FABRICATION OF Al-SiC$_p$ COMPOSITES THROUGH POWDER Metallurgy Process and Testing Of Properties

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Abstract

Metal matrix composites are the class of composite materials finding vast applications in automotive, aircraft, defense, sports and appliance industries. A horizontal ball mill has been fabricated for milling of aluminum and SiC particles. The change in powder particle morphology during mechanical alloying of Aluminum and SiC powders using horizontal ball mill was studied. Al-SiC$_p$ composites with 5 to 30 weight % of SiC$_p$ were fabricated using powder metallurgy process. The various properties viz. hardness, density, porosity, compressive strength, indirect tensile strength and surface roughness were measured. The density, porosity, hardness, compressive strength and indirect tensile strength of Al-SiC$_p$ composites were found to increase with increase in the wt. % of SiC$_p$ from 5 to 30 weight percent. Mechanical alloying of powders resulted in improvement in hardness and compressive strength of Al-SiC$_p$ composites with 5 to 30 weight % of SiC$_p$. The microstructure of polished and etched surfaces of powder metal Al-SiC$_p$ composite samples was studied using scanning electron microscope.

Key Words: Metal matrix composites, Mechanical characterization, Mechanical alloying, Microstructural analysis, Powder metallurgy.

1. Introduction

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. Aluminum based composite powders are highly compressible. Typically, green densities of more than 90 % of theoretical can be obtained utilizing low compacting pressures, (about 200MPa), allowing the use of presses with smaller capacity. Sintering of Al-SiC$_p$ composite parts is more energy efficient than for most other PM materials due to the relatively low sintering temperatures. Due to the low density of Al-SiC$_p$ composites, more than twice number of parts can be manufactured from unit weight of powder as compared to ferrous or copper based powders. During last 15 years various researchers have reported the fabrication of Al-SiC$_p$ composites and testing of their properties like tensile strength, hardness, wear resistance and microstructural characterization. Most of the researchers have observed an increase in tensile strength, hardness and wear resistance while decrease in ductility with increase in reinforcement content. Several researchers have studied the mechanical alloying of aluminum and SiC powders and identified improvement in mechanical properties of the Al-SiC$_p$ composites made from mechanical alloyed powders.

Mohanasundaram, et al. [1] have developed Al-SiC$_p$ composites by the powder metallurgy route and identified a significant improvement in tensile properties and wear resistance with increasing content of second phase. Madan [2] has fabricated 6061Al-SiC$_p$ and 6061Al-Al_2O_3 composites and tested their properties. The effect of fabrication method on the mechanical properties of the near net shape specimens was investigated by Ling, et al. [3]. Sinter /hot isostatically pressed compacts (sinter/ HIPed) composites of up to 30 volume % SiC were produced with a significant improvement in ductility and ultimate tensile strength compared with the other fabrication methods. The poor mechanical properties of composites produced by the other methods are attributed to the weak bonding between adjacent particles and to internal porosity. The microstructural examination of fracture surfaces in representative materials confirmed that the sinter/HIPing technique yielded the best composites. For composites with reinforcement less than 10% by volume, the ductile fracture of the matrix appears to be the limiting factor. At higher volume fractions, the strength of interfacial bonds, initiation and growth of voids and particle cracking all play an important role in controlling the mechanical properties.

Deevi and Sikka [4] have prepared Al-SiC_p composites with 5 - 80 wt. % of SiC particulates using hot compaction. Increasing the SiC_p content increased the yield and ultimate tensile strengths and reduced the tensile elongation at room temperature and at 450°C. The electrical resistivity and hardness of the composites increased with the increase of SiC content. The microstructure of the composites exhibited unique features with increases in SiC loading. SiC impinged into the Al particles, the extent and depth of impingement being severe above 50 volume % SiC content.

An Al-4 wt. %Cu, 10 volume % SiC_p composite has been prepared using mechanically alloying technique [5]. The structural evolution of the mechanically alloyed powder mixture was monitored using X ray diffractometry. The results showed that both the 0.2% yield and the ultimate tensile strengths increased with the duration of mechanical alloying. This increase was associated with the homogeneous distribution and refinement of the SiC particulates, the formation of oxides and the decreased grain size. Gingu and Orban [6] have studied the micro structural aspects of Al/(SiC+Cu) composite powders manufactured by mechanical alloying. Bhaduri et al. [7] used an attritor to mechanically alloy Al (7010) and SiC particulates with an addition of 2 wt. % stearic acid, which reduced cold welding of the Al particles. It was found that the equiaxed composite particles were formed. Several milling conditions (higher rpm and ball to powder ratio) have been used in the process whereas addition of SiC particulates retarded the process, due to possibility of the inhibiting effect on the formation and welding of lamellae in the initial stages of mechanical alloying.

Sankar and Singh [8] have synthesized the 7075 Al/SiC particulate composite powders by mechanical alloying in argon atmosphere in a high-energy attritor mill and 2 wt. % of stearic acid was used as process control agent. Powder samples were withdrawn periodically and characterized to find out the sequence of phase formation and the extent of alloying with time by X ray diffraction analysis. The surface morphology and nature of alloying of the composite powder was observed using scanning electron microscope. After 12 hour of milling, homogeneous equiaxed powders were obtained. One interesting observation of the XRD analysis is the absence of peak corresponding to Al_4C_3, which is often seen in the composite prepared by the liquid metallurgy route and is undesirable because of low strength and brittleness. Angers, et al. [9] have investigated the properties of 2024 Al/SiC_p composites prepared by low energy ball milling using tumbler ball mill. The process parameters studied were milling time (between 1 and 24 hours) and the volume proportions of SiC (between 5 and 35 %). It was reported that as compared to high-energy attritor, the risk of contamination by the balls and container material is significantly reduced in the case of low energy ball milling. Composites containing up to 25 volume % SiC_p exhibited superior mechanical properties and homogeneous distribution of reinforcement particles but their ductility decreased with increase in SiC_p content. Mechanical properties and stress-strain behavior of different types of commercially fabricated aluminum matrix composites, containing up to 40 volume % discontinuous SiC whisker, nodule or particulate reinforcement were evaluated by McDanels [10]. The elastic modulus of the composites was found to be isotropic, to be independent of type of reinforcement, and to be controlled solely by the volume percent of SiC reinforcement. The yield/ tensile strengths and ductility were controlled primarily by the matrix alloy and temper condition. Ductility decreased with increasing reinforcement content. AMC Ltd. Have used a powder metallurgy approach involving mechanical attrition and hot isostatic pressing to achieve an exceptionally uniform dispersion of SiC particles in aluminum matrix and consistent mechanical properties [11]. Microstructure and deformation behavior of 12 volume % SiC_p /6061 Al composites have been studied by Cheng, et al. [12]. It was reported that the load transfer between matrix and reinforcements, grain refinement of metal matrix and dislocation strengthening are the main strengthening mechanisms of Al-SiC_p composites. The ductile tearing of SiC_p/Al interfaces and the SiC particle cracking are the dominant failure modes of Al-SiC_p composites. The effect of reinforcement particle size, matrix to reinforcement particle size ratio and volume fraction of the reinforcement (0-20 vol.%) on the microstructure and mechanical properties of Al-6Cu-0.4Mn/ SiC_p composites manufactured by powder metallurgy was investigated by Slipenyuk et al. [13].

In the present work Al-SiC_p composites have been fabricated using powder metallurgy process. Mixture of six different compositions viz. 5,10, 15, 20, 25 and 30 weight percent of SiC particulates in aluminum matrix were prepared using horizontal ball mill. The changes in powder particle morphology during mechanical alloying of aluminum and SiC particles after each four hour intervals were studied. The Al-SiC_p composites were fabricated using isostatic compaction as well as direct compaction of powders and subsequent sintering in vacuum. The physical and mechanical properties of the Al-SiC_p composites were measured and microstructural analysis was also done using scanning electron microscopy.

2. Fabrication Of Horizontal Ball Mill

A horizontal ball mill (also called tumbler ball mill) was fabricated for mechanical alloying of aluminum and SiC particulates. The container of the mill was made of the same material as the powder to be milled (i.e. Al-15 weight % SiC_p composites) to prevent contamination of powders from the container walls. The ball mill was designed for milling a total powder charge of 0.50 kg per run. Following are the specifications of the horizontal ball mill:

Outer diameter = 300 mm
Width = 105 mm
Rotation speed = 78 rpm

The mill was filled with balls and powder charge up to about 20 to 35 % of its total volume and the milling was done for required period of time (12 to 15 hours). Due to the combined action of centrifugal force and the friction between balls and container wall, the balls move together with the container wall until the gravitational force is balanced by the centrifugal force and subsequently fall down in free space causing an impact with the powder particles. Figure 1 shows the photograph of the horizontal ball mill.

3. Experimental Procedures

3.1 Study of changes in powder particle morphology during mechanical alloying of Aluminum and SiC powders

The mixtures of aluminum with 5 to 30 weight percent of SiC particulates were prepared and ball milled using different ball mills in the argon atmosphere. 0.5 wt. % of Mg was also added to increase the wettability of SiC particulates with aluminum powders. The powder samples were taken from the ball mills at four hours intervals of milling to study the change in powder particle morphology during mechanical alloying. The parameters used for mechanical alloying in horizontal ball mill are shown in Tables 1. The steel balls with ball to powder weight ratio of ten were used as grinding media. In order to minimize the extreme tendency of aluminum to get itself welded during milling, 2 weight % of stearic acid was added as a process control agent. The milling was performed in Argon atmosphere to prevent contamination from atmospheric air. Argon was passed in the vials for 5 to 10 minutes to remove the air and create inert atmosphere in the vials to prevent contamination. The scanning electron micrographs of the powder samples were taken to study the change in powder particle morphology during mechanical alloying.

3.2 Fabrication of Al-SiC_p composites through powder metallurgy process

Standard samples of Al-SiC_p composites with 5, 10, 15, 20, 25 and 30 weight % of SiC_p were fabricated through powder metallurgy route in the following stages:

3.2.1 Sieve analysis of the powders

Aluminum powder of 5 to 50 μm size range and SiC particulates of about 400 to 600 μm were sieved separately and used in the present work. The equipment used for the purpose was horizontal vibratory sieving machine.

3.2.2 Mixing of powders

The Aluminum and SiC powders of particular size range, obtained after sieve analysis were weighed individually and mixtures of six different compositions (viz. 5, 10, 15, 20, 25 and 30 weight percent of SiC_p) were prepared. Figures 2 and 3 show the scanning electron micrograph of the aluminum and SiC particulates respectively used in the present work. The micrographs show that the aluminum powders are of about 5 to 50 μm size range and the SiC particulates are of about 400-600 μm average size. 0.5 wt. % of Mg was also added to increase the wettability of SiC particulates with aluminum powders. The mixtures were put in plastic containers and mixing was done manually. After this, the mixing was continued in a pastel mortar for three hours to ensure proper mixing. The quality of mixing was inspected using optical microscope to ensure uniform distribution of aluminum and SiC powders.

3.2.3 Mechanical alloying

As discussed in literature [14] the simple blending and mixing provide a mechanical mixture of the powder constituents. Mechanical alloying results in mixing at molecular level. The SiC particles get embedded into Al powder particles and powder particles of Al-SiC_p composite is obtained.

The powder mixtures were transferred to horizontal ball mill. The mill already contains the hardened steel balls as milling media. In order to minimize the extreme tendency of aluminum to get it self welded during milling 2 wt. % of stearic acid was added as process control agent. The mill was run at 78 rpm for 12 to 15 hours. The powder becomes hot during milling therefore it is allowed to cool for 3-4 hours then it is taken out of the vials and stored in plastic containers.

3.2.4 Mould cavity

For the manual compaction of Al-SiC_p composites in the shape of solid cylindrical pins of 15 mm diameter and 30 mm length a die and punch of mild steel have been fabricated. The die was lubricated to ensure easy extraction of the powder compacts. The Al-SiC_p composite powders of weighed amount were mixed with 2-wt. % ethyl acetate and poured into the die. The punch was introduced from top and pressing was done using an arbor press. The powder compact was ejected out of the die and put in a flexible mould and its mouth was tied tightly with the help of a string The flexible mould should be of appropriate size in order to avoid wrinkles on the mould surface. The rubber balloons were used as flexible mould. The flexible mould should be 100 percent leak proof to prevent the leakage of oil into the powder sample during isostatic compaction. Al-SiC_p composite specimens were fabricated with both ball milled and un-ball milled powder samples with different weight % of SiC particulates.

3.2.5 Powder consolidation

The Al-SiC_p composites specimens were fabricated using both die compaction and cold isostatic compaction process.

Cold Isostatic compaction

Cold Isostatic compaction process results in better and more uniform properties as compared to die compaction because of uniform application of pressure from all directions and absence of die wall friction.

The equipment used for this purpose was a pressure chamber, which is a compound cylinder designed for a pressure of 750 MPa [15]. Cold isostatic compaction was done using 2500 KN compression testing machine. The pressure chamber is provided with a neoprene 'O' ring along with a tellurium copper metal ring for perfect sealing. The chamber was filled with brake oil. The flexible mould was placed inside the chamber. The powder in the flexible mould was compacted to 600 MPa pressure. The compaction was done at a loading rate of 3.27 KN/second. The compact was extracted from the chamber and the mould was opened to remove the entrapped air. The rubber balloon was tied once again with a string and the above process of isostatic compaction was repeated. The green compacts were removed from the balloon.

Die compaction

For die compaction of Al-SiC_p composites a die set-up (consisting of a die and punch has been used [2]. 1.5 weight % of die lubricant (zinc sterate) was mixed with powders for ease in compaction and ejection of powder compacts. The Al-SiC_p composite powder of weighed amount was poured inside the die and the compaction was done on 500 KN press.

3.2.6 Sintering

The green die compacts and cold isostatically pressed compacts were sintered in a muffle furnace by gradually raising the temperature to 580^{o}C and the specimens were kept at this temperature for 30 minutes. The compacts were furnace cooled.

Vacuum sintering of the Al-SiC_p composites was also done which gave better properties. For this the Al-SiC_p composite samples were placed in a quartz tube and the tube was evacuated using a vacuum system. After the high vacuum (10^{-6} mbar) was created in the quartz tube the tube was sealed by glass blowing using (LPG and oxygen) burners. The sealed tubes were placed in muffle furnace for sintering of Al-SiC_p composites. The temperature was raised to 600°C and sintering was done for 45 minutes. A higher furnace temperature was used because the temperature inside the quartz tube is less then the outside temperature. After sintering the tube was furnace cooled and than the quartz tube was cut from one end and the sintered Al-SiC_p composite samples were taken out. Fig. 4 shows the photograph of the Al-SiC_p composite specimens fabricated by PM process.

3.3. Testing of properties

In order to evaluate the properties of the Al-SiC_p composites the hardness, porosity, density, compressive strength, indirect tensile strength, and microstructure were determined.

3.3.1 Hardness

Rockwell hardness was measured on the polished surfaces of the Al-SiC_p composite 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.

3.3.2 Porosity

Porosity of the sintered as well as un-sintered compacts was determined by Archimedes principle. The compacts were first weighed in air and then tied with string and weighed while hanging in water. The density was determined using the following formula:

$$\rho_s = (m_a \times \rho_w)/(m_a - m_w) \quad \text{-------------------------------(1)}$$

Where,

ρ_s = Density of sintered specimen (Kg/ m^3)

ρ_w = Density of water (Kg/m^3)

m_a = Weight of sample in air (kg)

m_w = Weight of sample in water (kg).

The density was also measured by measuring the weight and volume of the specimens. The volume was determined by measuring the accurate dimensions of the P/M specimen. The porosity was determined using the following formula:

$$E = 1 - \rho_s/\rho_t \quad \text{---(2)}$$

Where,

E = porosity (%)

ρ_s = Density of sintered part (Kg/ m^3)

ρ_t = Theoretical density (Kg/ m^3)

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

$$\frac{100}{\rho} = \frac{5}{3210} + \frac{0.5}{1770} + \frac{94.5}{2700} \quad \text{---------------------------(3)}$$

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

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

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

3.3.3 Compressive strength

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

3.3.4 Indirect tensile strength

The indirect tensile strength of the powder metal Al-SiC_p composites with 5, 10, 15, 20, 25 and 30 weight % of SiC_p were measured. For this purpose Al-SiC_p composite samples of right circular cylindrical shape were fabricated by powder metallurgy process. The indirect tensile strength was measured on 100 KN universal testing machine. In this test a right circular cylinder is compressed diametrically between two flat plates. The maximum tensile stress is developed normal to the loading direction with a constant magnitude between two lines of contact. The tensile stress G is given by

$$G = 2P/ \pi.d.t \quad \text{---------------------------------------(4)}$$

Where,

P = Applied load (N)

d = Specimen diameter (m)

t = Specimen thickness (m)

3.3.5 Surface roughness

The powder metal 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.

3.3.6 Microstructural analysis

The microstructures of the Al-SiC_p composites were studied using scanning electron microscope. For this purpose small samples were cut from the cylindrical pins fabricated by powder metallurgy 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. Then the scanning electron micrographs of powder metal Al-SiC_p composite samples with 5 to 30 weight % of SiC_p were taken and studied for microstructural analysis.

4. Results And Discussions

4.1 Study of changes in powder particle morphology during mechanical alloying of aluminum powders with 5 to 30 wt. % of SiC particulates

The changes in powder particle morphology of Al powders with 5, 10, 15, 20, 25 and 30 wt. % of SiC particulates at various stages of ball milling were studied. Fig. 5 shows the change in powder particle morphology of Al powders and 10 wt. % SiC particulates at magnification of 400X. Fig. 5 (a) shows irregular, morphology of Al powders with 10 wt. % SiC particulates before mechanical alloying. Fig. 5 (b) shows that after 4 hours of milling the equiaxed ductile aluminum particles are flattened due to micro-forging resulting in flat plate like structures while the SiC particulates were fragmented. Fig. 5 (c) shows a cluster type of powder particle morphology after 8 hours of milling. The increased surface area of aluminum particles results in cold welding of powder components while the SiC particulates were entrapped along the cold welded interfaces of Al powder particles. In the final stage of mechanical alloying, as shown in Fig 5 (d), a fine homogeneous equiaxed composite structure was obtained due to fracturing of composite lamella structure and their random welding orientation. Due to inert gas atmosphere the newly fractured surfaces were prevented from oxidation. The welding of powder particles took place. The individual lamellae were unresolved in an optical microscope. It has been observed that if the mechanical alloying is incomplete, it is very difficult to remove the powder from the balls and the inner walls of milling container while after completion of the mechanical alloying the composite powder can easily be taken off from the balls as well as the walls of the container. A similar type of change in powder particle morphology was observed by the SEM study of powder samples taken at four hour intervals during mechanical alloying of the mixture of aluminum and SiC particulates with 5, 15, 20, 25 and 30 weight % of SiC_p, e.g. Figure 6 show the change in powder particle morphology during milling of Al-30 weight % of SiC_p at X400 magnification.

4.2 Testing of Properties

4.2.1 Hardness

The average Rockwell hardness values of Al-SiC_p composites measured on the polished surfaces of the samples using C scale on Rockwell hardness tester are shown in Fig. 7. The Rockwell hardness of powder metal Al-SiC_p composites increases with increase in weight % of SiC_p from 5 to 30 wt. % of SiC_p. Fig. 7 shows the Rockwell hardness for Al-SiC_p composites fabricated using un-ball milled and ball milled powders. The Al-SiC_p composites prepared using ball-milled powders show higher hardness values than those prepared using un-ball milled powders. This is because the mechanical alloying involves severe deformation of the aluminum powders and embedding of the SiC particles uniformly into the aluminum matrix. This gives a uniform equiaxed composite powder structure, which gives improved properties after compaction and sintering. The values shown in the graph are average of the four readings for each composition of the composite and the scatter of the actual hardness values about the average was limited to within ± 5 % of the average hardness values for the Al-SiC_p composite samples. A relatively high variation in the hardness values measured at different positions on the samples made by PM process may be due to the presence of porosity.

4.2.2 Porosity

The densities of isostatically pressed Al-SiC_p compacts in green and sintered condition are shown in Fig. 8 and 9 respectively. Both the green and sintered densities were measured for 3-3 samples of each composition of the Al-SiC_p composites and the average values were shown in the graph. The variation of the measured values about the average density was limited to ± 5 % of the average value under both the green and sintered condition. The deviation in measured values was attributed to the slight variations in a large number of processing parameters involved in the fabrication of composites and also to the errors encountered during measurements. The theoretical densities of Al-SiC_p composite compacts increase with increase in weight % of SiC_p from 5 to 30 weight percent because the SiC particulates have higher density then the aluminum. However the measured density of Al-SiC_p composites does not increases with increase in weight percent of SiC_p because of increase in porosity with increasing weight percent of SiC_p. The comparison of figures 8 and 9 reveals that sintering results in de-densification, which is due to the removal of volatile material like stearic acid and ethyl acetate during sintering. The stearic acid was added during mechanical alloying as a process control agent and the ethyl acetate was added during manual compaction of powders. The de-densification is also due to the recovery of the compressed powder with passing of time as high compaction pressure was used in the green stage. Figure 10 shows the porosity of isostatically pressed Al-SiC_p composites in green and sintered conditions. The porosity in green stage increases with increase in weight % of SiC_p up to about 20 to 25 weight percent, which is due to the increase in percentage of coarser component (SiC_p). However at higher weight % of SiC_p the porosity of green compacts tend to become almost constant. The porosity of sintered compacts was more than the porosity of the green compacts.

4.2.3 Compressive strength

The compressive strengths were also measured for three samples of each composition of the Al-SiC_p composites and the average value of the compressive strength for PM samples were plotted in the graphs with weight % of SiC_p. Figure 11 shows the compressive strength for powder metal Al-SiC_p composites fabricated using ball milled and un-ball milled powders. The compressive strength of PM Al-SiC_p composites in both the cases increases with increase in weight % of SiC_p from 5 to 30 wt. % of SiC_p. The Al-SiC_p composites fabricated using ball-milled powders show higher values of the compressive strength than those fabricated using un-ball milled powders. This was attributed to the uniform dispersion and mechanical interlocking of SiC particles in the aluminum matrix obtained during mechanical alloying process, which strengthened the consolidated specimens. The scatter of the measured values of the compressive strength was limited to within ± 2.5 % of the average for the PM Al-SiC_p composite samples. The variations are attributed to the experimental errors during fabrication and testing of properties of the composites. The compressive strengths of powder metal Al-SiC_p composites are quite less, which is due to the inherent porosity of the powder metal compacts. Porosity is required for oil impregnation, which impart self-lubrication properties to the components.

4.2.4 Indirect tensile strength

The indirect tensile strengths were also measured for the three samples of the each composition of the Al-SiC_p composites and the average tensile strengths are shown in Fig. 12. The indirect tensile strength 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 [2, 10]. The Figure 12 shows that a remarkable increase in the indirect 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 [10]. The variation in measured values of the tensile strength about the average value was within ± 3.0 percent.

4.2.5 Surface roughness

The surface roughness for isostatically pressed Al-SiC_p composites measured on Taly surf-6 surface roughness measuring instrument are shown in Fig. 13. The surface roughness has an important effect on the wear properties of the any components. The surface roughness of PM samples (R_a value ranges from 2.28 to 2.95 μm for specimens with different weight % of SiC_p) is quite high, which is because of the coarseness of the powders used in the present work.

4.2.6 Microstructural analysis

Figures 14, 15 and 16 show the scanning electron micrograph of un-sintered Al-SiC_p composite samples with 10, 20 and 30 weight % of SiC_p at magnification of 340X. The micrographs show that the aluminum and SiC particles are not properly bonded to each other in the green stage. Figures 17, 18 and 19 show the scanning electron micrograph of the vacuum sintered Al-SiC_p composite with 10, 20 and 30 wt. % of SiC_p respectively. SiC particles are visible in the micrograph. The micrograph shows that the bonding has taken place between aluminum and SiC particles after vacuum sintering. Some amount of porosity is also visible in the micrographs.

5 Conclusions

1. Mechanical alloying of aluminum and silicon carbide powders for 12 hours of milling results in fine homogeneous equiaxed composite powder structure. SEM studies of ball milled powders at intermediate stages reveal that due to impact of steel balls, the repeated cold welding, fracturing and re-welding of powder particles takes place and SiC particulates get embedded in the aluminum matrix. Finally the Al-SiC_p composite powders are obtained.
2. During isostatic compaction of powders, the quality of final product depends upon the quality of initial manual compact; therefore the manual compact should be prepared carefully and should be given proper allowances in dimensions to get the desired final product.
3. Cold isostatic compaction at 600 MPa followed by vacuum sintering at 600°C has been successfully used to produce Al-SiC_p composites.
4. Rockwell hardness, Density, porosity, compressive strength and indirect tensile strength of powder metal Al-SiC_p composites increases with increase in reinforcement content from 5 to 30 weight percent of SiC_p.
5. Sintering of Al-SiC_p composites result in de-densification due to higher compaction pressure used in the green stage and also due to the removal of volatile materials during sintering and thus improving the oil retention properties.
6. Mechanical alloying of powders result in improvement in hardness, compressive strength and indirect tensile strength of Al-SiC_p composites with 5 to 30 weight percent of SiC particulates.

7. Scanning electron micrographs of powder metal Al-SiC_p composites reveals that the vacuum sintering results in bonding between aluminum and SiC particles. The micrographs also show some amount of porosity and uniform distribution of SiC particulates in aluminum matrix.

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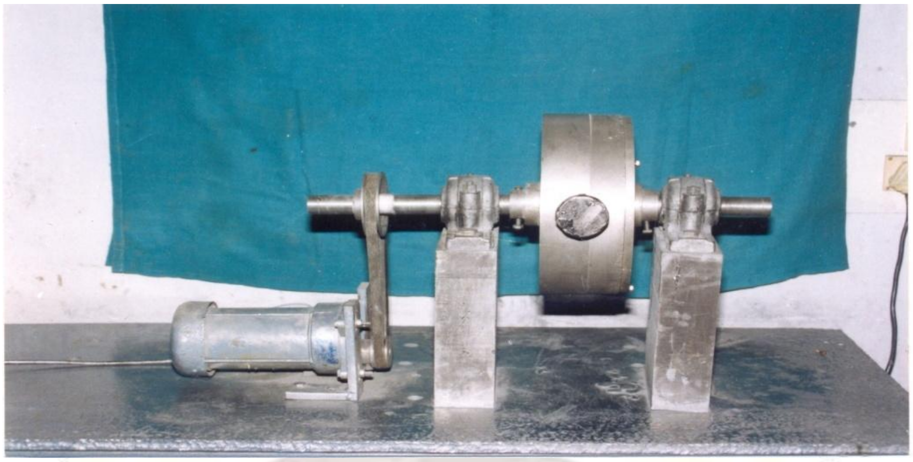

Fig. 1 Horizontal ball mill

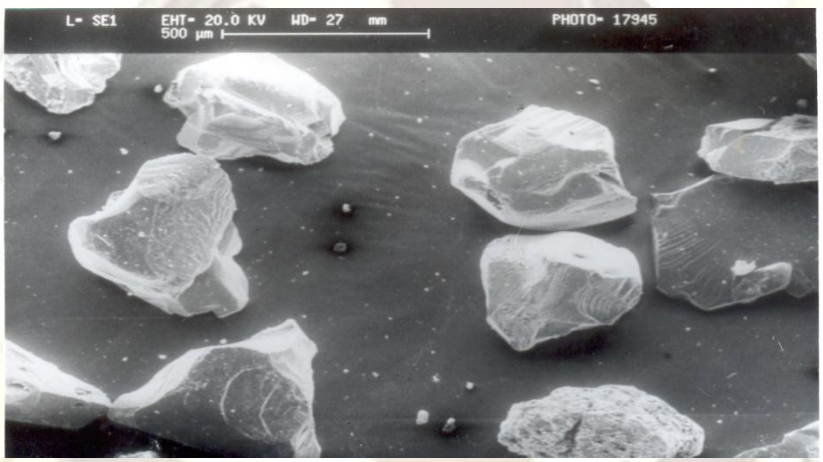

Fig. 2 Scanning electron micrograph of the aluminum powders used in the present work

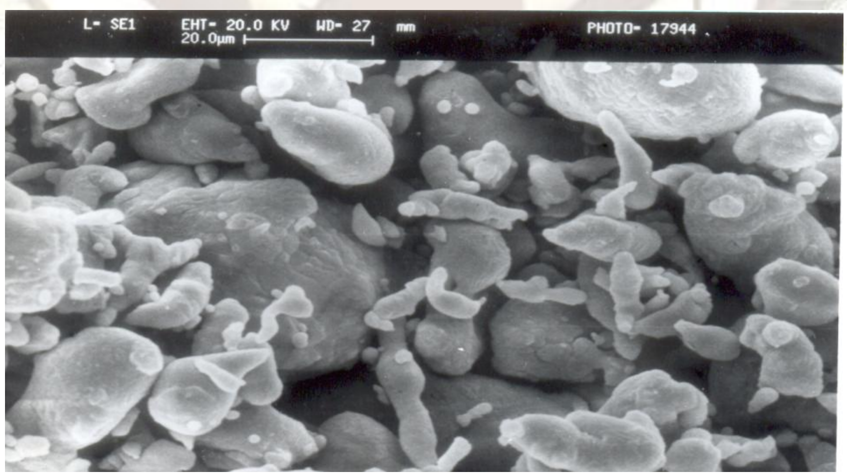

Fig. 3 Scanning electron micrograph of SiC particulates used in the present work

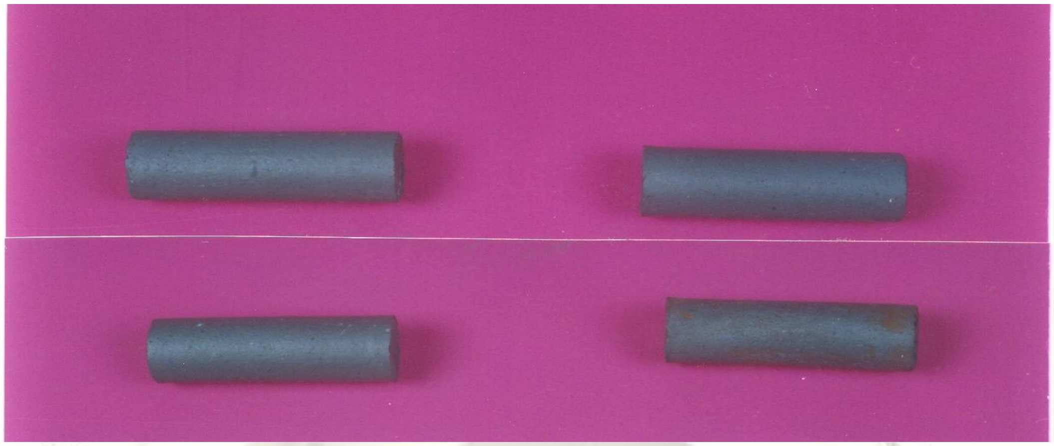

Fig. 4 Photograph of the Al-SiC$_p$ composite specimens fabricated by powder metallurgy process.

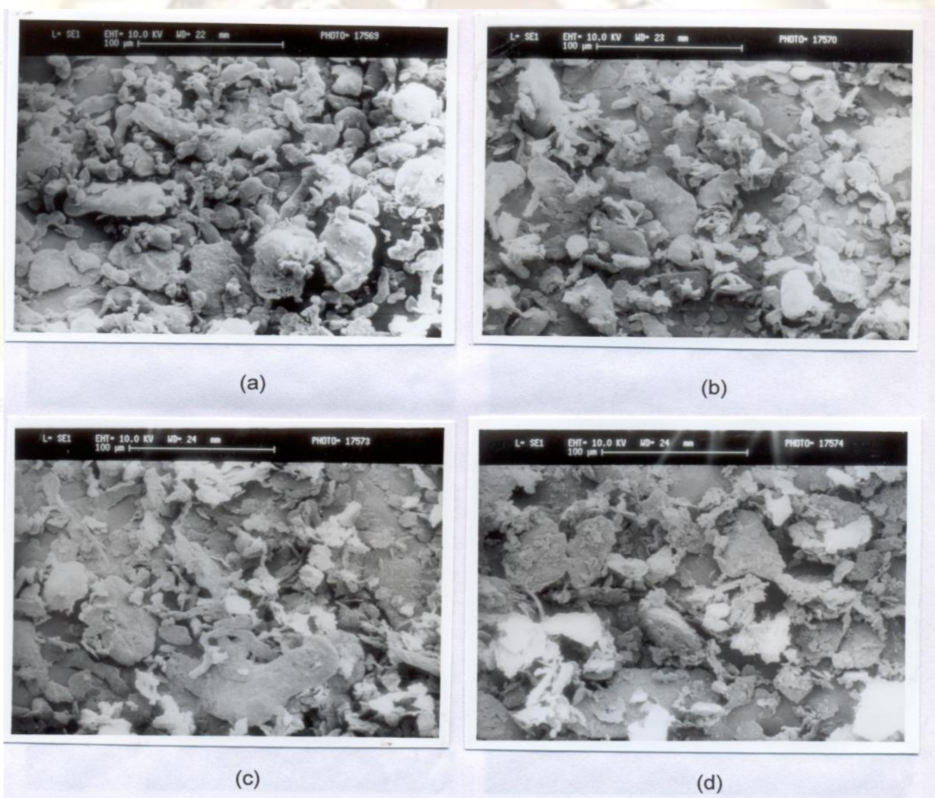

Fig. 5 Scanning electron micrographs of the Al powders with 10 weight % of SiC particulates (a) before ball milling, irregular particles; (b) after 4 hours of ball milling, flat lamellaer structure; (c) after 8 hours of ball milling cluster type structure and (d) after 12 hours of ball milling, equiaxed. (Mag. X400)

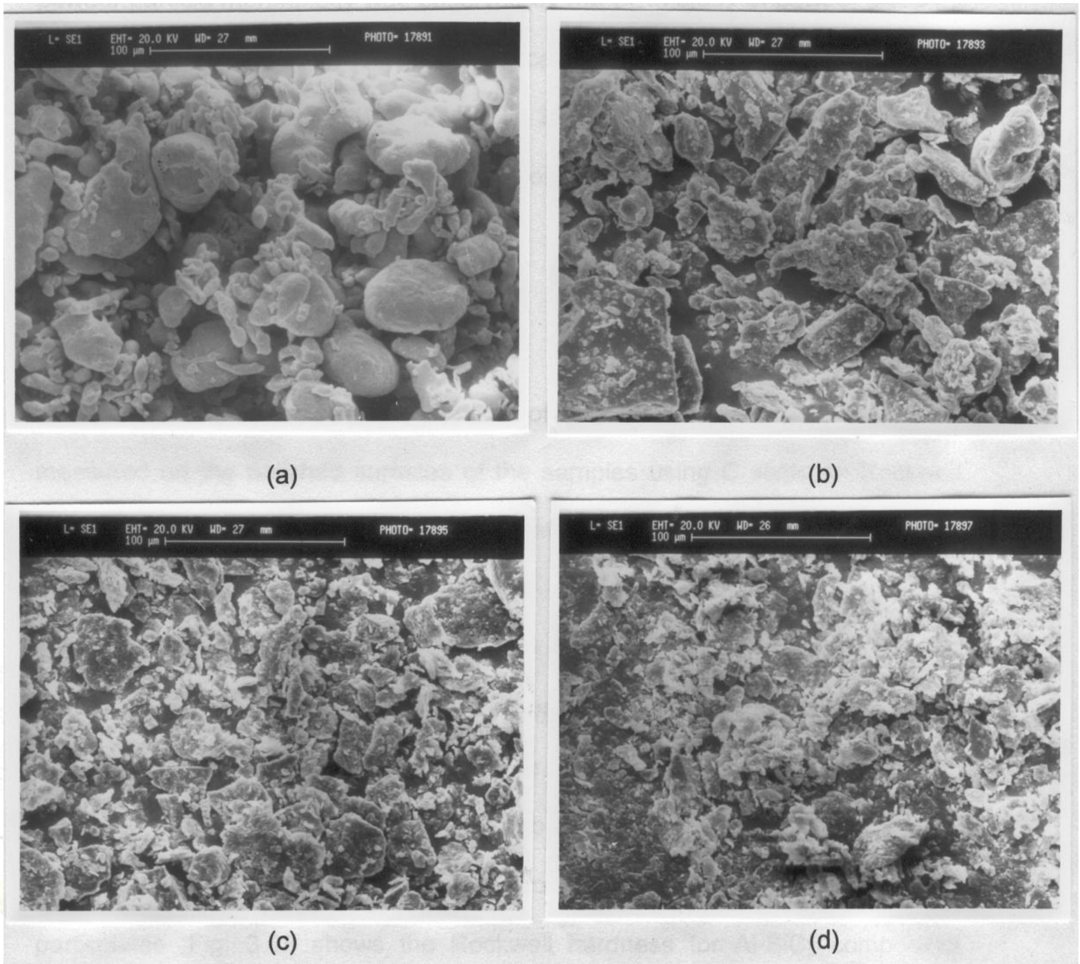

Fig. 6 Scanning electron micrographs of the Al powders with 30 weight % of SiC particulates (a) before ball milling, irregular particles; (b) after 4 hours of ball milling, flat lamellaer structure; (c) after 8 hours of ball milling, cluster type structure and (d) after 12 hours of ball milling, equiaxed. (Mag. X400)

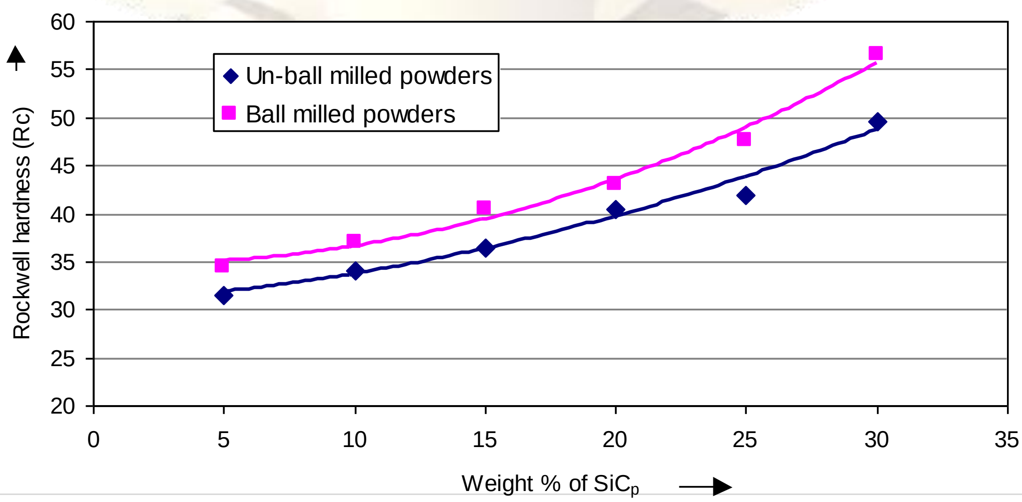

Fig. 7 Rockwell hardness of isostatically pressed Al-SiC_p composites prepared using un-ball milled and ball milled powders

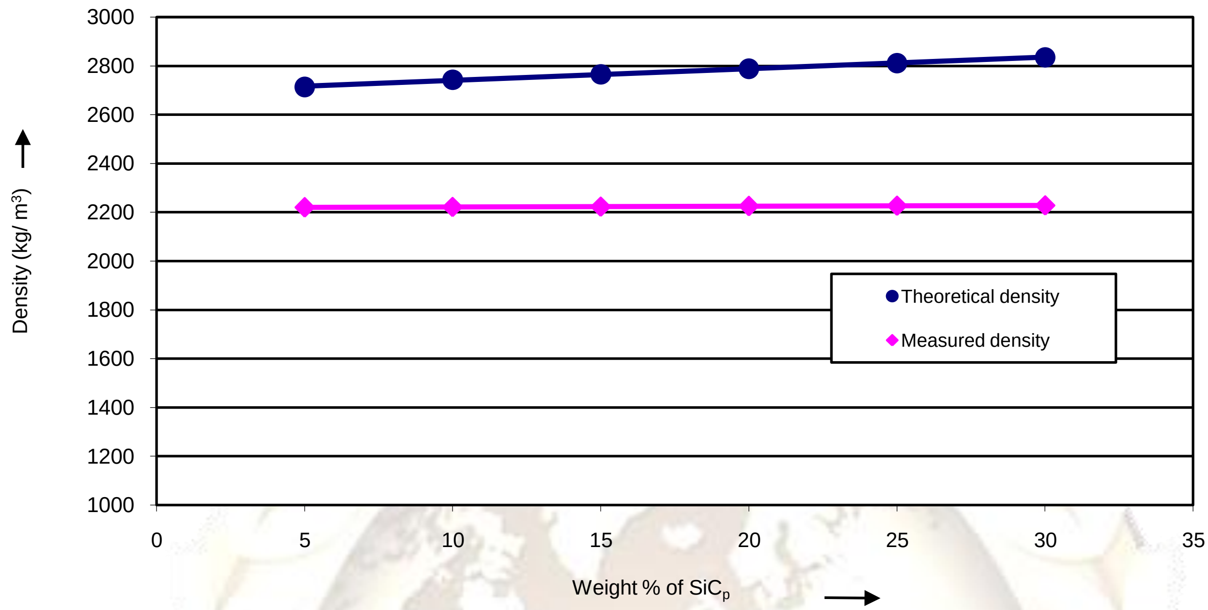

Fig. 9 Density of sintered Al-SiC_p composites

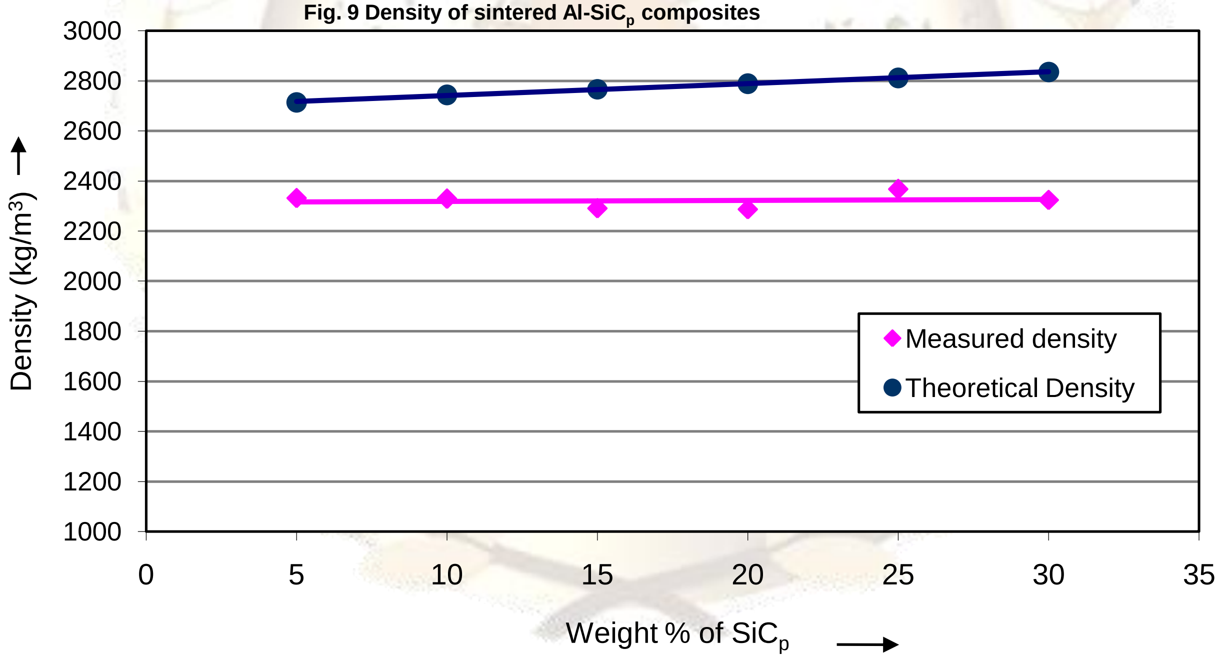

Fig. 8 Density of un-sintered Al-SiC_p composites

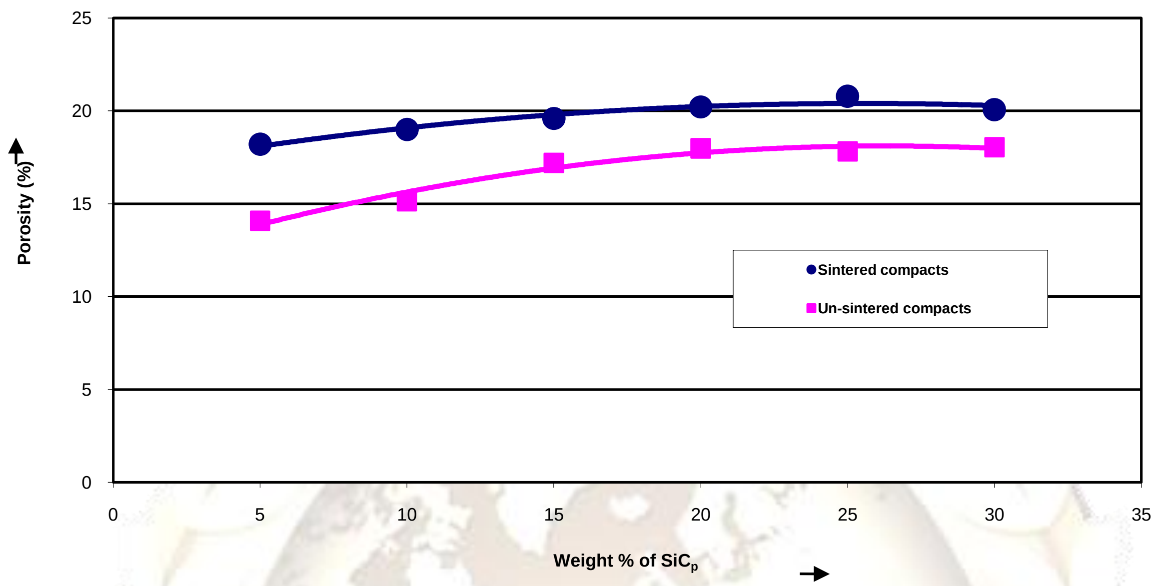

Fig. 10 Porosity of Al-SiC_p composites in green and sintered conditions

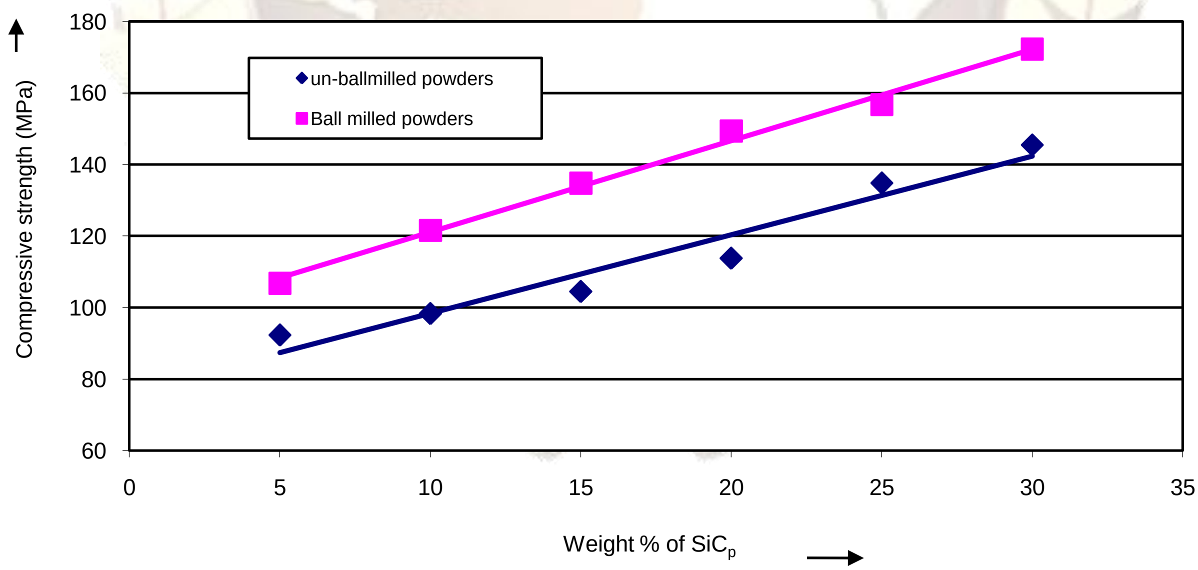

Fig. 11 Compressive strength of sintered Al-SiC_p composite samples prepared from un-ballmilled and ballmilled powders

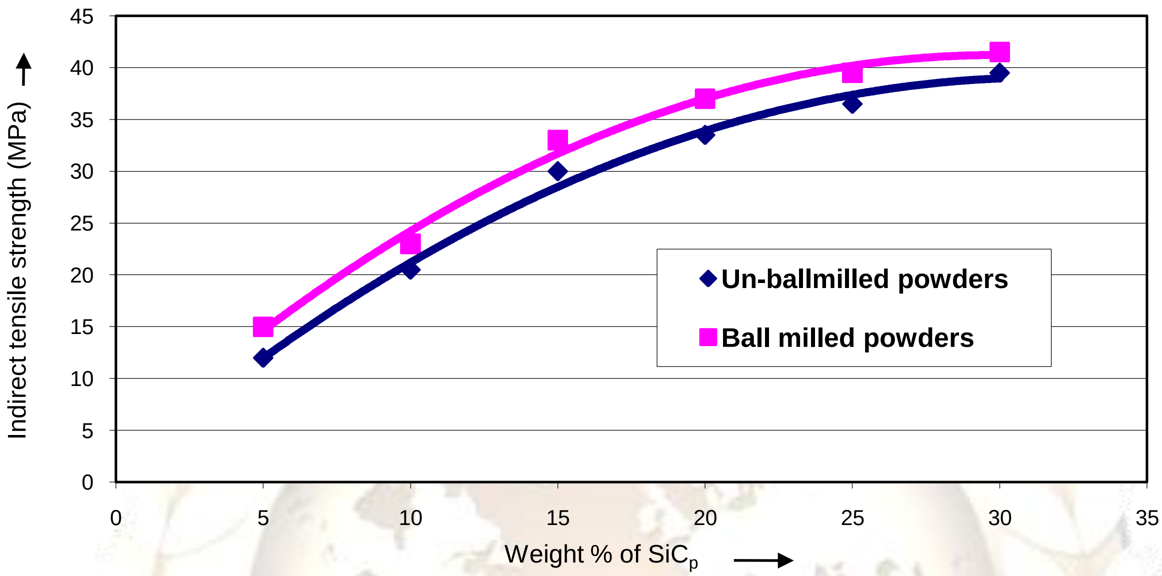

Fig. 12 Indirect tensile strength of PM Al-SiC_p composite fabricated using un-ballmilled and ballmilled powders

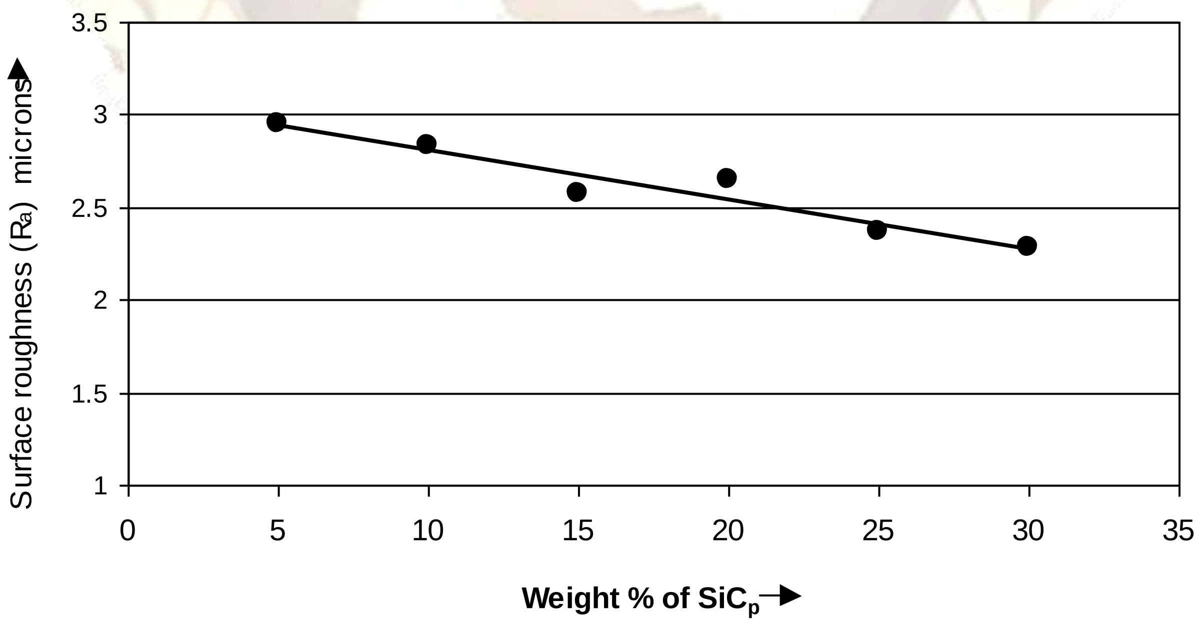

Fig. 13 Surface roughness of PM Al-SiC_p composites

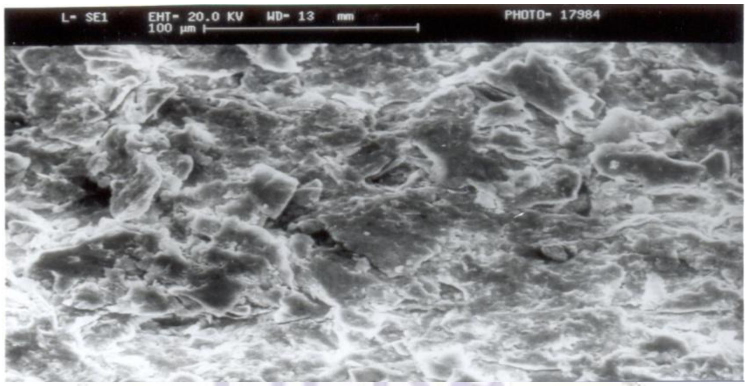

Fig. 14 Scanning electron micrograph of un-sintered Al-10 weight % SiC_p composite sample at magnification 340X

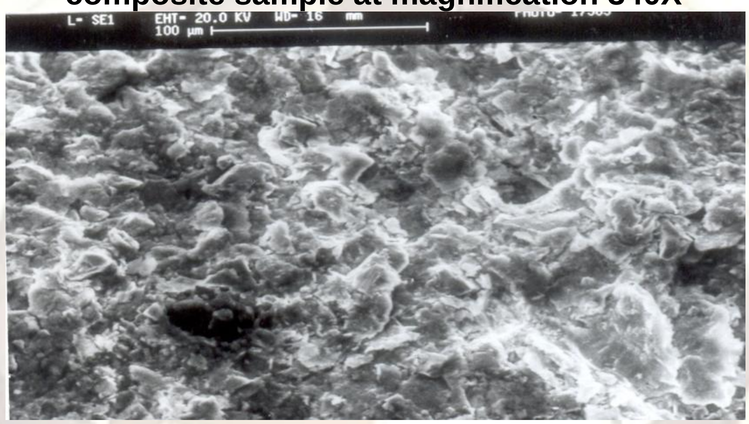

Fig. 15 Scanning electron micrograph of un-sintered Al-20 weight % SiC_p composite sample at magnification 340X

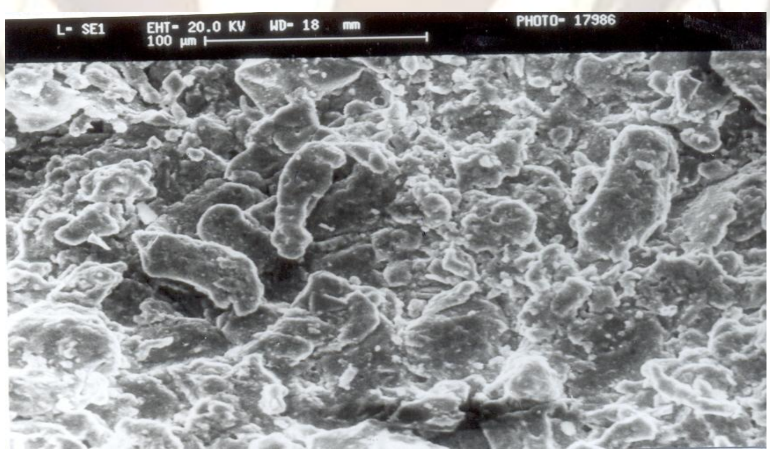

Fig. 16 Scanning electron micrograph of un-sintered Al-30 weight % SiC_p composite sample at magnification 340X

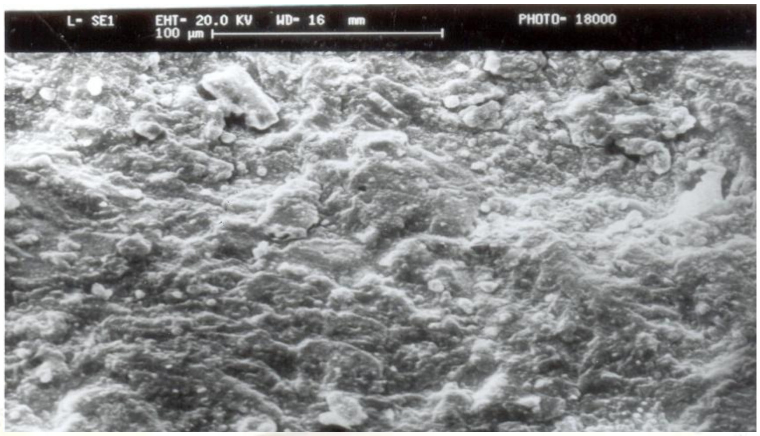

Fig. 17 Scanning electron micrograph of the vacuum sintered Al-10 weight % SiC_p composite sample at magnification 360X

Fig. 18 Scanning electron micrograph of the vacuum sintered Al-20 weight % SiC_p composite sample at magnification 600X

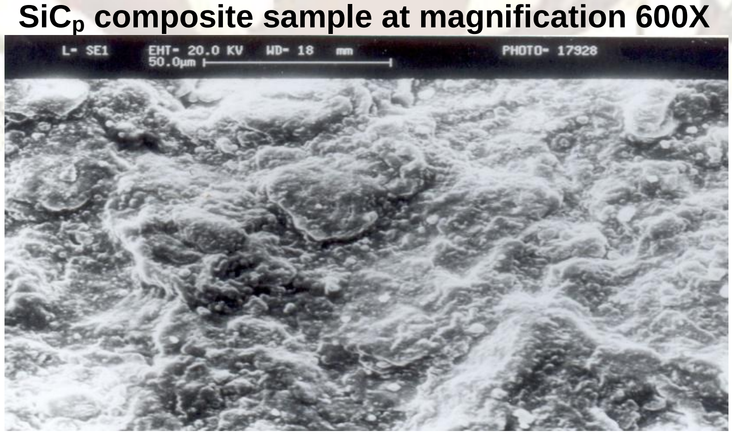

Fig. 19 Scanning electron micrograph of the vacuum sintered Al-30 weight % SiC_p composite sample at magnification 600X.

Table 1 Parameters used during horizontal ball milling of Al and SiC particles

S. No.	Parameters	Values
1.	Speed of ball mill	78 rpm
2.	Ball diameter and their volume percentage	9 mm (50 %), 10.5 mm (50 %)
3.	Weight of powder charge	0.5 Kg
4.	Weight of the steel balls	5 Kg
5.	Percentage filling of ball mill	30 % (by volume)
6.	Total duration of milling	12 hours