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MECHANICAL PROPERTIES AND FRACTURE BEHAVIOR OF 6061/SiC$_P$ METAL MATRIX COMPOSITES CAST BY LOW PRESSURE DIE CASTING PROCESS

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ABSTRACT

The use of low pressure die casting process has been studied to fabricate 6061/SiCp metal matrix composites. The tensile and fatigue properties have been evaluated. The results conclude that the Si crystals are not observed to be attached to the surface of SiC particles. The formation of $A1_4C_3$ is not found. The yield strength and fracture strength increase with increase in volume fraction of SiCp, whereas ductility decreases. With increasing volume fraction of SiC particles, the fatigue strength of the composite increases.The fracture mode is ductile in nature.

Key words: low pressure die casting process, 6061, SiC, tensile, fatigue

1. INTRODUCTION

Metal matrix composites usually consist of a continuous phase called the matrix and discontinuous phase in the form of fibers, whiskers or particles called the reinforcement. The addition of ceramic particles into light alloys guarantee exceptionally high specific elastic modulus, strength-to-weight ratio, fatigue strength, wear resistance, are few of the important characteristics that have made the reinforced aluminium alloy based metal matrix composites an attractive and viable nominee for automobile and aerospace applications (Hunt et al., 1991; Chawla, 1997).

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The material selection criteria involves the requirement of high strength, and good corrosion resistance aluminum alloys for the matrix materials, and the inexpensive reinforcement particles which can result in increased yield strength and elastic modulus at little expense of ductility (Srivatsan and Hajri, 2002; Wu et al.,1996; Arsenault et al., 1991). Nardone and Prewo (1986) projected that silicon carbide particles (SiC_p) were the most preferred reinforcement materials; because enhanced properties were achievable with little or no density penalty through the matrix/reinforcement interface to the reinforcement. Dutta and Prewo (1990) established that the high density of dislocations both at and near the reinforcement/matrix interfaces was aroused as a result of the mismatch in the coefficient of thermal expansion between the SiC particle and the aluminium alloy matrix. Several related studies have focused on understanding the influence of reinforcement particle on the matrix microstructure, and influence of composite microstructure on the stress-controlled and strain-controlled fatigue behavior of the metal matrix composites [Llyod, 1991; Whitehouse and Clyne, 1993; Wu and Arsenault., 1991; Sugimura and Suresh, 1992; Zhang et al., 1991). Srivatsan et al (1991) addressed that 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. Zhou and Xu (1997) used a two-step stirring for homogeneous particle distribution to prepare particulate metal matrix composites. Low pressure die casting is suitable to the production of components that are symmetric about an axis of rotation. Light automotive wheels are normally manufactured by this technique (Bonollo et al., 2005).

With this underlying background 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 fatigue properties, and fracture behavior of 6061 aluminium alloy metal matrix composite reinforced with silicon carbide (SiC_p). In the present work, the low pressure die casting process was tried with double the pressure that conventionally employed for unreinforced Al-alloys. The pressure was raised to lift the silicon carbide particles along with the matrix alloy and to provide uniform distribution of SiC particles in the composite, because the density of SiC particles is higher than that of 6061 matrix alloy. In the present work, the interfacial reactions were also observed for the possibility of Al_4C_3 formation in the 6061/SiC_p metal matrix composite.

2. EXPERIMENTAL PROCEDURE

The matrix alloys and composites were prepared by the stir casting and low pressure die casting process. The chemical composition of 6061 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.

Preparation of Melt and Metal Matrix Composites

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 from the furnace and treated with sodium modifier. 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) reinforcement particles were added to the liquid melt. The molten alloy and reinforcement 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 cast iron die was filled with dross-removed melt by the compressed (2.0 bar) argon gas. The schematic representation of low-pressure die-casting is shown in figure 1.

Table- 1: Chemical composition of alloys

Alloy	Composition determined spectrographically, %								
	Al	Si	Fe	Cu	Ti	Mg	Mn	Zn	Cr
6061	97.6	0.62	0.61	0.021	0.053	0.98	0.044	0.072	0.0051

Table- 2: Mechanical properties of matrix materials

Matrix Material	Density, g/cc	Modulus of Elasticity, GPa	Ultimate Tensile strength, MPa	Elongation, %
6061	2.7	68.9	124	30
6061(T4)	2.7	68.3	296.6	17

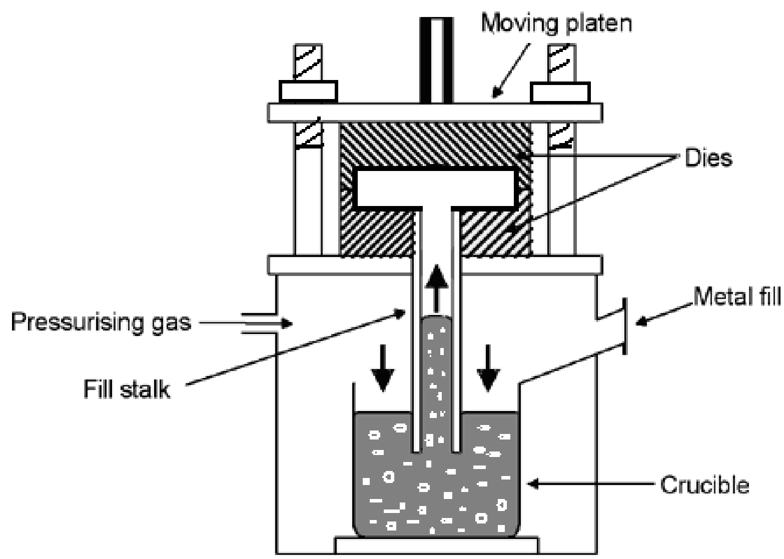

Figure 1: Schematic representation of low pressure die casting process

Heat Treatment

Prior to the machining of composite samples, a solution treatment was applied at 500^0 C for 1 hour, followed by quenching into cold water. The materials were then naturally aged at room temperature for 100 hours.

Tensile and Fatigue Tests

The as-cast and heat treated samples were machined to get dog-bone specimen for tensile test. The shape and dimensions of the tensile specimen are shown in Figure 2. 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. The fatigue tests were conducted to count the number of cycles that caused the complete failure of the samples.

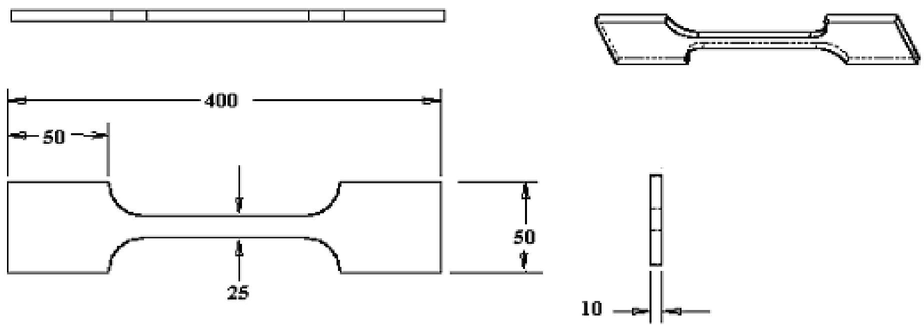

Figure 2: Tensile specimen, all dimensions are in mm

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 aluminum 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 and fatigue loadings) 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 using S-3000N Toshiba SEM. The EDS analysis of heat treated samples was also carried out to understand the metal matrix/reinforcement interfacial reactions.

3. RESULTS AND DISCUSSION

The tested tensile specimens are shown in figure 3. Three samples were tested for each trial. The average values of yield strength, ultimate tensile strength, fatigue life and ductility in terms of tensile elongation are presented in the graphical forms.

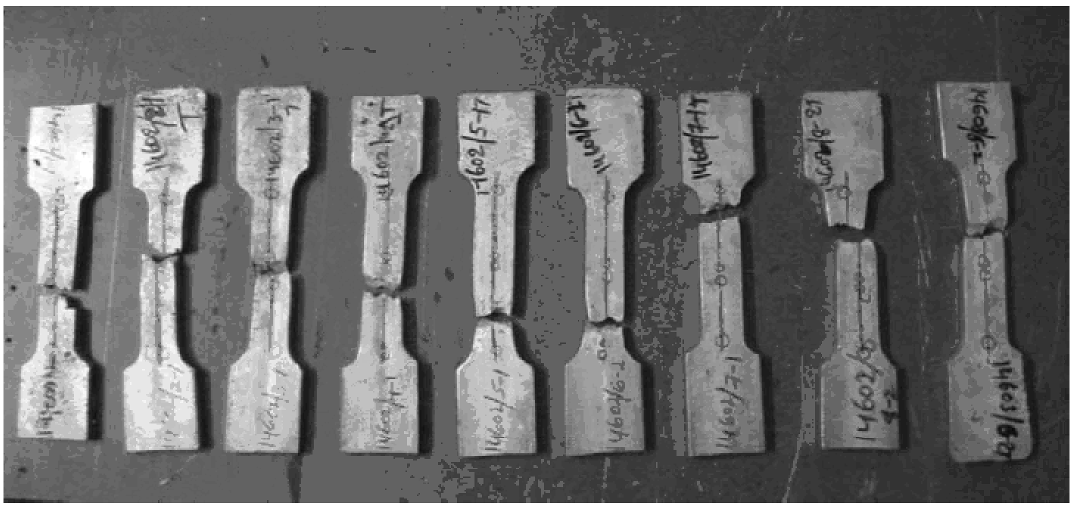

Figure 3: Tested tensile Al/SiC Composite specimens

Undeformed Microstructure

The optical micrographs illustrating the microstructure of the as-cast 6061/SiC_p metal matrix composites are shown in figure 4. In the present work, the SiC_p particles in 6061 matrix alloy were randomly dispersed (figure 4a). 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. An agglomerated site consisted of the smaller SiC_p intermingled with few larger SiC_p. The formation of larger clusters of SiC_p is minimal in the low pressure die casting process as compared to the gravity die casting process (Zhou and Xu., 1997). This is due to the fact that the large clusters of SiC_p have larger weight than the smaller clusters or SiC_p alone. The large clusters of SiC_p are not lifted and forced into the die cavity in the low pressure die casting process. The large clusters of SiC_p are left in the crucible. In the gravity die casting process, the large clusters of SiCp are also poured into the die cavity. Magnesium and silicon combine to form a compound magnesium silicide (Mg_2Si), which in turn forms a simple eutectic system with aluminium. The microstrucutres of as-cast 6061/SiC_p and heat treated 6061/SiC_p reveal particles of Fe_3SiAl_{12} (gray, scriptlike) and Mg_2Si (black) in the aluminium-rich solid solution matrix.

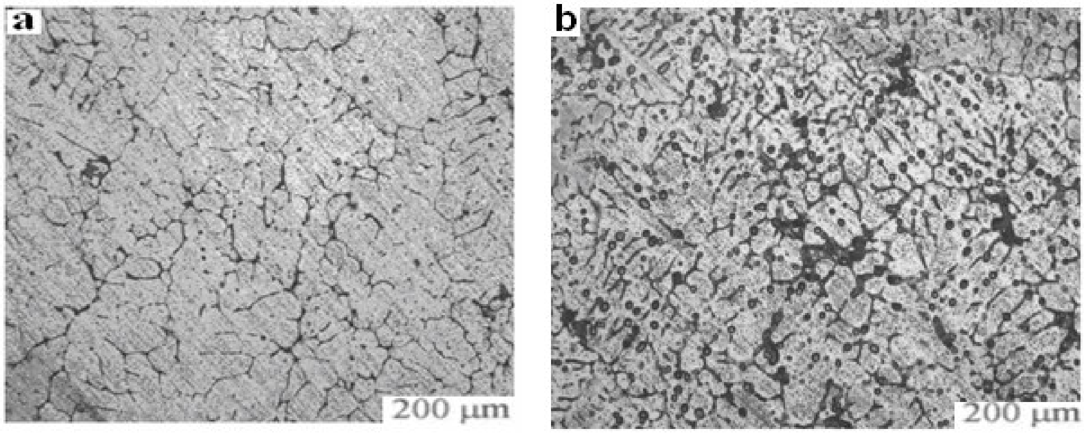

Figure 4: Microstructure of (a) as-cast 6061/SiC_p metal matrix composite and (b) heat treated 6061/SiC_p metal matrix composite (volume fraction = 20%).

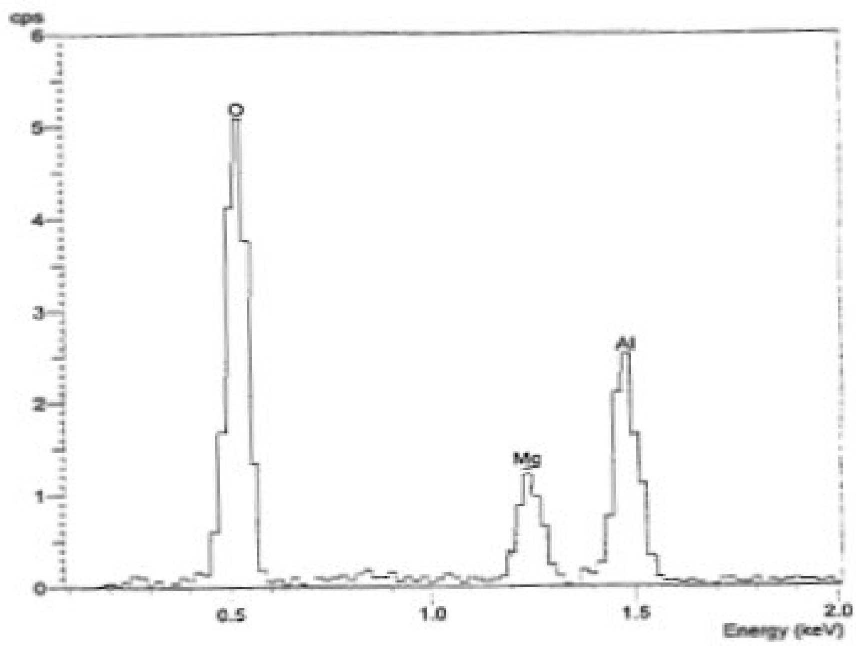

Figure 5: EDS analysis of heat treated 6061/SiC metal matrix composite (SiC particle size = 10µm and volume fraction = 30%)

Chennakesava and Sundararajan (2005) investigated that the interfaces would play an essential role in determining the mechanical properties. Accordingly the focus was also through the study of interface reactions between the SiC particles and alloy matrix in the present study. The optical micrographs illustrating the microstructure of the heat-treated 6061/SiC_p metal matrix composite is shown in figure 4b. The precipitated interfaces are revealed in the heat-treated 6061/SiCp metal matrix composite as shown in figure 4b. The reaction products were also observed at metal matrix/reinforcement interfaces. From the EDS analysis (figure 5), it is found that 6061/SiC_p metal matrix composites are rich in both O and Mg. This may suggest the existence of spinels (either $MgAl_2O_4$ or MgO). The existence of $MgAl_2O_4$ at interfaces was confirmed in a detailed study on the interfaces in discontinuously reinforced metal-matrix composites (Mitra and Mahajan, 1993). The spinel compound may result from the following possible reaction:

$$2SiO_2 + 2Al + Mg \rightarrow MgAl_2O_4 + 2Si$$

Zlaticanin et al (2004) established that the formation of MgO and $MgAl_2O_4$ at the interface enhances the wettability between Al and SiC particles, by reducing the SiO_2 layer on the surface of the SiC_p. Lloyd (1997) confirmed that the formation of $A1_4C_3$ was detrimental to the properties of composite. He also stated that A1-Si alloys (with Si levels of up to 9%) were typically used with SiC_p reinforcement. In the present work, Si crystals are not observed to be attached to the surface of SiC particles. Si content in 6061 matrix alloy is 0.62%. The formation of $A1_4C_3$ is not found.

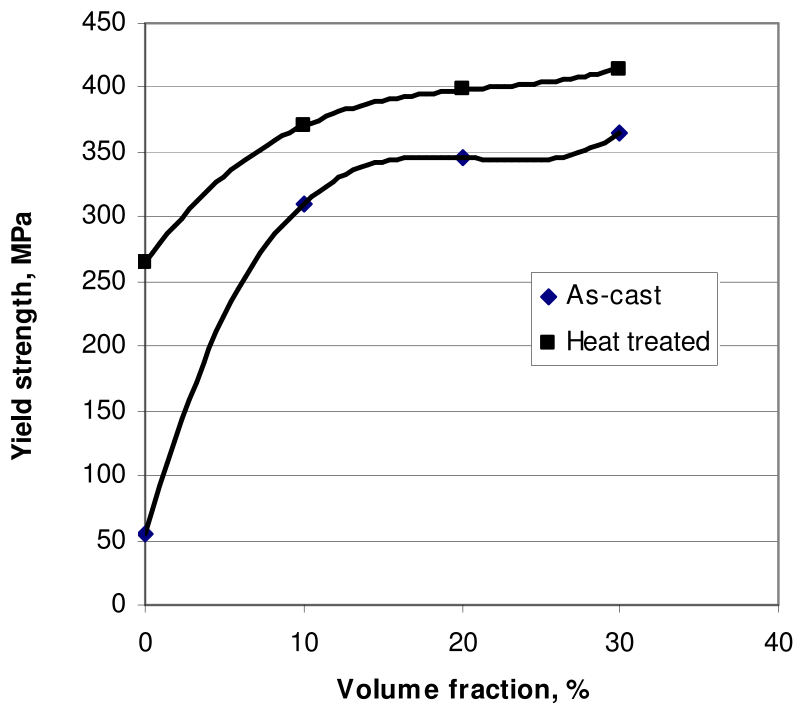

Figure 6: Variation of the yield strength with the volume fraction of SiC particles

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 6061/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 85% yield strength in the reinforced composite over the as-cast 6061 alloy and an increase of 36% yield strength in the heat treated composite over the heat treated 6061 alloy when the metal matrix alloy 6061 is reinforced with 30% volume fraction of SiC_p (figure 7). The yield strength increases after heat treatment. This is on account of thermal mismatch between the high thermal expansion 6061 metal matrix and the low thermal expansion SiC_p reinforcement. Upon cooling, dislocations form at the matrix/reinforcement interface owing to the thermal mismatch. Dutta and Bourell (1990) and Flom and Arsenault (1980) found that the thermally induced dislocations were resulted in indirect strengthening of the composite. The area between the upper line and the lower line in figure 6 represents the strengthening effect due to dislocations. An increase in volume fraction of SiC_p increases the amount of strengthening due to dislocations.

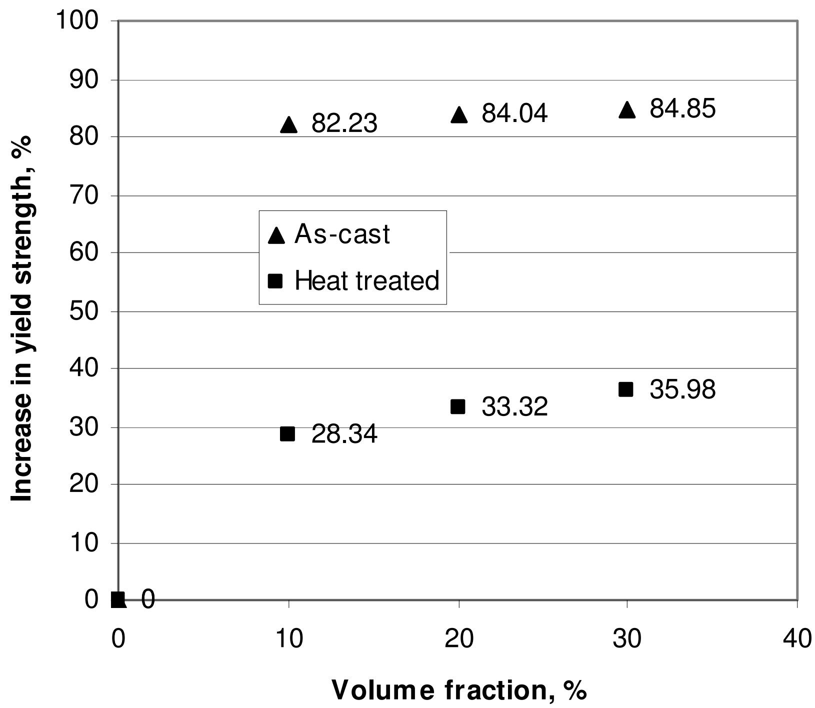

Figure 7: Increase in yield strength due to reinforcement and heat treatment

Figure 8 shows the effect of volume fraction on the fracture strength (ultimate tensile strength). The variation in the fracture strength 6061/SiC_p composites is largely affected by the work hardening rate. The fracture strength follows the same trend as the yield strength of 6061/SiC_p composite. The fracture strength is only marginally higher than the yield strength. This indicates that the work hardening rate past yielding is low. Chawla and Shen (2001) 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.

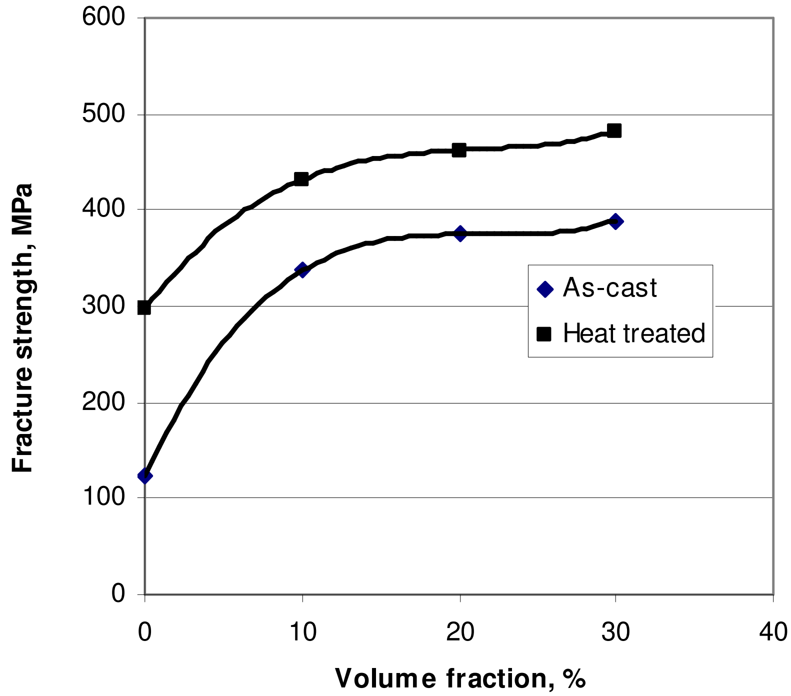

Figure 8: Variation of the fracture strength with the volume fraction of SiC particles

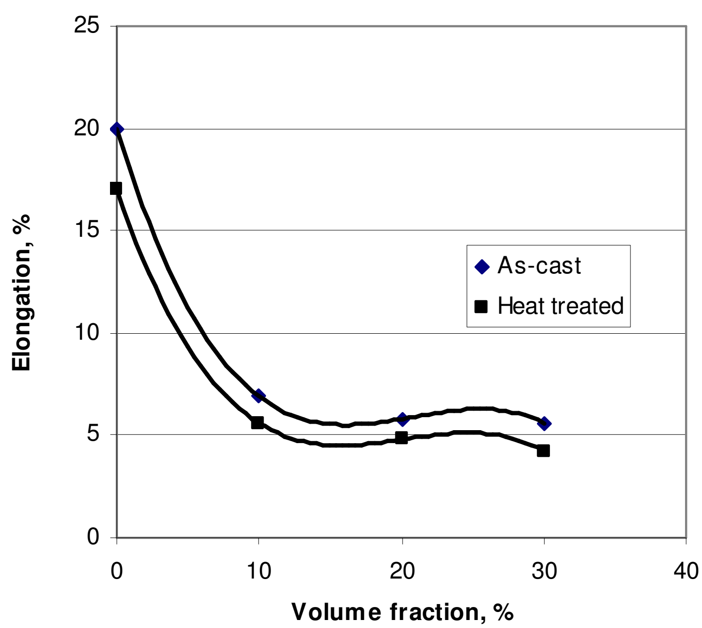

Figure 9: Variation of the ductility with the volume fraction of SiC particles

Fatigue Properties

In the fatigue testing, the test stress was decreased for each succeeding specimen until one or two specimens did not fail in the specified number of cycles, which was at least 10^7 cycles. The heat treated composite and unreinforced matrix alloy samples were tested for high cyclic fatigue behavior. The S-N curve behavior of 6061/SiC_p composite is shown in figure 10. With increasing volume fraction of SiC particles, the fatigue strength of the composite increases. The figure also shows an improved fatigue behavior compared to the unreinforced matrix alloy. Such an improvement in stress controlled high cyclic fatigue is attributed to the higher stiffness of the composite (Manoharan and lewandowski., 1990; Chawla etal., 2000). The effect of solid-solution alloying elements on the fatigue properties is same as their effects on the tensile properties.

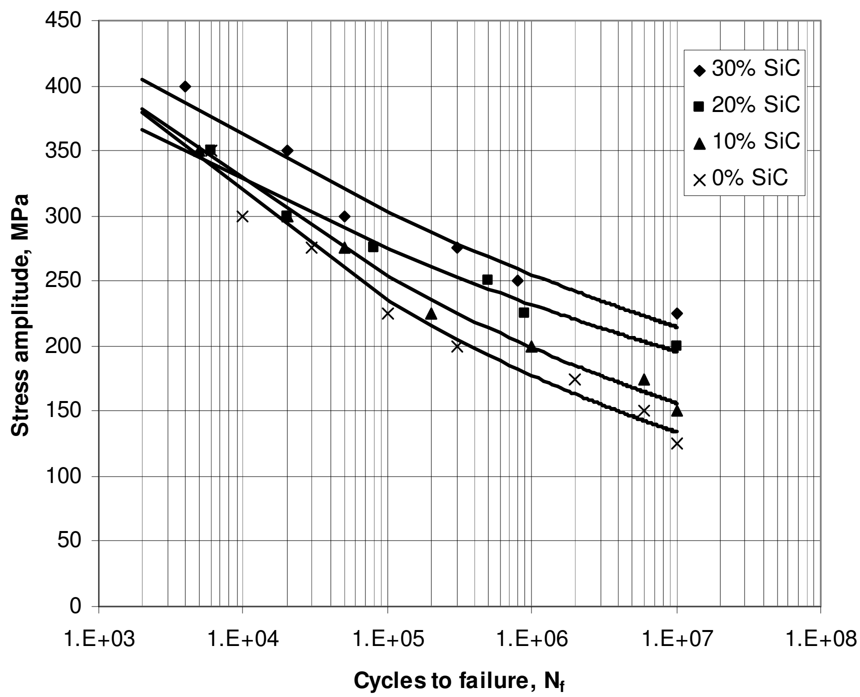

Figure 10: S-N curves of heat treated 6061/SiC composites and 6061 matrix alloy

4. FRACTURE BEHAVIOR

Both the tensile and fatigue fracture behaviors of heat treated 6061/SiC_p metal matrix composites, which were cast by low pressure die casting process were studied in the present work. The fracture of SiC particles is not seen in Al 6061/SiC_p metal matrix composite. The fracture is only due to the matrix failure and the particle/matrix interface cracking (figure 11). The fracture due to tensile loading is ductile in nature. The fracture process in high volume fraction (more than 20%) aluminium/SiC_p composites is very much localized and the failure path in these composites is through the matrix due to the matrix cracking and the connection of these microcracks to the main crack. Arsenault (1988) reported that the cracking of SiC particles was a rare event when the size of the particle was less than 10μm.

Fatigue crack initiation by voids at aluminium/SiC matrix interfaces and growth of such cracks through the matrix was observed. The presence of SiC reinforcement particles reduces the average distance in the composite by providing strong barriers to dislocation motion (figure 12). The interaction of dislocations with other dislocations, precipitates, and SiC particles causes the dislocation motion. The damage caused by fatigue cycling increases with the fatigue cycles. An earlier works (Sugimura and Suresh., 1992; Zhang et al., 1991) accomplished that at high stress levels, the generation of defects such as dislocations, vacancies, voids and microcracks was very high.

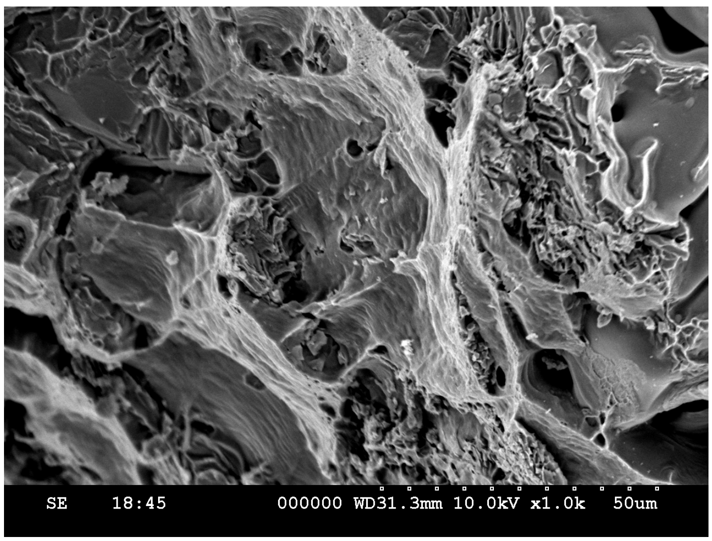

Figure 11: SEM of fracture surface of heat treated tensile sample (SiC particle size = 10μm and volume fraction = 20%)

5. CONCLUSIONS

The micrographs of as-cast and heat treated 6061/SiCp composites indicate random distribution of SiC_p particles in the metal matrix composites. The low pressure die casting process avoids the transport of clustered SiC particles into the die cavity. In the microstructures, the Si crystals are not observed to be attached to the surface of SiC particles. The EDS report confirms the absence of $A1_4C_3$ compound in the 6061/SiC_p composites. The yield strength and fracture strength increase with increase in volume fraction of SiCp, whereas ductility of 6061/SiC_p composites decreases. With increasing volume fraction of SiC particles, the fatigue strength of the composite increases.The fracture mode is ductile in nature.

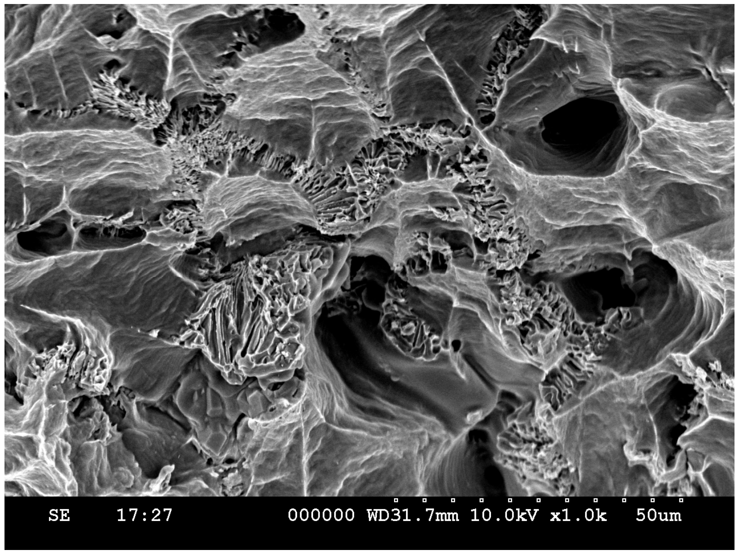

Figure 12: SEM of fracture surface of heat treated fatigue sample (SiC particle size = 10μm and volume fraction = 20%)

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