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CASTING OF AL-SiC$_P$ COMPOSITES AND TESTING OF THEIR PROPERTIES

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ABSTRACT

Al-SiC$_p$ composites with 5, 10, 15, 20, 25 and 30 weight % of SiC$_p$ in the shape of solid cylindrical pins were fabricated using stir die casting process. The various properties viz. density, hardness, compressive strength, tensile strength, surface roughness and wear resistance were measured. The density, hardness, compressive strength and tensile strength of Al-SiC$_p$ composites were found to increase with increase in the weight % of SiC$_p$ from 5 to 30 weight percent. The wear resistance of Al-SiC$_p$ composite pins was studied using a pin on disc wear testing machine under dry as well as lubricated conditions. The wear tests revealed that the wear resistance of Al-SiC$_p$ composites increases with increase in reinforcement content from 10 to 20 weight % of SiC$_p$ while the wear resistance decreases on further increase in reinforcement content from 20 to 30 weight % of SiC$_p$. The coefficient of friction was also monitored during the wear tests. The microstructure of polished and etched surfaces of cast Al-SiC$_p$ composite samples were studied using scanning electron microscopy.

KEY WORDS: Metal matrix composite, cast Al-SiC$_p$ composite, stir casting, induction furnace, mechanical testing, wear resistance, scanning electron microscopy.

INTRODUCTION

The last few decades have witnessed unprecedented development of harder metals and alloys. Among these lie the category of composite materials, the metal matrix composites (MMCs), which are increasingly being used in automobile, aircraft, space, defense and other industries. As a result, worldwide attention has been focused on processing and fabrication of these materials. The basis for this is reduction in manufacturing cost and improvement in performance. Aluminum alloys provide a good matrix for the development of these composite materials because of their low density, ease of fabrication and good intrinsic properties. Most of MMC development has been focused on aluminum alloys as matrix material and SiC particulates as reinforcement. The addition of the second phase results in improved physical and mechanical properties such as higher wear resistance, higher specific strength, lower coefficient of thermal expansion and good thermal stability. Apart from low cost of production, they are amenable to secondary processing such as rolling, forging, extrusion etc. The Al-SiC_p composites have seen most wide spread applications and hold the greatest promise for future growth because of their tailorable properties, good forming characteristics and the availability of comparatively low cost, high volume production methods. Several work have been reported on fabrication of different aluminum alloys reinforced with one or two particular weight percent of SiC_p and testing of some particular mechanical or wear properties or microstructural examination. However none of the works have reported the fabrication of Al-SiC_p composites with a wide range of SiC_p (5 to 30 wt. %) and testing of all the mechanical properties, wear behavior and microstructural analysis at one place. In the present work Al-SiC_p composites with 5 to 30 weight percent of SiC_p have been fabricated using stir die casting process. The physical and mechanical properties of the cast Al-SiC_p composites were determined. The wear behavior of the Al-SiC_p composites was studied under dry and lubricated conditions using pin on disc wear testing machine. The wear tests under lubricated conditions have rarely been reported till now.

Stir casting usually involves prolonged liquid-ceramic contact, which can cause substantial interfacial reaction. In the case of Al-SiC system the formation of Al_4C_3 and Silicon has been observed (Clyne, 2001; Ling, Bush and Perera, 1995; Sunghak, Dongil and Dongwoo, 1996). These degrade the final properties of the composites, reduce interfacial adhesion and raise the viscosity of the slurry and make subsequent casting difficult. This interfacial reaction can be effectively avoided by increasing the Si and Mg level of the matrix alloy, since it involves the dissolution of the SiC into Si and C. Kong and Jialan (1998) have investigated the micro-crack initiation, crack growth processes and fractography of a cast SiC_p /6061 Al composite by SEM in-situ tensile test observations. The results indicated that the de-bonding of the particulate-matrix interface, the pre-existed cracks in the clustered SiC_p and the dendrite phase were probably responsible for the damage and fracture of the composite. Sagar, Das and Purohit (2002) have done microstructure and fractographic study of Al-SiC_p composites. The tensile and impact tests were performed on the cast Al-5 wt. % SiC_p composite specimens. The fracture surfaces obtained after tensile and impact test were subjected to fractographic study using scanning electron microscope (SEM). The fracture analysis of Al-5 wt. % SiC_p composites revealed that the fracture produced by tensile tests and impact tests were brittle fracture. A negligible amount of necking and/or elongation was observed during tensile failure of the Al-SiC_p composites. Most of the tensile and impact fractographs show the presence of cellular dendritic shrinkage cavities, which become the sites of stress concentration and hence make the material brittle. The toughness of Al-5 wt. % SiC_p composites was very less compared to aluminum. The microstructural study of the polished and carefully etched Al-5 wt. % SiC_p composite specimens have shown that the structure consisted of a network of silicon particles, which were formed in inter- dendritic aluminum silicon eutectic composition. This causes segregation (coring) of silicon in the grains, which develops strain and makes the material brittle. Das, Mondal and Dixit (2001) have synthesized Al-Si alloy reinforced with 10 wt. % of SiC_p composites using gravity and pressure die casting processes. The microstructure of the pressure die cast composite was found to be finer than those of the gravity cast composites. The effect of hardness, strength and young's modulus on wear rate of Al-Si alloys-SiC_p composite was also studied. It was noted that the wear rate was primarily controlled by hardness even though other mechanical properties influence the wear behavior of the materials to some extent. Dasgupta and Meenai (2005) have fabricated 7075 Al-15 wt. % SiC composites and observed improvement in the mechanical and wear properties with addition of SiC reinforcement. Kalkanli and Yilmaz (2008) have synthesized the 7075 Al-SiC_p composites with 10 to 30 wt. % SiC by vertical pressure squeeze casting. The hardness of the 7075 Al-SiC_p composites were found to increase from 133 to 188 VHN with increase in SiC content from 0 to 30 wt. %. Pramila Bai, Ramaseash and Surappa (1992) have performed wear test on A356-Al-SiC_p composites with 15 and 25 weight % of SiC particles at a sliding speed of 0.5 m s^{-1} at different loads using pin on disc machine under dry condition. Composites exhibited better wear resistance compared with unreinforced alloy up to a pressure of 26 MPa. Zhang, Zhang and Mai (1996) have reported that the wear of 2014 Al-SiC_p composites against the steel disc under low sliding speed condition was dominated by abrasion and fracture of reinforced particles. Hassan et al. (2009) have studied the friction and wear behavior of Al-Mg-Cu alloy-SiC Composites at a pressure of 3.18 MPa and sliding speed of .393 m/s and observed significant improvement in wear resistance with increase in SiC content. Mondal et al. (2005) have studied the effect of running in wear on sliding wear behavior of Al-Zn-Mg alloy-SiC_p Composites under varying loads and measured the coefficient of friction, rise in temperature, wear rate and seizure pressure.

CASTING OF Al-SiC_P COMPOSITES

Standard samples of Al-SiC_p composites with 5, 10, 15, 20, 25 and 30 weight % of SiC_p were prepared using casting process. Al-SiC_p composites in the shape of solid cylindrical pins of two different sizes (16-mm diameter & 40 mm length and 20-mm diameter & 50 mm length) were cast through gravity die casting process. Two cylindrical mild steel dies were fabricated for this purpose. Since casting requires sufficient fluidity of the slurry there is a limit to the amount of SiC particulates, which can be incorporated by casting process. For the purpose of casting Al-SiC_p composites, a furnace with a blower and a graphite crucible was used. Pure aluminum metal was melted in the graphite crucible and the temperature was increased a little beyond melting point of aluminum. SiC particulates were introduced into the melt. 0.5 wt. % Magnesium was added to improve the wettability of SiC particulates in aluminum melt. Simultaneously a stirrer was used for mixing which was continued for about 10 minutes so as to avoid settling of SiC particles at the bottom. After removing the graphite crucible from the furnace, the melt was once again stirred and subsequently poured into the die. The same procedure was repeated using different weight % of SiC to fabricate Al-SiC_p composites with different compositions. Al-SiC_p composite samples were also prepared using induction furnace melting. Figure 1 shows the photograph of the induction furnace used of casting of Al-SiC_p composites. Figure 2 shows the scanning electron micrograph of SiC particulates used for casting of Al-SiC_p composites. The micrograph shows that the SiC particulates are of about 400-600 μm average size. Ten samples of each composition were cast to test the various properties of the composites. The die casting process results in reasonably good surface finish. Figure 3 shows the photograph of the cast Al- SiC_p composite specimens with 5 to 30 weight % of SiC_p.

TESTING OF PROPERTIES

In order to evaluate the properties of the Al-SiC_p composites the hardness, compressive strength, tensile strength, microstructure, and wear resistance were measured.

Hardness

Rockwell hardness was measured on the polished surfaces of the samples using C scale on Rockwell hardness tester. A diamond indentor with fixed indentation load of 150 kg was used for all tests. The angle of diamond indentor is 120°. Five readings were taken for the samples of each composition and the average hardness was determined.

Fig. 1 Photograph of the induction furnace used for casting of Al-SiC_p composites

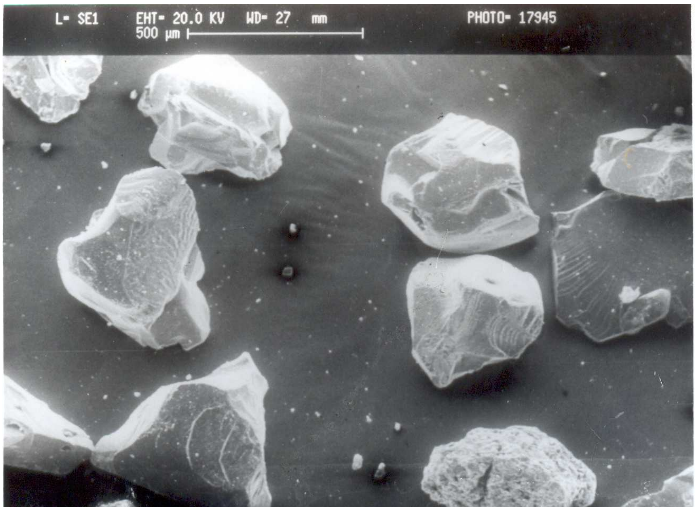

Fig. 2 Scanning electron micrograph of SiC particulates used for casting of Al-SiC_p composites

Fig. 3 Photograph of the cast Al-SiC_p composite specimens

Density

The theoretical density was determined by comparing the sum of volume (weight divided by the density) of constituents and the volume of composite. For example, the density of Al-5 wt. % SiC_p composites with 0.5 wt. % of Mg was determined as follows:

Density of SiC = 3210 Kg/ m^3
Density of aluminum = 2700 Kg/ m^3
Density of Magnesium = 1770 Kg/ m^3

$$\frac{100}{p} = \frac{5}{3210} + \frac{0.5}{1770} + \frac{94.5}{2700} \qquad \text{----------------------------(1)}$$

Which gives the theoretical density (ρ) for Al-5 wt. % SiC_p composites

$$= 2714.432 \text{ Kg/ m}^3$$

Similarly the densities of other compositions of Al-SiCp composites were determined. In all composites addition of 0.5 wt. % magnesium was considered.

Compressive strength

Compression test was performed on the cast Al-SiC_p composite specimens with length to diameter ratio of 1.5. Tests were performed on universal testing machine (UTM) of 100 KN capacity. The sample was compressed between two flat platens and the maximum failure load was recorded.

Tensile strength

The tensile strength of the cast Al-5, 10, 15 and 20 weight % of SiC_p composites were measured. For this purpose Al-SiC_p composite samples were fabricated as per the ASTM standard (Fig. 4). The samples were fabricated by casting and further machining processes. The tensile strength was measured on 100 KN universal testing machine.

Wear testing of Al-SiC_p composites in dry condition

For wear testing of Al-SiC_p composites a pin on disc wear testing machine has been used. Figure 5 shows the photograph of the pin on disc wear testing machine. The machine consists of a flat circular plate coupled with the shaft of a 0.75 kW D.C. motor whose speed can be varied from 0 to 1500 rpm with an autotransformer. The ground EN-31 steel disc as a counter surface is mounted on the circular plate and the test specimen is clamped in specimen holder. The bottom face of the specimen rests against the ground surface of the disc. A step less variation of sliding speeds from 0 to 8 m/s can be obtained by varying the motor speed and/or the distance of specimen from the center of the rotating disc (i.e. track radius). A control panel is provided to control and measure the various parameters such as sliding speed, test duration, temperature near contact region etc. To measure the friction force a load cell unit has been provided. Four resistance strain gauges were pasted on an elastic member in the vertical-supporting arm. The small signal obtained from the strain gauge bridge circuit is amplified and measured by a mili-voltmeter, which was calibrated by the application of known loads. To determine the friction force the mili-voltmeter reading was measured during the test and the corresponding friction force was obtained from the calibration curve. The machine was standardized by performing wear tests on the same material using the present machine and a standard wear testing machine. The variations in the reading of the two machines were within ± 6% of the results of standard wear testing machine. To perform wear test on Al-SiC_p composites in dry condition, specimens in the shape of solid cylindrical pins of 15 mm diameter and 40 mm length, were weighed up to an accuracy of 0.1mg on digital electronic balance and then mounted on the wear-testing machine with its one end resting against the steel disc. A track radius of 35 mm was used for all the tests. The sample was allowed to wear against the ground En-31steel disc (surface roughness, $R_a \approx 0.1$ μm) rotating at 273 rpm (sliding speed =1m/s) for 2 hours (sliding distance of 7.2 Kms) under different load of 19.6, 39.24 and 58.9 N. The machine was stopped at each one-hour interval and the specimen was removed from the specimen holder and washed with acetone and weighed to determine the weight loss. The specimen was once again mounted on the wear testing machine for next one hour test.

Wear testing of Al-SiCp composites in lubricated condition

Wear tests were also performed on Al-SiC_p composites under lubricated condition using a pin on disc wear testing machine. To perform the tests Al-SiC_p composite specimen in the shape of solid cylindrical pins of 15 mm diameter were first weighed up to an accuracy of 0.1mg on digital electronic balance. The accurately weighed sample was then mounted on the pin on disc wear testing machine with its one end resting against a circular EN-31 steel disc. The distance of pin from the center of disc was kept 35 mm. The sample was allowed to wear against the flat circular disc of EN-31steel. The disc was rotated at a speed of 936 rpm, which gives a sliding velocity of 3.5 m s^{-1}. Wear tests were performed on Al-SiC_p composite samples with 10, 15, 20, 25 and 30 weight % of SiC_p at 49 N load, under lubricated condition for two hours. Mobile oil was used as lubricant.

Surface roughness

Cast Al-SiC_p composite specimens were ground using surface grinder. They were polished using emery paper and then finished using diamond-lapping paste. The surface roughness on polished specimens was determined using Taly surf-6 surface roughness measuring instrument.

Microstructural analysis

The microstructures of the cast Al-SiC_p composites were studied using scanning electron microscope. For this purpose small samples were cut from the cylindrical pins fabricated by casting process. The flat samples were first ground using belt grinder and then using polishing papers of gradually increasing fineness. The polished samples were then lapped on polishing machine using diamond-lapping paste and velvet cloth for about 30 minutes so that mirror finish is obtained on the samples. The samples were etched with 5 % NaOH solution for about 45 seconds and washed with distilled water before the microstructural analysis. A number of scanning electron micrographs of cast Al-SiC_p composite samples with 5 to 30 weight % of SiC_p were taken and studied for microstructural analysis.

RESULTS AND DISCUSSIONS

Hardness

The average Rockwell hardness values of cast Al-SiC_p composites measured on the polished surfaces of the samples using C scale on Rockwell hardness tester are shown in Fig. 6. The Rockwell hardness of cast Al-SiC_p composites increases with increase in weight % of SiC_p from 5 to 30 wt. % of SiC_p. Fig. 6 shows the Rockwell hardness for cast Al-SiC_p composites fabricated using open furnace melting and induction furnace melting. The induction furnace melting results in higher value of hardness as compared to open furnace melting. This is due to the improved mixing of SiC_p during induction heating of aluminum and SiC particulates. The values shown in the graph are average of the three readings for each composition of the composite and the scatter of the actual hardness values about the average was limited to within ± 7 % of the average hardness values for the cast composite samples.

Density

The theoretical densities of the Al-SiC_p composites are shown in Fig. 7. The densities of Al-SiC_p composites increase with increase in weight % of SiC_p from 5 to 30 weight percent.

Compressive strength

The compressive strengths were measured for three samples of each composition of the cast Al-SiC_p composites and the average value of the compressive strength for cast samples were plotted in the graphs with weight % of SiC_p. Figure 8 shows the compressive strength for cast Al-SiC_p composites fabricated using open furnace melting and induction furnace melting. The compressive strength in both the cases increases with increase in weight % of SiC_p from 5 to 30 weight percent. The Al-SiC_p composites fabricated using induction melting show higher compressive strength values than those fabricated using open furnace melting. This was attributed to the self-stirring action produced by eddy current formation during induction heating of aluminum and SiC particulates. The Figure 8 shows that the difference in compressive strength of Al-SiC_p composites fabricated using induction furnace melting and open furnace melting decreases at higher weight % of SiC_p. The scatter of the measured values of the compressive strength was limited to within ± 3 % of the average for the cast samples. The variations are attributed to the experimental errors during fabrication and testing of properties of the composites.

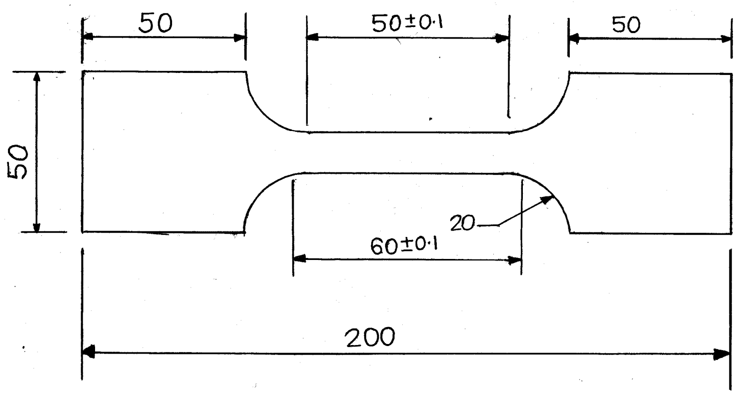

Fig. 4 Specifications of the tensile test specimen

Fig. 5 Pin on Disc Wear Testing Machine

Tensile strength

The tensile strengths were measured for the three samples of the each composition of the cast Al-SiC_p composites and the average tensile strengths are shown in Fig. 9. The Figure 9 shows the tensile strength for cast Al-SiC_p composites fabricated using open furnace melting and induction furnace melting. The tensile strength in both the cases increases with increase in weight % of SiC_p from 5 to 30 weight percent. The increase in the tensile strength of Al-SiC_p composites with increasing wt. % of SiC_p was reported to be due to the increase in the modulus of elasticity and the elastic limit of the material (Madan, 1995; McDanels, 1985). The Figure 9 shows that a remarkable increase in the tensile strength with increase in reinforcement content was observed only up to 20 wt. % of SiC_p, however, a very small increase in tensile strength was observed above 20 wt. % of SiC_p. This was due to the brittleness of the material at higher wt. % of SiC_p

(McDanels, 1985). The variation in measured values of the tensile strength about the average value was within ± 3.0 percent. The variations are attributed to the experimental errors during fabrication and testing of properties of the composites.

Wear test in dry condition

The Fig. 10 shows variation of wear volume of cast Al-SiC_p composites with weight % of SiC_p. The wear volume of Al-SiC_p composites decreases with increase in reinforcement content from 10 to 20 weight % of SiC_p while the wear volume increases on further increase in reinforcement content from 20 to 30 weight % of SiC_p. Therefore the Al-20 weight % SiC_p composites have maximum wear resistance as compared to the other compositions of the composites tested**.** The increase in wear volume of Al-SiC_p composites with higher weight % of SiC_p is probably due to the removal of loosely bonded SiC particulates from the matrix. Figure 11 shows the variation of wear volume of Al-SiC_p composites with applied load. The wear volume increases with increase in the contact load from 2 to 6 Kg. The Figure 10 and 11 show single test values of the wear volume but wherever discrepancy in reading was observed the wear tests were repeated to confirm the readings.

Figure 12 shows the variation of the coefficient of friction for cast Al-SiC_p composites with weight % of SiC_p at different loads. The variation of coefficient of friction is complex. However in general it can be observed from the figure that with increase in wt. % of SiC_p, the coefficient of friction decreases up to about 20 to 25 wt. % of SiC_p but on further increase in reinforcement content up to 30 wt. % the coefficient of friction increases. This can be explained as follows. The coefficient of friction for Al-SiC_p composites (against steel as counter surface) mainly depends upon two factors namely the adhesion of the micro projections (surface asperity) on the sliding surfaces under the normal force and the scratches produced on the counter surface due to rubbing of the hard silicon carbide particles. The aluminum has more tendencies for adhesion, therefore at low weight % of SiC_p the first factor predominates and with increasing weight % of SiC_p (decreasing content of Al) the coefficient of friction decreases. However at high weight % of SiC_p (above 25 wt. % of SiC_p) there is excessive scratch formation on the mating surfaces due to rubbing of bonded and loose silicon carbide particles. Here the second factor predominates. This results in increase of coefficient of friction at 30 weight % of SiC_p. The values of the coefficient of friction shown in Figure represent average of a large number of readings taken during the test for each composition of the composite. The scatter of these readings about the average value was within ± 5.5 %. The variation is relatively high due to the variation of coefficient of friction during the test.

Only a very small amount of wear material was observed flowing out of the specimen surface to curl up along the edges because the tests were conducted under low pressure conditions

(0.11- 0.33 MPa). The curled up material is detached, resulting in the formation of wear debris. High amount of wear debris was observed during wear testing of all the Al-SiC$_p$ composites tested at low speed (1 m/s) and low load conditions, which has also been observed by a number of other researchers and was reported to be due to the abrasive wear mechanism under low load and low sliding speed condition (Kwok and Lim, 1999; Pramila Bai, Ramaseash and Surappa, 1992; Zhang, Zhang and Mai, 1996). The hard SiC particles are dislodged from the composite and cause the abrasion of the steel counter face. The improvement in the wear resistance of the aluminum alloys by reinforcement of ceramic particles has been attributed to the formation of mechanical mixed layer on the composite pin surface (Saravanan, Kang and Lee, 2001).

Wear tests in lubricated condition

Figure 13 shows the variation of wear volume for Al-SiC$_p$ composites with wt. % of SiC$_p$. The wear volume decreases with increase in wt. % of SiC$_p$ from 5 to 25 weight percent. However at 30 wt. % of SiC$_p$ the wear volume again increases. This was attributed to the removal of loosely bonded SiC particles from the pin surface.

Surface roughness

The surface roughness for cast Al-SiC$_p$ composites measured on Taly surf-6 surface roughness measuring instrument are shown in Fig. 14. The average surface roughness (Ra value) first decreases then increases with increase in reinforcement content of SiC particulates from 5 to 30 weight percent. The surface roughness values depend upon the extent of polishing done on the Al-SiC$_p$ composite samples. The surface roughness has an important effect on the wear properties of the automotive and other components.

Microstructural analysis

Fig. 15 shows the scanning electron micrograph of gravity die cast pure aluminum sample at magnifications of 360X. Fig. 16, 17, and 18 show the scanning electron micrograph of gravity die cast Al-SiC$_p$ composite samples with 10, 20 and 30 weight % of SiC$_p$ respectively. In the micrographs the black regions show the dendrites of alpha crystals while the white regions show the eutectic mixture. The SiC particles are also visible in the micrographs.

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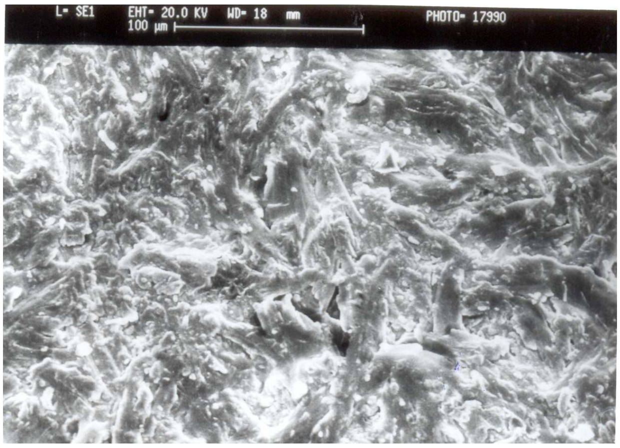

Fig. 15 Scanning electron micrograph of gravity die cast pure aluminum sample at magnification 360X

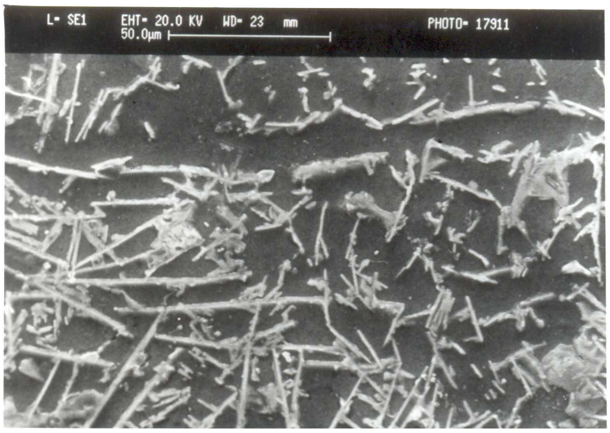

Fig. 16 Scanning electron micrograph of gravity die cast Al-10 weight % SiC_p composite sample at magnification 600X

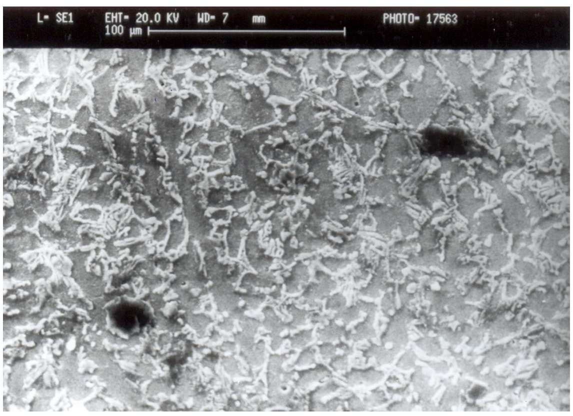

Fig. 17 Scanning electron micrograph of gravity die cast Al-20 weight % SiC_p composite sample at magnification 400X

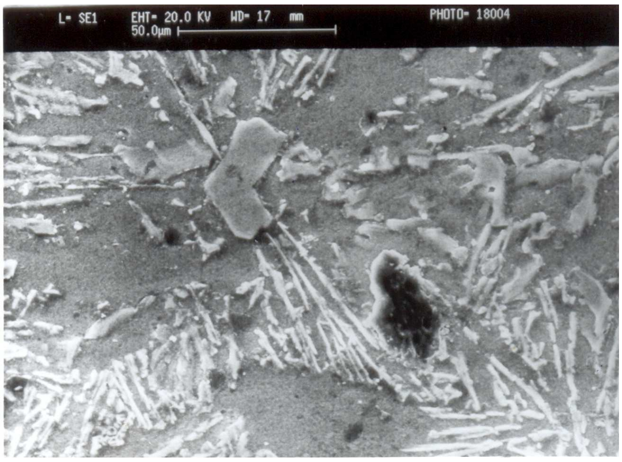

Fig. 18 Scanning electron micrograph of gravity die cast Al-30 weight % SiC_p composite sample at magnification 600X

CONCLUSIONS

1. The density, Rockwell hardness, compressive strength and tensile strength of Al-SiC_p composites increases with increase in reinforcement content from 5 to 30 weight percent of SiC_p.

2. The dry sliding wear tests using pin on disc wear testing machine reveal that the wear resistance of Al-SiC_p composites increases with increase in reinforcement content from 10 to 20 weight % of SiC_p while the wear resistance decreases on further increase in reinforcement content from 20 to 30 weight % of $SiC_{p.}$ Increased wear of Al-SiC_p composites with higher weight % of SiC_p composites is due to the removal of loosely bonded SiC particulates from the matrix.

3. The variation of coefficient of friction is complex. However in general the coefficient of friction decreases up to about 20 to 25 wt. % of SiC_p with increase in wt. % of SiC_p, but on further increase in reinforcement content up to 30 wt. % the coefficient of friction increases.

4. The wear resistance of Al-SiC_p composites tested under an imposed load of 49 N in lubricated condition at a sliding velocity of 3.5 m s^{-1}, was found to increase with increase in reinforcement content from 5 to 25 weight % of SiC particulates. However the wear resistance of Al-30 weight percent SiC_p composites was less than that of the Al-25 weight percent SiC_p composites.

5. The average surface roughness (Ra value) of cast Al-SiC_p composites first decreases then increases with increase in reinforcement content of SiC particulates from 5 to 30

weight percent. The surface roughness values depend upon the extent of polishing done on the Al-SiC_p composites.

6. Scanning electron micrographs of Al-SiC_p composites with 5 to 30 weight percent of SiC_p show black regions of the dendrites of alpha crystals and white regions of eutectic mixtures. They also show some amount of porosity and uniform distribution of SiC particulates in aluminum matrix.

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