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Tensile Properties and Fracture Behavior of 6063/SiC_p Metal Matrix Composites Fabricated by Investment Casting Process

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ABSTRACT

The use of investment casting process has been studied to fabricate 6063/SiCp metal matrix composites. The tensile properties have been evaluated. The results conclude the presence of $(Fe, Mn, Cu)_3SiAl_{12}$ and Mg_2Si compounds in the 6063/SiC-$_p$ composites. The yield strength and fracture strength increase with increase in volume fraction of SiC-p-, whereas ductility decreases. The fracture mode is ductile in the composites having low volume fraction (10%) of SiC and it is brittle in the composites having high volume fraction (30%) if SiC.

Keywords: *investment casting, fused silica, colloidal silica, 6063, SiC, tensile*

1. INTRODUCTION

The term metal matrix composites (MMC) take in a wide range of materials that consist of a metallic alloy reinforced with a ceramic phase in the form of particles, platelets, whiskers, short fibers or continuously aligned fibers. According to the type of reinforcement, MMC's can be broadly classified into continuous MMC, whisker reinforced MMC and particulate reinforced MMC.

Aluminum and its alloy is the most common used material for the matrix due to its low density, ease of processing and potential property improvement as a result of reinforcement. Aluminium alloy based metal matrix composites an attractive and viable nominee for automobile and aerospace applications [1, 2]. Silicon carbide (SiC) is the commonly used reinforcement material because of its high modulus, broad availability and affordable [3]. The major rationale of producing metal matrix composite is to develop lightweight materials with high specific strength and stiffness. These materials possess not only high specific strength and modulus of elasticity at room temperature but also excellent wear resistance, low coefficient of thermal expansion and good dimensional stability. Particulate reinforced metal matrix composites are much easier to fabricate than continuous fiber reinforced metal matrix composites. Consequently, production of the material is possible at lower costs as compared to that of MMC materials with fibers. The high density of dislocations both at and near the reinforcement/matrix interfaces is aroused as a result of the mismatch in the coefficient of thermal expansion between the SiC particle and the aluminium alloy matrix [4].

Among all the liquid-state processes, stir casting technology is considered to be the most potential method for engineering applications in terms of production capacity and cost efficiency [5]. A two-step stirring was developed for homogeneous particle distribution to prepare particulate reinforced metal matrix composites [6].

The motivation for this work was to study the influence of microstructure (as-cast and heat treatment conditions), volume fraction of SiC_p reinforcement on the tensile and fracture behavior of 6063 aluminium alloy metal matrix composite reinforced with silicon carbide particles (SiC_p). In the present work, the investment casting process was employed to fabricate 6063 alloy/SiCp metal matrix composites.

2. EXPERIMENTAL PROCEDURE

The chemical composition of 6063 matrix alloy is given in Table 1. The properties of the matrix alloy are given in Table 2. The volume fractions of SiC_p reinforcement are 10%, 20% and 30%. The particle size of SiC_p reinforcement is 10 μm.

2.1. Preparation of Ceramic Shells, Melt and Metal Matrix Composites

Dip-coating slurries were prepared by adding the refractory filler to the liquid binder using sufficient agitation to breakup agglomerates and thoroughly wet and disperse the filler. Colloidal silica binder and fused silica filler (particles of size 45 μm) were used to prepare dip-coating slurring. The colloidal concentration in the binder was 30%. The filler to binder ratio was 0.75. Ceramic shells were made by applying a series of ceramic coating to the patterns [7]. The wax pattern was first dipped into the dip-coating slurry bath. The pattern was then withdrawn from the slurry and manipulated to drain-off excess

Table 1
Chemical Composition of Matrix Alloy 6063

	Composition determined spectrographically, %								
Alloy	*Al*	*Si*	*Fe*	*Cu*	*Ti*	*Mg*	*Mn*	*Zn*	*Cr*
6063	98.2	0.271	0.325	0.0047	0.0376	0.58	0.0076	0.076	0.0005

Table 2
Mechanical Properties of Matrix Alloy 6063

Matrix Material	*Density, g/cc*	*Modulus of Elasticity, GPa*	*Ultimate Tensile, MPa strength*	*Elongation, %*
6063	2.70	68.9	172	22
6063(T6)	2.70	68.1	245	12

slurry and to produce uniform layer. The wet layer was immediately stuccoed with coarse silica sand. Each coating was allowed to dry for four hours in the open air. The operations of coating, stuccoing, and drying were repeated six times (Figure 1). The seventh coat was left unstuccoed to avoid the occurrence of loose particles on the shell surface. The first two coats were stuccoed with a sand of AFS fineness number 120 and the next four coats were stuccoed with coarse sand of AFS fineness number 50. After all coats the shells were air dried for 24 hours (Figure 1).

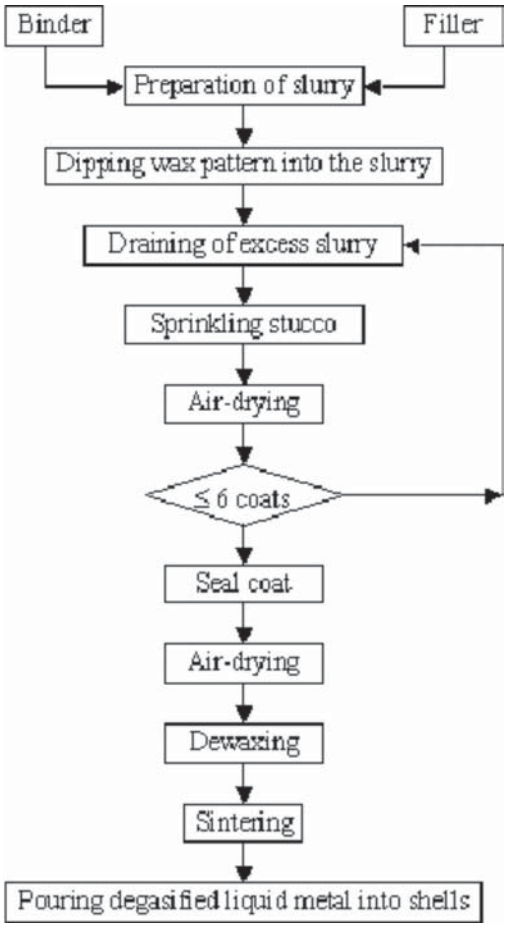

Figure 1: Flowchart of Investment Casting Process

Al alloys were melted in a resistance furnace. The crucibles were made of graphite. The melting losses of alloy constituents were taken into account while preparing the charge. The charge was fluxed with coverall to prevent dressing. The molten alloy was degasified by tetrachlorethane (in solid form). The crucible was taken out of the furnace and modified with sodium. Then the liquid melt was allowed to cool down just below the liquidus temperature to bring the melt semi solid state. At this stage, the preheated (1000^0C for 1 hour) SiC particles were added to the liquid melt. The molten 6063 alloy and SiC particles are thoroughly stirred manually. After sufficient manual stirring, the semi-solid liquid melt was reheated to a fully liquid state in the resistance furnace followed by automatic mechanical stirring using a mixer to make the melt homogenous for about 15 minutes at 200 rpm. The temperature of the melt was measured using a dip type thermocouple. The preheated ceramic shell was poured with dross removed melt by gravity. The ceramic shell and the casting are seen in Figure 2.

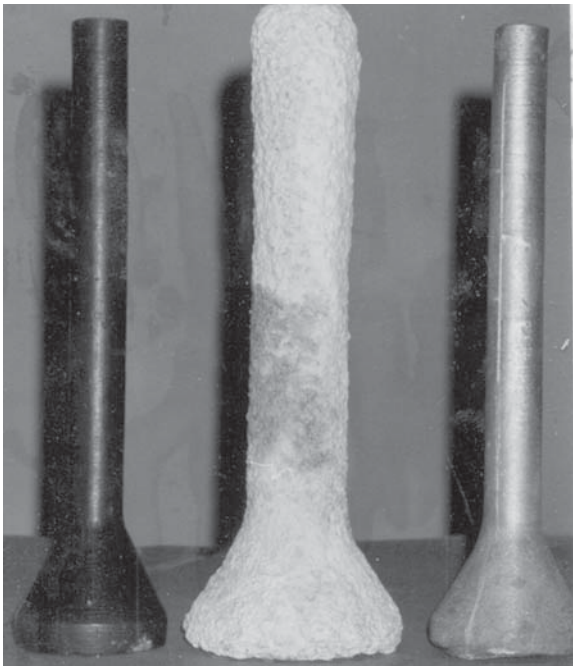

Figure 2: Wax Pattern, Ceramic Shell, and Ceramic Casting

2.2. Heat treatment

Prior to the machining of composite samples, a solution treatment was applied at 550^0C for 15 min quenched in cold water, and aged at 150^0C for 100 hours.

2.3. Tensile tests

The as-cast and heat treated samples were machined to get specimens for tensile test. The shape and

dimensions of the tensile specimen are shown in Figure 3. The computer-interfaced UTM (Universal Testing Machine) was used for the tensile test. The specimens were loaded hydraulically. The loads at which the specimen has reached the yield point and broken were noted down. The extensometer was used to measure the elongation.

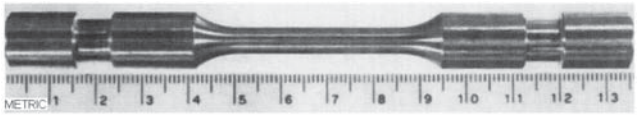

Figure 3: Standard 6 m Diameter Cylindrical Tensile Specimen

2.3. Optical and Scanning Electron Microscopic Analysis

Microscopic analysis of the cast composite samples was performed by optical microscopy. An image analyzer was used to examine the distribution of the reinforcement particles within the 6063-alloy matrix. The mechanical properties of any particle reinforced metal matrix composites depend on the particle distribution, particle size, particle flaws, surface irregularities, and particle-matrix bonding. It is therefore, necessary to conduct a microscopic analysis on the new material in order to gain better understanding of its micro structural characteristics. The polished specimens were ringed with distilled water and etched with 0.5% HF solution.

Fracture surfaces of the deformed/fractured (under tensile loading) test samples were examined in a scanning electron microscope (SEM) to determine the macroscopic fracture mode and to characterize the fine-scale topography and establish the microscopic mechanisms governing fracture. Samples for SEM observation were obtained from the tested specimens by sectioning parallel to the fracture surface and the scanning was carried in IICT (Indian Institute of Chemical Technology - Hyderabad) S-3000N Toshiba. The EDS analysis of heat-treated samples was also carried out to understand the metal matrix/reinforcement interfacial reactions.

3. RESULTS AND DISCUSSION

Three tensile specimens were tested for each trial. The average values of yield strength, fracture strength (ultimate tensile strength), and ductility in terms of tensile elongation are presented in the graphical forms.

3.1. Undeformed Microstructure

The optical micrographs illustrating the microstructures of the as-cast and heat-treated 6063/SiC_p metal matrix composites are shown in Figure 4. In the present work, the SiC_p particles in 6063 matrix alloy were randomly dispersed. At regular intervals, a clustering or agglomeration of SiC_p, of varying sizes, was observed resulting in SiC_p-rich and SiC_p-depleted regions. Magnesium and silicon combine to form a compound magnesium silicide (Mg_2Si), which in turn forms a simple eutectic system with aluminium. The microstructures of as-cast 6063/SiC_p and heat-treated 6063/SiC_p reveal particles of $(Fe, Mn, Cu)_3SiAl_{12}$ and Mg_2Si in the aluminium-rich solid solution matrix. The as-cast microstructure (Figure 4a) reveals coarse grain structure whereas the heat-treated microstructure (Figure 4b) represents the fine grain structure.

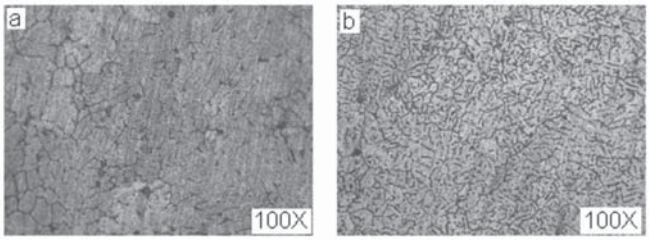

Figure 4: Microstructure of as-cast 6063/SiC_p Metal Matrix Composite (Particle Size = 10µm and Volume Fraction = 20%) (a) as-cast; (b) Heat-treated

Highly alloyed 6063 had complex intermetallics originating from cast ingots. Since iron was the omnipresent impurity element and had a very low solubility in aluminum, iron-rich phases could be seen in all aluminum alloys. The presence of manganese, chromium or copper leads to the formation of $(Fe, Mn, Cu)_3SiAl_{12}$ is confirmed by the EDS analysis. The other phase, Mg_2Si, was the main ingredient of 6063, which would readily dissolve during solutionizing and contribute to the precipitation hardening for the period of artificial aging.

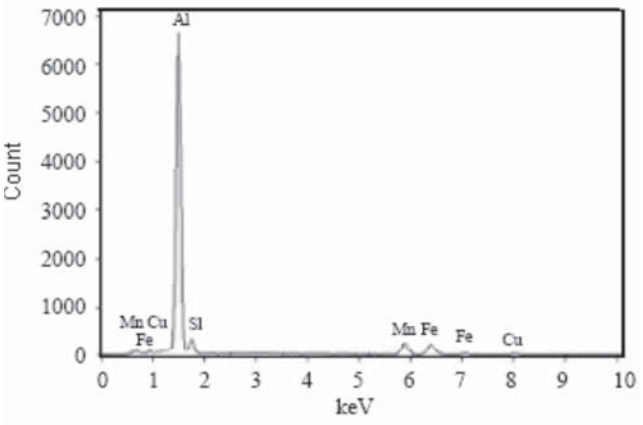

Figure 5: EDS Analysis of Heat Treated 6063/SiC Metal Matrix Composite (Volume Fraction = 20%)

3.2. Tensile Properties

The variation of yield strength with volume fraction is shown in Figure 6. The yield strength, defined as the stress corresponding to a plastic strain of 0.2%, increases with an increase in volume fraction of SiC_p. The strengthening in the 6063/SiC_p composite takes places by the reinforcement particles carrying much of the applied load transferred through the matrix/ reinforcement interface. There is an increase of 86% yield strength in the reinforced composite over the as-cast 6063 alloy and an increase of 47% yield strength in the heat treated composite over the heat treated 6063 alloy when the metal matrix alloy 6063 is reinforced with 30% volume fraction of SiC_p. The yield strength increases after heat treatment. This is on account of thermal mismatch between the high thermal expansion 6063 metal matrix and the low thermal expansion SiC_p reinforcement. Upon cooling, dislocations form at the matrix/reinforcement interface owing to the thermal mismatch. It was detected that the thermally induced dislocations were resulted in indirect strengthening of the composite [4]. The precipitation hardening also influences the direct strengthening of the composite [8]. The area between the upper line and the lower line in figure 6 represents the strengthening effect due to dislocations and precipitation hardening. An increase in volume fraction of SiC_p increases the amount of strengthening due to dislocations.

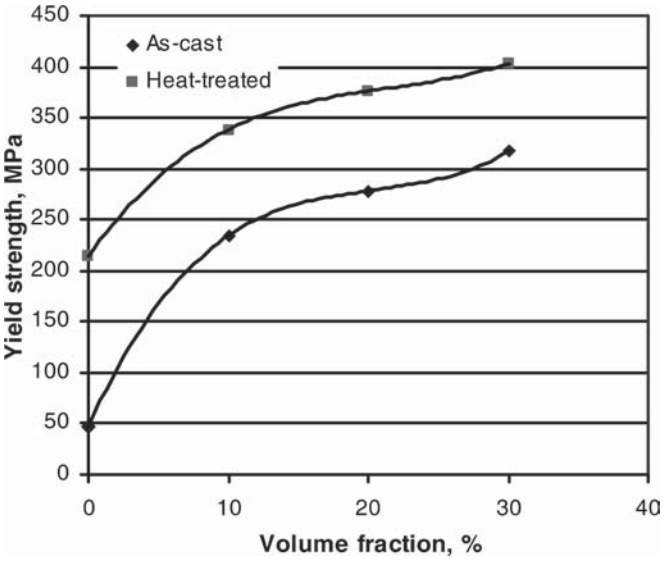

Figure 6: Variation of the Yield Strength with the Volume Fraction of SiC Particles

Figure 7 shows the effect of volume fraction on the fracture strength (ultimate tensile strength). The fracture strength is only marginally higher than the yield strength. The variation in the fracture strength 6063/SiC_p composites is largely affected by the work

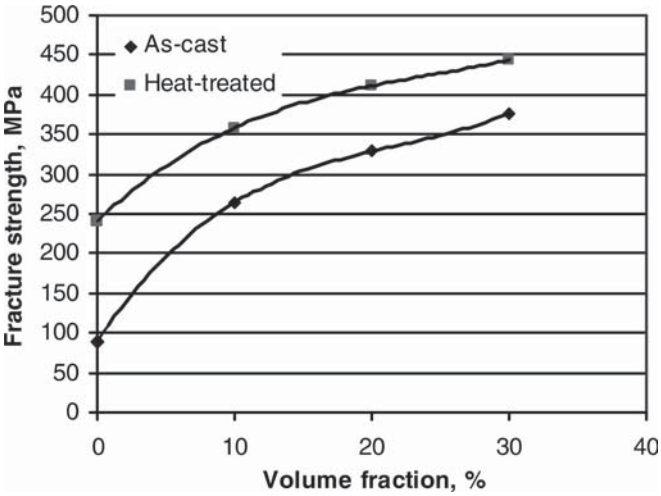

Figure 7: Variation of the Fracture Strength with the Volume Fraction of SiC Particles

hardening rate. It was reported that the work hardening rate was a simple function of lower matrix volume (the matrix volume decreases with increase in volume fraction of reinforcement) and did not necessarily due to a change in work hardening mechanisms [9].

The influence of volume fraction of SiC_p on the ductility (measured in terms of tensile elongation) is shown in Figure 8. The decrease in the ductility can be attributed to the beginning of void nucleation in advance with increasing amount of SiC_p reinforcement. It was verified that the microplasticity took place in the metal matrix composites due to stress concentrations in the matrix at the poles of the reinforcement and/or at sharp corners of the reinforcing particles [9].

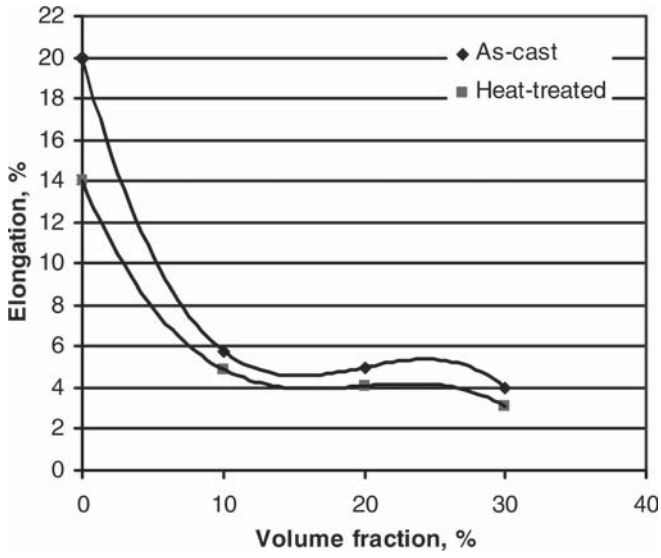

Figure 8: Variation of the Ductility with the Volume Fraction of SiC Particles

4. FRACTURE BEHAVIOR

The tensile fracture behavior of heat treated 6063/SiC_p metal matrix composites, which were cast by investment casting process were studied in the present work. The $(Fe, Mn, Cu)_3SiAl_{12}$ and Mg_2Si compounds act as void nucleation sites during deformation by the interfacial decohesion or particle fracture. Material rupture then takes place through a mechanism, which involves the growth of the voids by plastic straining and subsequent coalescence by localized necking of the intervoid matrix. The necking of the specimen (with volume fraction of 10% SiC) at the fracture plane is clearly shown in Figure 9. The fracture is due to the particle/matrix interface cracking (Figure 10). The fracture due to tensile loading is ductile in the 6063/SiC composite having volume fraction of 10%. Void nucleation occurs at particle/matrix interfaces and can be realized by the interface decohesion. The voids then grow under both the applied load and the influence of local plastic constraint until a coalescence mechanism is activated, and this followed by the total failure of the specimen. The void coalescence occurs when the void elongates to the initial intervoid spacing. This leads to the dimpled appearance of the fractured surfaces (Figure 10). Medium size dimples with tear ridges are observed.

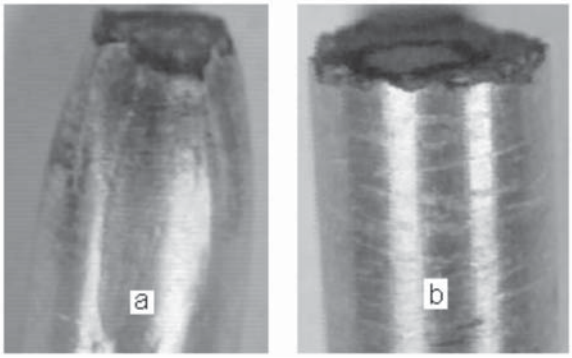

Figure 9: Fracture Surface of 6063/SiC_p (a) Volume Fraction = 10% and (b) Volume Fraction = 30%

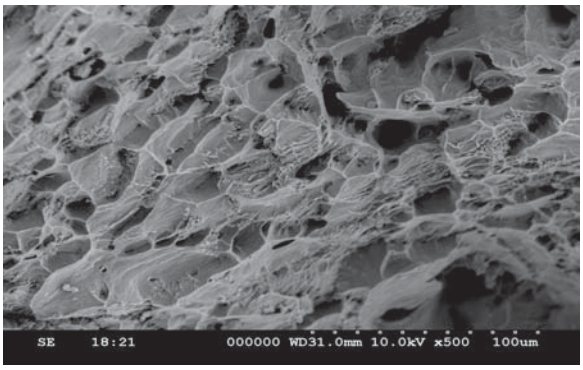

Figure 10: SEM of Fracture Surface of Heat-treated Tested Specimen (Volume Fraction = 10%)

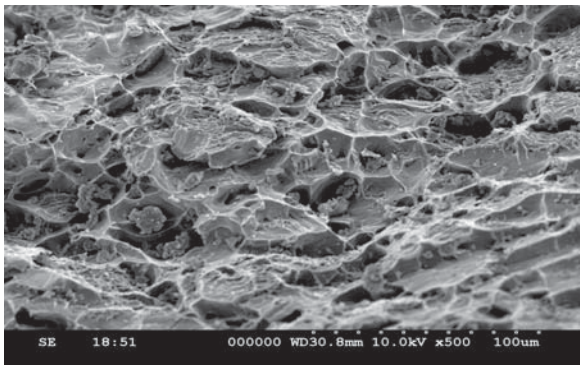

Figure 11: SEM of Fracture Surface of Heat Treated Tested Specimen (Volume Fraction = 30%)

The fracture surface ductile in the 6063/SiC composite having volume fraction of 30%appears to be flat and normal to the axis of loading (Figure 9b). The fracture process in high volume fraction (more than 20%) 6063/SiC_p composites is very much localized and the failure path in these composites is through the matrix due to the matrix rupturing and the connection of these microcracks to the main crack. The presence of SiC reinforcement particles reduces the average distance in the composite by providing strong barriers to dislocation motion. The fracture surface (Figure 11) appears to contain many microvoids in the matrix, with dimples much different, both in size and shape, from those observed in figure 10. Brittle fracture of 6063/SiC composite (having volume fraction 30%) indicates that void growth and coalescence occurred rapidly. The interaction of dislocations with other dislocations, precipitates, and SiC particles causes the dislocation motion. An earlier works accomplished that at high stress levels, the generation of defects such as dislocations, vacancies, voids and microcracks was very high [10, 11]. The fracture in the 6063/SIC composite having volume fraction of 20% is intermediate between the ductile and brittle fracture.

5. CONCLUSIONS

The micrographs of as-cast and heat treated 6063/SiCp composites indicate random distribution of SiC_p particles in the metal matrix composites. The EDS report confirms the presence of $(Fe, Mn, Cu)_3 SiAl_{12}$ and Mg_2Si compounds in the 6063/SiC-$_p$ composites. The yield strength and fracture strength increase with increase in volume fraction of SiC-p-, whereas ductility of 6063/SiC_p composites decreases. The fracture mode is ductile in the composites having low volume fraction (10%) of SiC and it is brittle in the composites having high volume fraction (30%) if SiC.

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