanisms are mentioned for fracture of MMCs including: (i) particle fracture, (ii) debonding or cracking along the reinforcement/matrix interface, (iii) failure in the matrix by microvoid nucleation, growth and coalescence, and (iv) failure in the matrix by shear. While these damage processes may operate simultaneously in a particular composite, one mode is often dominant [11].
The objective of this research paper is to examine the ductility and fracture behavior of a silicon carbide particle reinforced aluminum alloy metal matrix composite before and after applying the extrusion process.

2- MATERIALS AND EXPERIMENTAL PROCEDURES

Aluminum 6061 alloy and SiC particles of 46 µm average size were utilized to prepare 10 Vol. % composite ingots by the stir casting technique. The composition of the Al6061 alloy used in the present study (unreinforced material) is given in Table 1.

Table 1. Chemical composition of the aluminum alloy 6061.

Alloy Type	Composition (wt.%)						
	Mn	Cr	Fe	Cu	Si	Mg	Al
6061	0.01	0.05	0.17	0.33	0.71	1.12	Balance

The SiC particles had irregular shapes and are shown in Fig. 1. They were artificially oxidized in air at 950ºC for 120 minutes to form a very thin layer of SiO_2 on their surface in order to improve wettability with molten aluminum and prevent the potential attack of the SiC reinforcements by liquid aluminum to form Al_4C_3 at the Al/SiC interface which could be harmful to the mechanical properties of the composite.

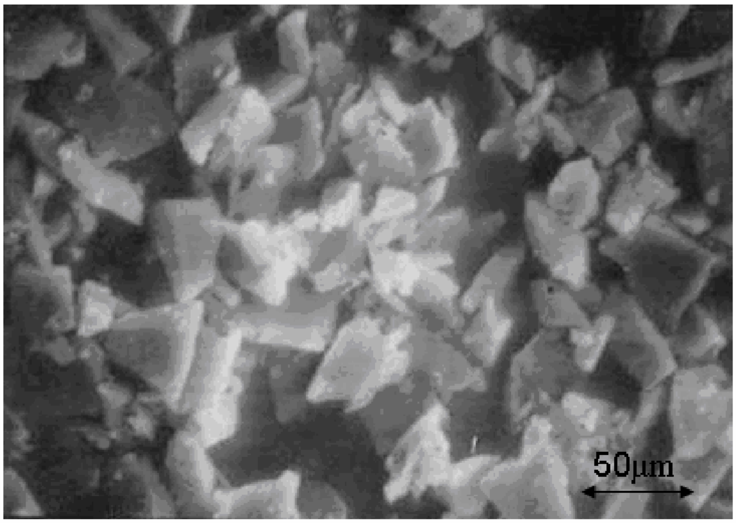

Figure1. SEM micrograph of the SiC particles used in this work.

In order to produce the composite the following steps were taken: The alloy was melted in a graphite crucible with the capacity of 10Kg Al-melt by the use of an electrical resistance-heated laboratory furnace. The temperature was raised to 750ºC and the melt was stirred at 680 rpm using a graphite impeller attached to a variable speed AC motor. After 30 seconds a specific quantity of oxidized silicon carbide particles equal to 10 vol. % was added to the matrix alloy at a low rate for about 5 minutes while stirring was continued. The slurry was allowed to mix isothermally for another 15 minutes, then the impeller was taken out of it and the composite slurry was poured into metallic molds. The produced ingots were cut into approximately 1Kg pieces. Then they were separately remelted and cast in cylindrical metallic permanent molds of low-carbon steel having 44mm diameter, 50 or 100mm height and 7mm wall thickness with an inner 3º tilt.

The 50mm height-billets were then hot extruded by using a hydraulic press and a graphite-based high temperature lubricant at a ram speed of 1mm/s with the extrusion ratios of 6:1 12:1 and 18:1, and the temperature of 450ºC. Schematic diagrams of stirring devices and extrusion equipments used in the present work are shown respectively in Fig. 2 and Fig. 3.
The microstructures of the MMCs in as-cast and extruded states were examined using an optical microscope to determine the distribution of the SiC particles.
The density of the samples was measured using according to ISO 2738 standard. The measured density was compared to the value obtained using rule-of-mixtures so as to determine the volume fraction of porosity. The samples were precision weighed in an electronic balance to an accuracy of 0.1 mg.

Round tensile samples were machined along the extrusion direction According to ASTM E8, and room temperature uniaxial tension tests were carried out in a fully automated MTS tensile testing machine at a constant cross head speed of 1mm/s. The shape and dimensions of a standard round tensile specimen is shown in Fig. 4.

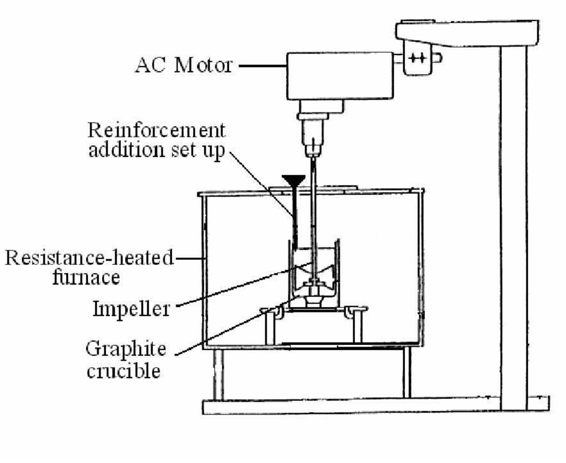

Figure2. Schematic illustration of stirring devices

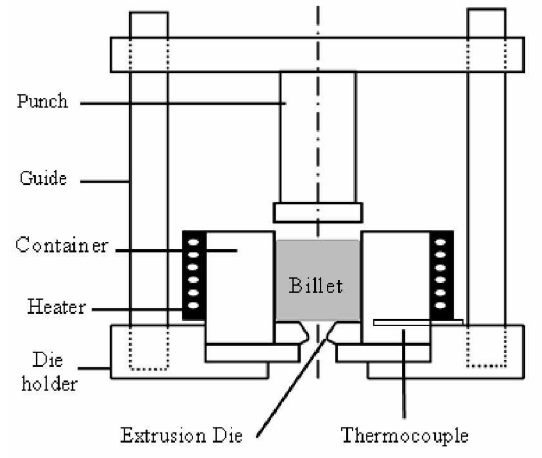

Figure3. Geometry of the extrusion equipments

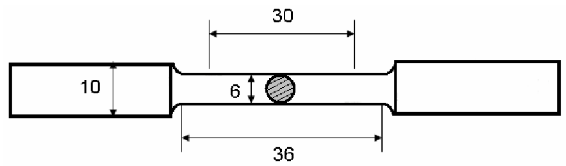

Figure4. Drawing of an ASTM standard round tensile specimen.

Fracture surfaces of the deformed tensile specimens in both as-cast state and after the extrusion were examined in a scanning electron microscope (SEM) to determine the predominant fracture mode. Samples for SEM observation were obtained from the deformed and failed tensile specimens by sectioning parallel to the fracture surface.

3. RESULTS AND DISCUSSION

3.1 Microstructure

The microstructure examination of the as-cast composites generally revealed that SiC particles were not distributed evenly in the matrix, regional clusters of particles exist and some pores are resolvable in the as-cast samples. But after applying the extrusion process the number of resolvable pores is reduced, some particle fragmentation is noticeable and some particle orientation into the direction of extrusion has taken place. Typical microstructures of the composites in the as-cast and extruded state are shown in Fig. 5.

The density measurements were carried out to determine the porosity levels of the samples. The volume fraction of porosity, and its size and distribution in a cast metal matrix composite play an important role in controlling the material's mechanical properties. It is necessary that porosity levels be kept to a minimum. In general, porosity arises from three causes: (a) gas entrapment during mixing, (b) hydrogen evolution, and (c) shrinkage during solidification. The porosity of a composite results primarily from air bubbles entering the slurry during the stirring period or as an air envelope to the reinforcement particles [12]. Hydrogen is also a source of difficulty in light alloy foundry since there is a substantial drop in solubility as the metal solidifies.

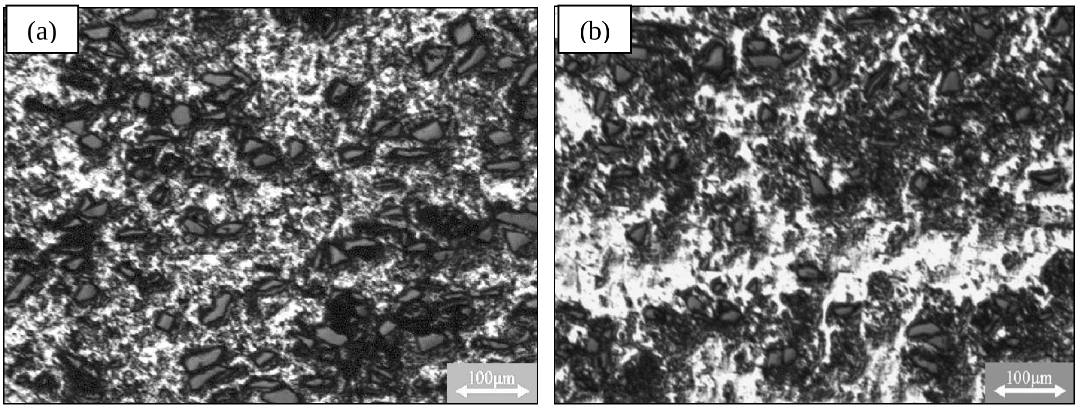

Figure5. Microstructures of Al6061/SiC/10p: (a) as-cast, (b) extruded at the ratio of 12:1.
The porosity values of the composites in the as-cast state and after the extrusion are illustrated in Fig. 6. As seen in Fig. 6, the as-cast samples possess a higher level of porosity than the extruded ones. The application of the hot extrusion process results in more than 50% reduction in porosity volume fraction and the extent of the reduction in porosity increases with the extrusion ratio.

The decreased porosity of MMCs during extrusion is due to the compressive forces generated by the interaction of the composite billet with the extrusion container and die, resulting in the flow of the matrix alloy under the applied shear forces and filling the voids. In fact, the major reason for extruding the particulate metal matrix composites is to close the pores and attain improved mechanical properties. By increasing the extrusion ratio, higher forces are required for material's deformation providing higher hydrostatic stresses and hence decreasing the porosity content.

3.2 Ductility

As has been reviewed by Lloyd [13], the tensile elongation decreases with the addition of reinforcing particles. It has been demonstrated that the failure of composite materials is related to particle cracking and void formation in the matrix within clusters of smaller particles. Particle fracture is expected in larger particles as they will be loaded to higher levels and are more likely to contain defects of critical size for initiating fracture. The failure related to the particle clusters can be explained by higher stress triaxiality generated in these regions.
In as-cast composites a low level of ductility is unavoidable due to the high porosity content and early void formation at low strains during tensile elongation. However, it is possible to obtain an improvement in ductility by altering some microstructural features such as the matrix microstructure and the porosity content. The bond between the reinforcing particles and the matrix is also important in improving the ductility of particulate reinforced composites [14].

The ductility values of the composites in the present work are shown in Fig. 7 as percentage elongation to fracture. Fig. 7 illustrates that the increase in the extrusion ratio increases the percentage elongation to fracture in the composite samples. The ductility level is very low in the as-cast materials but the application of hot extrusion process improves the ductility of the composites considerably, resulting in ductility levels more than four times those of the as-cast samples.

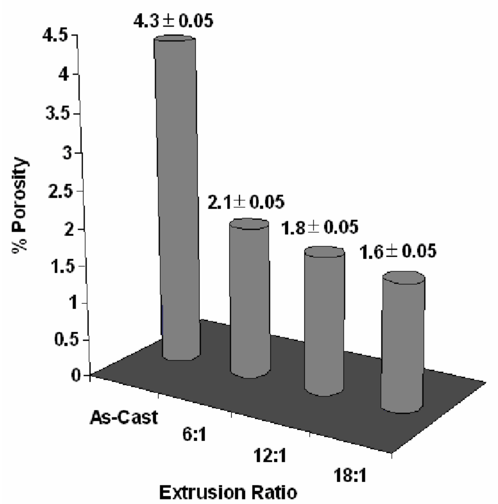

Figure6. The variation in the porosity content of Al-SiC_p composites before and after extrusion with extrusion ratio.

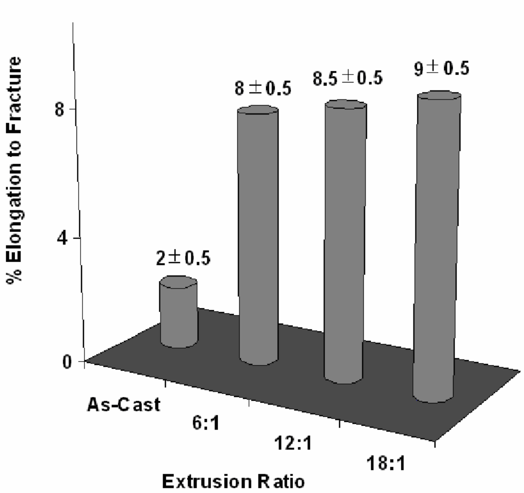

Figure 7. The effect of extrusion on ductility, and the change of elongation to fracture with extrusion ratio.The observed low ductility in the as-cast samples can be explained by the heterogeneity in particle distribution and mainly by high porosity content. Moreover, an increase in ductility is expected with increasing the extrusion ratio since particle clustering and porosity content decrease as well.

3.3 Tensile fracture behavior

The tensile fracture surfaces are helpful in elucidating microstructural effects on the ductility and fracture properties of the Al6061/10 Vol. % SiC_p composite. It is fairly well established that the fracture of unreinforced aluminum alloys is associated with void nucleation and growth, with the nucleation essentially occurring at the coarse constituent particles and other second-phase present in the microstructure [15].
SEM fractographs of the composite in as-cast condition are shown in Fig. 8. On a macroscopic scale the fracture surfaces of the composite were relatively rough and evidence of porosity were observed on the surface (Fig. 8a). When viewed on a microscopic scale, the fracture surfaces revealed agglomerations of reinforcement particles which caused local stress concentrations in the composite and led to crack formation in the matrix (Fig. 8b). Presence of hard and brittle SiC particles in the ductile aluminum matrix exerts constraints on the plastic

flow of the matrix. When combined with concentration and triaxiality of stress in clustered particles regions, the composite undergoes brittle fracture without showing appreciable ductility.

Fig. 8b shows the non-uniform distribution of reinforcing particles on the fracture surface of Al6061/SiC composite. Some of the fractured particles on the fracture surface are marked in the micrographs.

Fractographs of the composites extruded at 450ºC and extrusion ratios of 6:1, 12:1 and 18:1 are shown in Fig. 9. It is obviously seen in Figs. 9a and 9b that clusters of reinforcement particles are eliminated after applying the extrusion process, thus some ductility is expected in the absence of those highly stress raisers. However Fig. 9c shows that applying extrusion at the lowest ratio (6:1) does not efficiently influence the distribution of particles in the matrix.

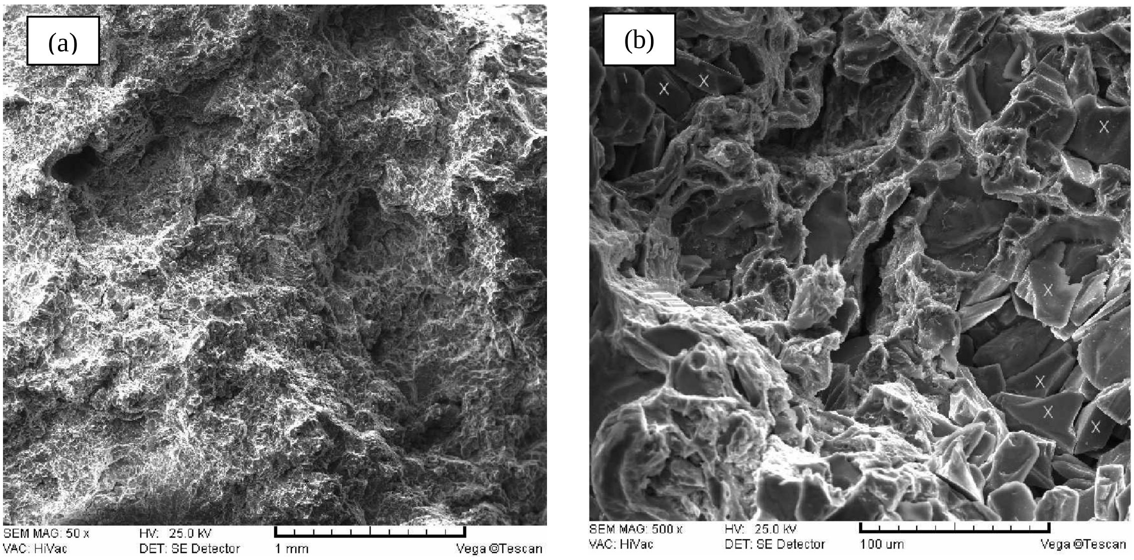

Figure 8. Scanning electron micrographs of the tensile fracture surfaces of the as-cast Al6061/SiC/10p composite at room temperature, showing:(a) overall morphology; (b) non-uniform distribution and fractured SiC_p and crack formation in the matrix.

The fracture surfaces revealed cracked and/or fractured particles in Figs. 9a and 9b surrounded by ductile regions described as tear ridges. These hallow and featureless dimples on the fracture surface are related to ductile failure. Some of the fractured particles are marked in Fig. 9a and vectors in Fig. 9b point at cracked particles. It is also noticed that broken particles are found at the bottom of relatively large dimples, confirming that these voids are nucleated by broken particles. The lack of formation of ductile dimples, as a dominant fracture mode, is attributed to be due to constraints on plastic flow in the composite matrix caused by the presence of the discontinuous SiC_p reinforcement and not to limited ductility of the aluminum alloy.

Generally, particle cracking and fracture is associated with the following factors: 1- Residual stresses caused by the difference between the coefficients of thermal expansion of the reinforcement and the matrix material. 2- Local stress concentrations caused by the constraints in plastic deformation. 3- Applied stress during the tensile test and 4- The brittle

nature of ceramic particles. When particle fracture occurs, microvoids are nucleated and then by growth and coalescence of these voids, crack propagation would occur.
During tensile deformation, as the strain increases, the larger-sized reinforcing particles fracture first, followed by fracture of the smaller-sized reinforcing SiC particles. In regions of particle clustering, or agglomeration, the short interparticle distance facilitates linkage between microscopic cracks and neighboring voids as a direct result of decreased propagation distances between the cracked SiC particles.

According to Srivatsan et al [2] the stress adjacent to any SiC particle is a combination of stress components imposed by the macroscopic applied stress and the stress component that develops on a microscopic scale. The microscopic scale components arise as a result of the conjoint influence of strain incompatibility between the reinforcing particle and the deforming matrix, individual stresses arising from thermal expansion mismatch between the second phase particles and the matrix, and load sharing by the reinforcing particulates. Observation of the fracture surface shows that the fracture plane of cracked SiC particles is almost always perpendicular to the loading axis, suggesting the importance of the tensile stress in inducing particle fracture.

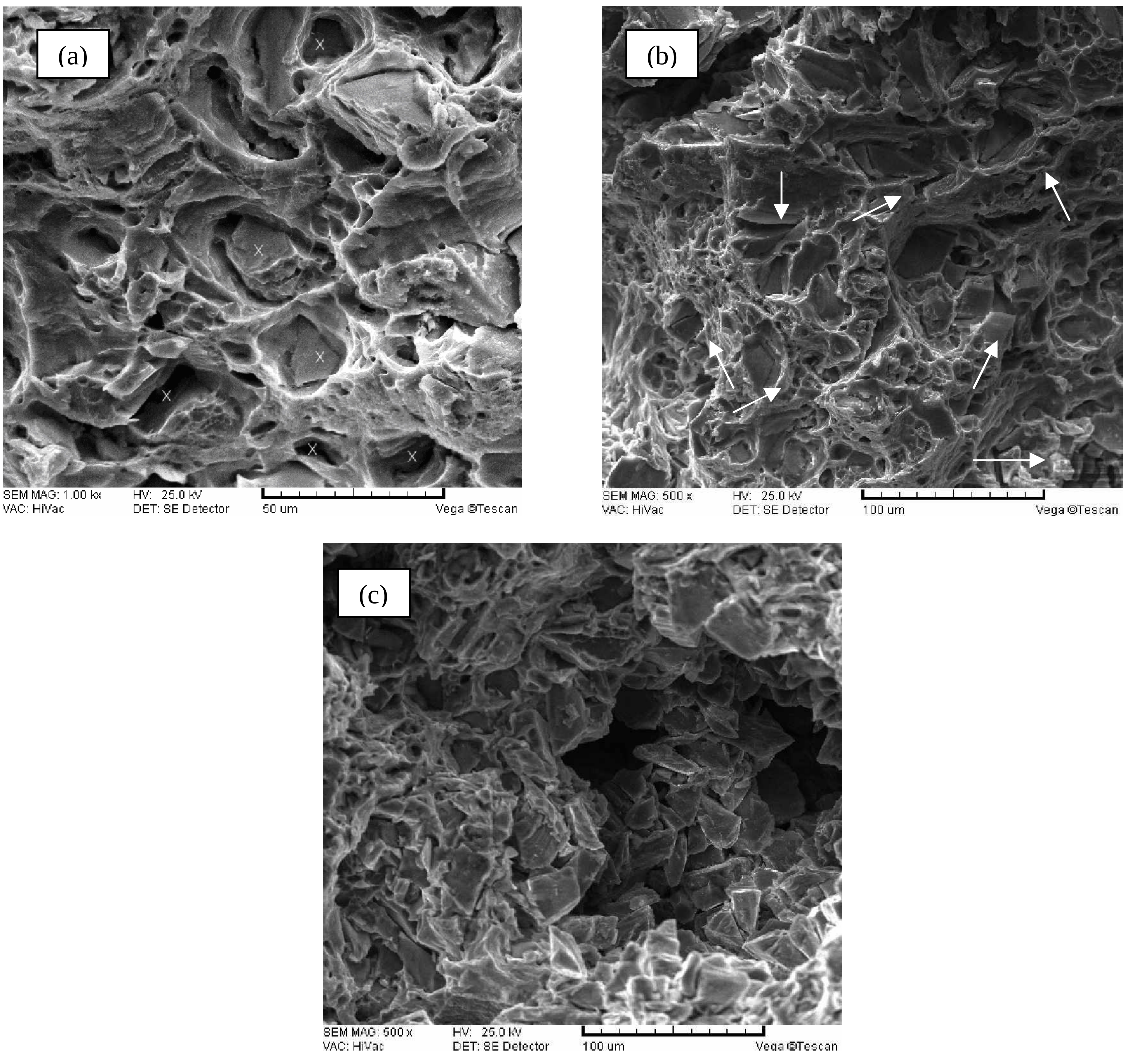

Figure 9. Scanning electron micrographs of the tensile fracture surfaces of the extruded Al6061/SiC/10p composite, at the extrusion ratios of:(a) 18:1; (b) 12:1; (c) 6:1.

The overall ‘damage’ resulting from uniaxial straining of the Al6061/SiC/10p is due to the conjoint action of the two mechanisms: (1) damage associated with the discontinuous SiC_p reinforcement particle, i.e. failure by cracking of the SiC particles, and (2) lattice damage arising from the interactive influences of point defects, dislocations and residual stress associated with the presence of discontinuous SiC particles [16].

4. CONCLUSION

Al6061 based composites reinforced with SiC particles were produced under ordinary foundry conditions, and the cast ingots were hot extruded to improve the mechanical properties. Microstructure, ductility and tensile fracture behavior were studied in the as-cast state and after the extrusion process, and the following points were concluded:

1) In as-cast composites a very low level of ductility is observed due to the heterogeneity in particle distribution and high porosity content resulting in early void formation at low strains during tensile elongation. But after applying the hot extrusion process, ductility was improved considerably leading to ductility levels more than four times those of the as-cast samples.

2) Examination of the tensile fracture surfaces revealed that damage associated with fracture to be highly localized at the discontinuous SiC_p reinforcement with little evidence of void formation away from the fractured SiC particle.

3) In as-cast samples fracture of the SiC particles was observed to be greater in regions of particle clustering due to enhanced local stresses resulting from restriction of plastic deformation. However, clusters of reinforcement particles are eliminated after applying the extrusion process, thus some ductility is observed in the absence of those highly stress raisers.

4) A combination of thermally induced stress, local stress concentration and macroscopic applied stress and the intrinsic brittle nature of the ceramic reinforcement is responsible for particle cracking.

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