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Effect of Heat Treatment on Mechanical Behavior and Structural Response of Al-Si Composite

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Abstract

The present work deals with Al-Si Composite developed by reinforcing 10 wt% SiC particles in the Al matrix. The effect of heat treatment has been studied on the mechanical properties of the composites. The mechanical properties such as tensile strength, 0.2% proof stress, hardness and impact strength of the composites in as cast and heat treated condition were studied in order to achieve the maximum properties. Microstructural examination of the composite in as cast and heat treated condition was carried out paying special emphasis to the distribution of SiC particle in Al matrix and interface bonding between SiC and Al matrix. Fracture surface study was also done to see the type of fracture occurring in the tensile test. It is observed that there is a substantial improvement in the mechanical properties of the composite due to heat treatment as compared to the as cast composite. The microstructural study of the cast composite shows aluminum dendrites with dendretic arm spacing in the range of 25 microns. The eutectic silicon solidifies in the inter-dendretic region and around the dendrites. On heat treatment the plate shaped eutectic silicon is fragmentated into spherical shape and there is a good interface bonding between the SiC particle and Al matrix. The tensile fracture study shows inter-granular fracture and SiC particle embedded on the surface. By careful observation of fracture surface it is depicted that particle decohesion and fracture both are occurring simultaneously in tensile fracture. In some instances the segregation of particle in aluminum matrix is also observed.

Key words: Al-Si Composites; AMC; heat treatment; tensile strength; 0.2% proof stress; hardness; impact strength; tensile fracture.

INTRODUCTION

In the recent technological innovations there is a growing awareness to synthesize Al-alloy composites with an aim to achieve a combination of properties which are not normally available in any one of the constituent phases. Composite materials can be selected to give combination of properties such as stiffness, strength, high temperature performance, corrosion resistance, hardness, conductivity etc. Aluminum matrix composites are finding wide range of applications in automobile, aerospace, defense and general engineering sectors, because of their higher specific strength and stiffness, good wear and seizure resistance and improved high temperature properties as compared to the base alloy. The strength and wear resistance of AMCs were found to be comparable to cast irons. AMCs are lighter than cast iron or steels and the former one have better specific strength and wear resistance as compared to the later one. Thus, considerable efforts are being made to replace these components with AMCs. It will not only improve the life of components but also reduce the weight and improve the fuel efficiency [1-4]. Addition of second phase particles to aluminium based alloys has emerged as a potential technique for the development of (aluminium-alloy) composite materials especially suitable for tribological, structural and elevated temperature applications. In this case, usually one set of properties is improved at the cost of the other and hence a compromise has to be made in the case of composite materials in this regard. [5-9]

In Al-Si alloy the eutectic is formed between aluminium solid solution containing just over 1% silicon and virtually pure silicon as second phase. The eutectic composition has been a matter of debate but it is now generally accepted as being close to Al-12.7% Si. Slow solidification of a pure Al-Si alloy produces a very course microstructure in which the eutectic comprises large plates and needles of silicon in a continuous aluminium matrix. The eutectic itself is composed of individual cells within which the silicon particles appear to be inter-connected. Alloys having this course eutectic exhibit low ductility because of the brittle nature of the large silicon plates. Rapid cooling, as occurs during permanent mould casting, greatly refines the microstructure and the silicon phase assumes to be of fibrous form with the result that both ductility and tensile strength are much improved. [10-16]

Al-Si alloys, up to the eutectic composition retain good levels of ductility, providing the iron content is controlled to minimize formation of large, brittle plates of the compound such as Al-Fe-Si. In this regard additions of manganese have been found to be beneficial. The mechanical properties of eutectic alloys are related to the size and morphology of the discontinuous phase being better when granulated than when flake-like and so considerable effort is being made to develop effective methods of discontinuous phase granulation. Great improvements have been achieved in cast iron by the spheroidization of graphite during solidification, but it has not proved possible to spherodize all the discontinuous phase during the solidification of Al-Si alloys.

It has been reported [1-8] that D-type graphite in cast iron and eutectic silicon in Al-Si alloys are granulated during heat treatment, and the properties of the related alloys have consequently improved substantially. Preliminary work [9] showed that the granulation of eutectic silicon in Al-Si alloys, and hence the ductility of the alloys,

was improved with increasing solution time. This suggests that it is possible to granulate the discontinuous phase in eutectic alloys through heat treatment, to improve further properties of the alloys.

The granulation of eutectic silicon in Al-Si alloys shows that the factors affecting the granulation of discontinuous phase depend on the as-cast microstructure and the heat treatment condition. Granulation can therefore be controlled by means of appropriate solidification processing and heat treatment. By taking measurements during solidification, such as the modification of Al-Si alloys with sodium to get the optimum morphology of discontinuous phase for easy fragmentation, and then carrying out the annealing treatment at as high a temperature as possible, the optimum spheroidized discontinuous phase can be achieved. [16-22]

In the present investigation AMC has been synthesized through Stir Casting technique using Al-Si (ADC 12) alloy as matrix alloys and SiC particle as reinforcement [12-16]. The size range of SiC lies between 40 - 80 microns and the amount of SiC used is 10wt%, the effect of heat treatment has been studied on the mechanical properties of the composites with an aim to get maximum properties.

2. EXPERIMENTAL WORK

2.1 Material

Aluminium-Silicon alloy (ADC12) is selected as matrix alloys for synthesis of AMCs. The chemical compositions of aluminium alloy was analyzed using glow discharge spectrometer (Model: GDS 500A, Leco) which is shown in the Table 1.

Table 1 Chemical composition of ADC 12 alloy

Element	Si	Mn	Mg	Cu	Fe	Ni	Al
ADC-12	1 0.29	0.12	0.47	1.98	0.75	0 .80	Rest

2.2 Reinforcement

The SiC particles, used as reinforcement in the aluminium matrix for synthesizing the composites, were obtained from M/s. Grindwell Norton ltd., Bangalore, India. The particles are sieved using standard sieving practice through different grades of sieves in a vibratory sieving machine, with an aim to get particles within the size range of 40-80 µm. The various properties of SiC particles are shown in table 2.

Table 2 Properties of SiC reinforcement

Particle	Elastic Modulus GPa	Density gm/cc	Coefficient of Thermal expansion K^{-1}	Specific Heat Kg^{-1} K^{-1}	Thermal Conductivity Wm^{-1} K^{-1}	Poisons Ratio
SiC	420-450	3.2	$4.3x10^{-6}$	840	10-40 at 1100/^{o}C	0.17

2.3 Heat Treatment

The specimens of Al-Si-SiC composite were heat treated in a programmable furnace to compare the properties in aged and as cast condition. There were three stages involved in the heat treatment.

Solutionising: The specimens were heated to a temperature of 490 ± 5 ^{o}C for 8 hours until the alloy solute elements are completely dissolved in the Al solid solution.

Quenching: the solution treated specimens were rapidly cooled into oil to prevent the precipitation of the solute elements and to obtain a super saturated solid solution and

Artificial aging: To improve the strength and hardness of the material the specimens were reheated to 135 ^{o}C/150 ^{o}C/175 ^{o}C/200 ^{o}C/240 ^{o}C for 6 hours each and then allowed to cool in the still air.

2.4 Composite Preparation

Melting of the ADC-12 alloy was carried out in graphite crucibles using a oil-fired furnace. When the alloy reaches semi pasty stage the surface is covered with a fluxing agent (coverall 11). About 70 g of flux is added to 10 kg of the molten alloy. The dross is removed from the surface of the melt using a refractory skimmer. The dissolved gases were removed by purging dry nitrogen gas into the melt for 5 minutes. After degassing the surface is again cleaned and the temperature of the melt is increased to 660^{o}C to take care of the minimum gas absorption during bubbling. The composite was prepared by the stir casting method developed and patented by AMPRI, formerly RRL, (CSIR) Bhopal. The method comprises of dispersing the second phase particles (α-SiC) on to the vortex of the molten alloy. The vortex was created with the help of a rotating mechanical stirrer. The speed of rotation was maintained around 500 to 600 rpm. The SiC particles 10 wt% of the desired size range (40 to 80 µm) were heated to 1000^{o}C in a graphite crucible in a muffle furnace. The SiC particles were introduced into the melt by churning action of the stirrer. To obtain a uniform pattern of stirring a baffle is used in the melt along the sides of the crucible. It produces great amount of turbulence in the flow pattern and induces better mixing of the SiC particles in the aluminium alloy melt. After the complete addition of SiC particles, the speed of the stirrer is brought down to 200-400 rpm and the stirring continued for 3-5 minutes. The stirrer is then withdrawn from the melt. The composite melt was then solidified into a cast iron permanent die in the form of fingers (10mm/20mm diameter and 200mm long) for preparation of specimens for evaluation of different mechanical properties.

2.5 Specimen Preparation

The specimens for various mechanical tests were prepared in accordance with the BIS code mentioned in table 3.

Table 3

TEST	Code	Size	No of specimens
Tensile	IS 1608	10 mm Ø	6 x 2
Charpy Impact	IS 1757	55x10x10 V notch 2mm	6 x 3
Vickers Hardness	IS 1501	20x20 mm	6 x 1

2.6 Mechanical Testing:
The specimens in as cast and heat treated condition were then tested for various tests. Mechanical properties such as UTS, and 0.2% proof stress, were evaluated on computerized Universal testing machine (INSTRON M/c, Model 5586) 300KN Capacity at a strain rate of 0.5 mm/min at Metallurgical services Lab, Mumbai, hardness and impact were evaluated on Optical Vickers hardness tester (FIE make, model VM 50) and Charpy Impact Tester (FIE make, model FIT 30) at MANIT, Bhopal.

2.7 Microstructural Examination:
Samples for Microstructural characterization were polished according to standard metallographic procedures. Various steps involved during the process were polishing the specimens with different grade of emery papers and then finally with fine polishing alumina using polishing cloths. The samples were etched with Keller's reagent and observed in a Scanning Electron Microscope (JEOL make, Model JSM-6390)

2.8 Fracture Surface Study
For fracture surface study the fractured tensile specimens were cut, cleaned with acetone and fixed on a copper holder using double sided copper tape and coated with platinum, before keeping under observation through a Scanning Electron Microscope.

3. RESULTS AND DISCUSSION

3.1 Mechanical properties

Fig (3.1) shows the variation of tensile strength of the composites with aging temperature. It is noted from the figure that the tensile strength value was 126.4 MPa in as cast condition which increases to 149.0 MPa at 150 C aging condition. This value further increases to 172.5 MPa at 175 C aging temperature. On further increase in aging temperature the tensile strength values decreases. The values were 160.2 MPa and 120.8 MPa at 200 C and 240 C aging temperature respectively. So it is observed here that there is an improvement of around 36% in the tensile strength at peak age temperature as compared to as cast condition. It is understood that at peak age temperature there are every possibility of formation of coherent precipitates. The lattice coherency between the matrix and the precipitates exist upto a certain temperature beyond which the lattice vibration form the non coherent precipitates with the matrix. It is well known fact that during the aging process after the

solutionising treatment the fine precipitates are formed on the soft aluminium matrix which results in enhancing the properties. It is also noted that aging at higher temperature in turn have coarsening effect of the precipitates which results into poor mechanical properties.

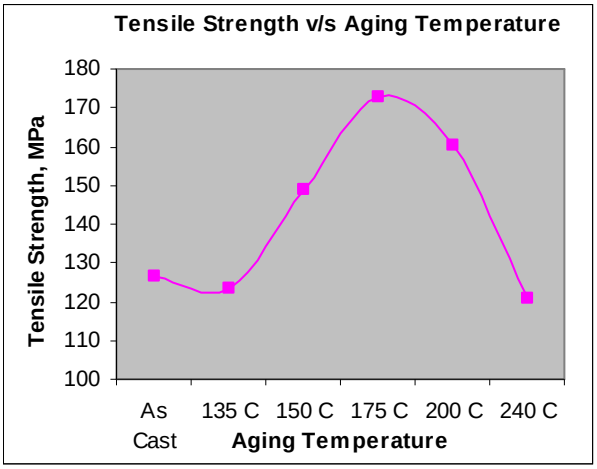

Fig 3.1

Fig (3.2) shows the variation of 0.2% proof stress with aging temperature. It shows that the 0.2% proof stress increases gradually upto 200 C aging temperature. The value of 0.2% proof stress in as cast condition was 99.9 MPa which increases gradually to 155.5 MPa at 200 C aging temperature and decreases to 95.6 MPa at 240 C there by showing an improvement of nearly 56% due to heat treatment.

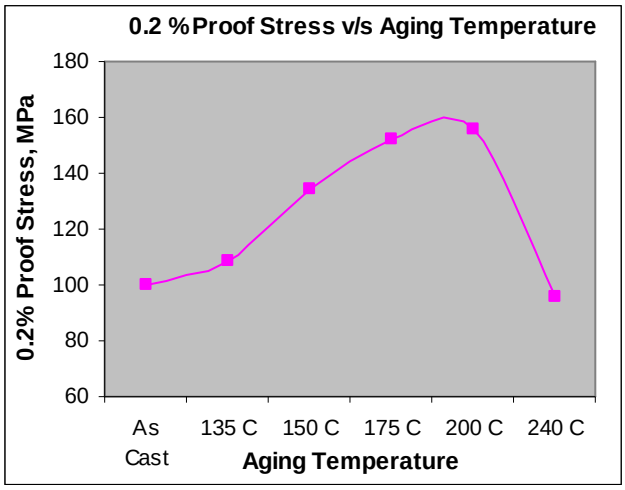

Fig 3.2

Fig (3.3) shows the variation of hardness of the composites at different aging temperature. It is noted from the figure that hardness of the composite increases with increase in aging temperature upto a certain temperature and decreases on further increases in temperature. The value of hardness being 100.7 Hv in as cast condition which increases to 128.3 Hv at 150 C. The value of hardness being highest at 175 C which is 138.6 Hv. On further increase in aging temperature the hardness values decreases. The values were 137 Hv and 100.2 Hv at 200 C and 240 C aging temperature respectively. There is an improvement of around 38% in the hardness due to heat treatment. The reason for improvement in hardness value is explained earlier, also a good interface between the SiC and aluminium matrix always give rise to higher hardness value.

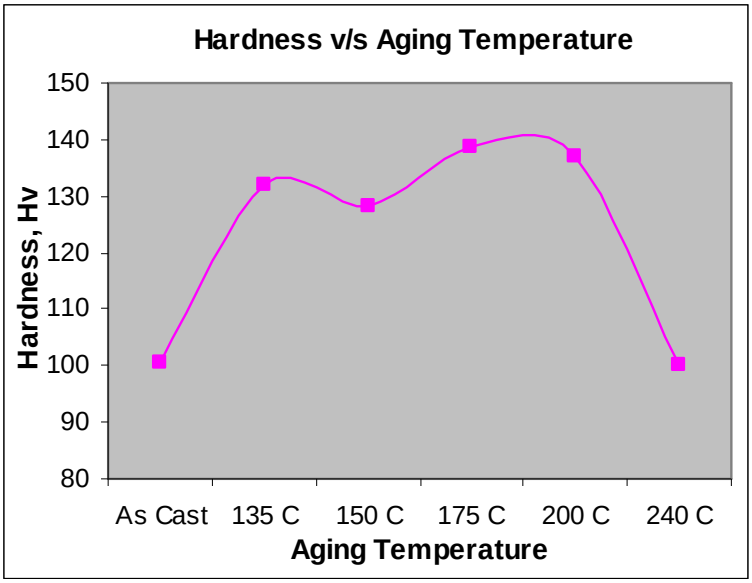

Fig 3.3

Fig (3.4) shows the variation of impact strength of the composites with aging temperature. It is observed from the figure that the impact strength for as cast specimen was 0.116 Kgm which increases to 0.15 Kgm at 150 C and 240 C aging condition. The impact strength values at 175 C and 200 C were 0.133 Kgm which indicate that impact strength increases initially with aging temperature and thereafter it remains almost constant with increase in aging temperature.

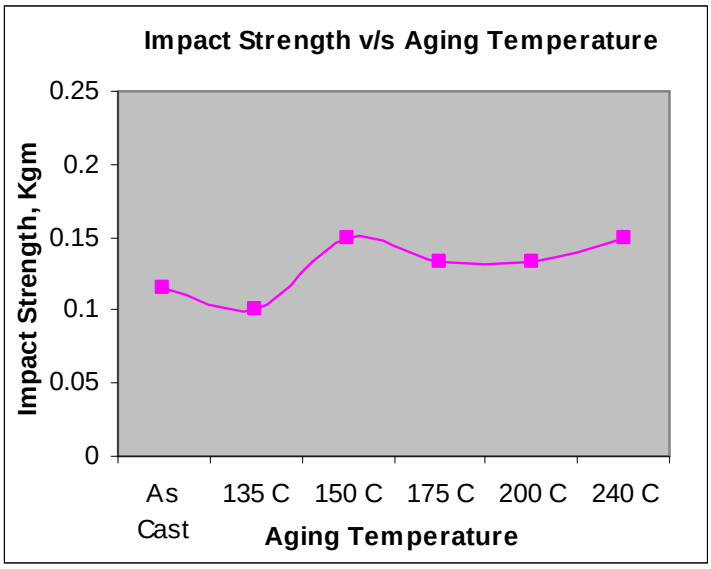

Fig 3.4

3.2 Microstructural Examination

The micro structure of the composite in as cast condition shows secondary aluminum dendrites and eutectic silicon in the dendretic spacing and around the dendrites and SiC particles are seen distributed in the matrix (fig 3.5). It is to be noted that the SiC particle feature in the range of 40-50 micron are usually pushed by the aluminum dendrites into the last freezing eutectic liquid. Usually the spacing between the dendrites is in the range of 4-5 microns hence the chance of entrapment of SiC particle in the interdentretic region does not arise. In fact the SiC particles are pushed by the Aluminum dendrites and the particles are found along with the eutectic liquid.

A higher magnification micrograph shows the entrapment of SiC particles in the last freezing eutectic liquid (fig 3.6). This clearly shows the eutectic silicon at the interphase of SiC particle and primary aluminum. (Fig 3.7) shows the faceted or plate shaped eutectic silicon at the interphase of SiC particle and aluminum matrix.

(Fig 3.8) shows heat treated (aged at 175 C) aluminum composite (ADC 12 -10 % SiC), it shows distribution of SiC particles in the heat treated aluminum silicon matrix. A higher magnification micrograph (fig 3.9) shows the interphase of SiC particles and aluminum matrix. The spherical shaped eutectic silicon can be seen at the interphase. (Fig 3.10) clearly shows a higher magnification micrograph depicting the interphase of SiC particles and heat treated ADC12 alloy matrix. The spherical shaped eutectic silicon can be seen at the interphase.

(Fig 3.11) shows heat treated (aged at 240 C) ADC 12 -10% SiC composite, it is noted that at high temperature aging, in some instances, cracking of the matrix is observed this may be due to the expansion of gases which entrap into the coarsening matrix or coarsening of the phases. Both of these phenomenons will lead to generate internal stresses which in turn results into cracking of the matrix (fig 3.12).

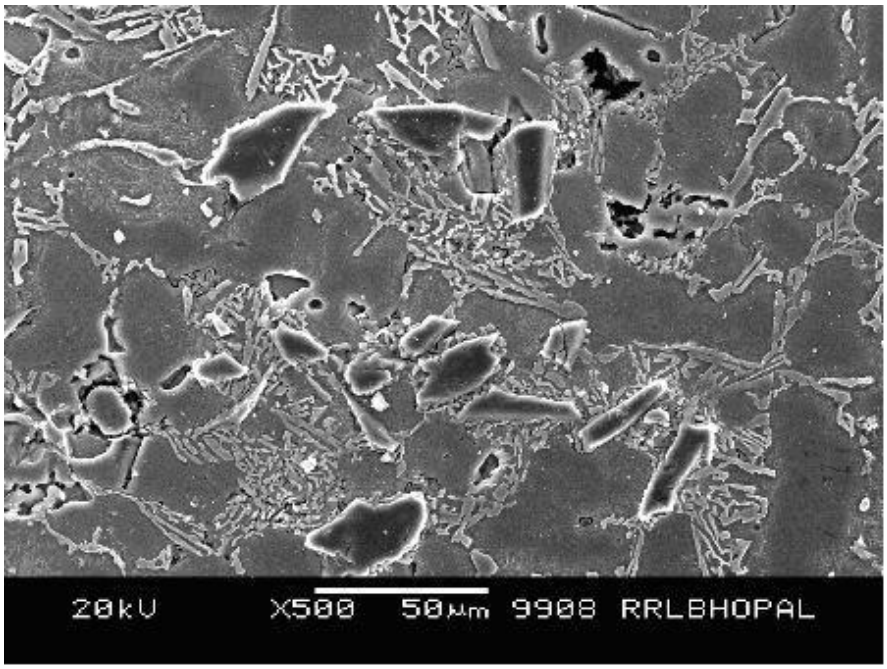

Fig 3.5 SEM micrograph showing SiC particles distribution in the matrix also the secondary aluminum dendrites and eutectic silicon in the dendretic spacing and around the dendrites

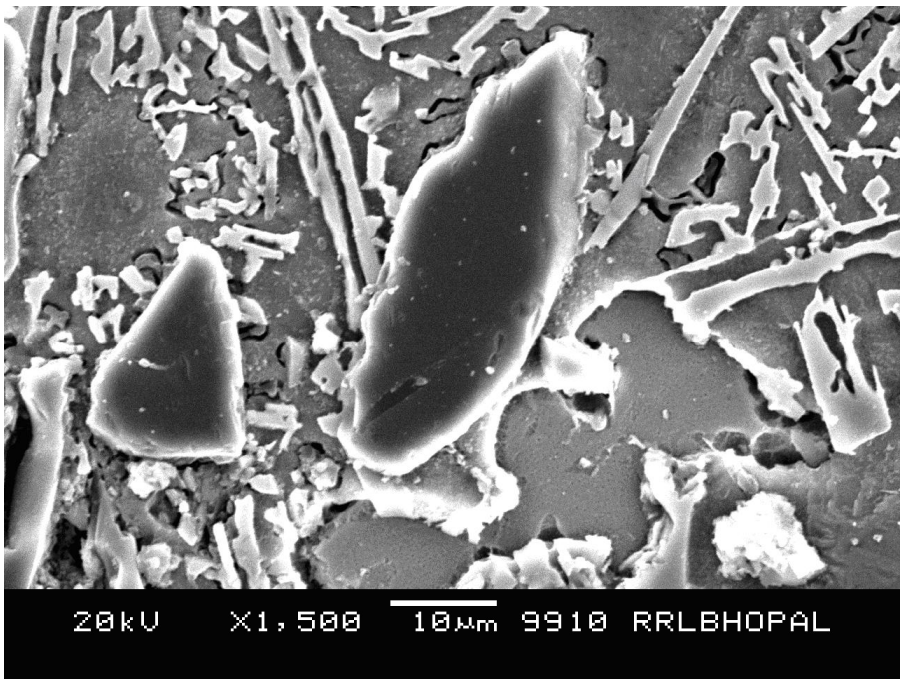

Fig 3.6 SEM micrograph showing eutectic silicon at the interphase of SiC particle and primary aluminum

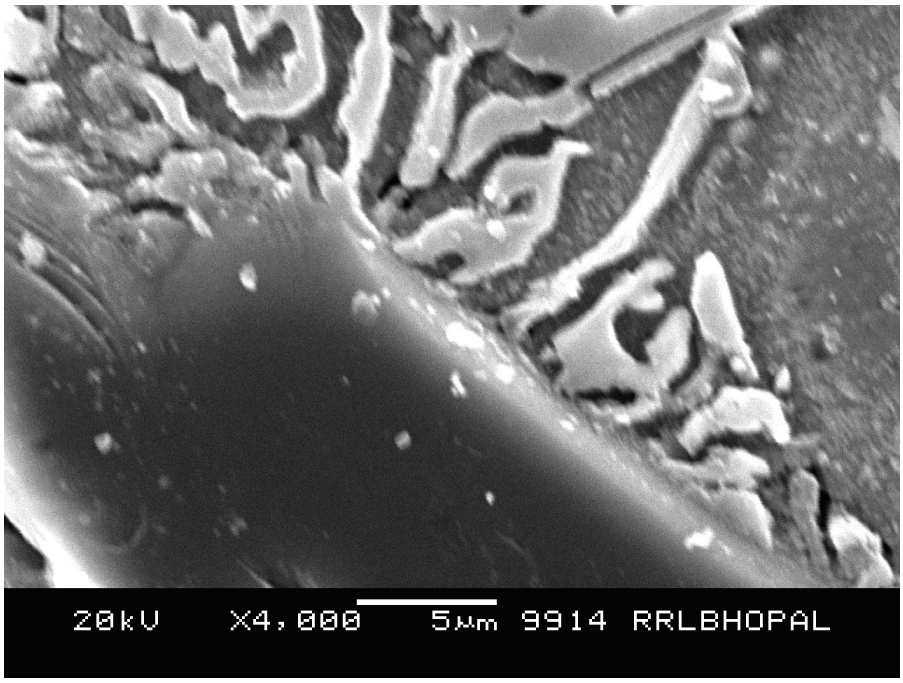

Fig 3.7 A higher magnification micrograph showing plate shaped eutectic silicon at the interphase of SiC particle and aluminum matrix

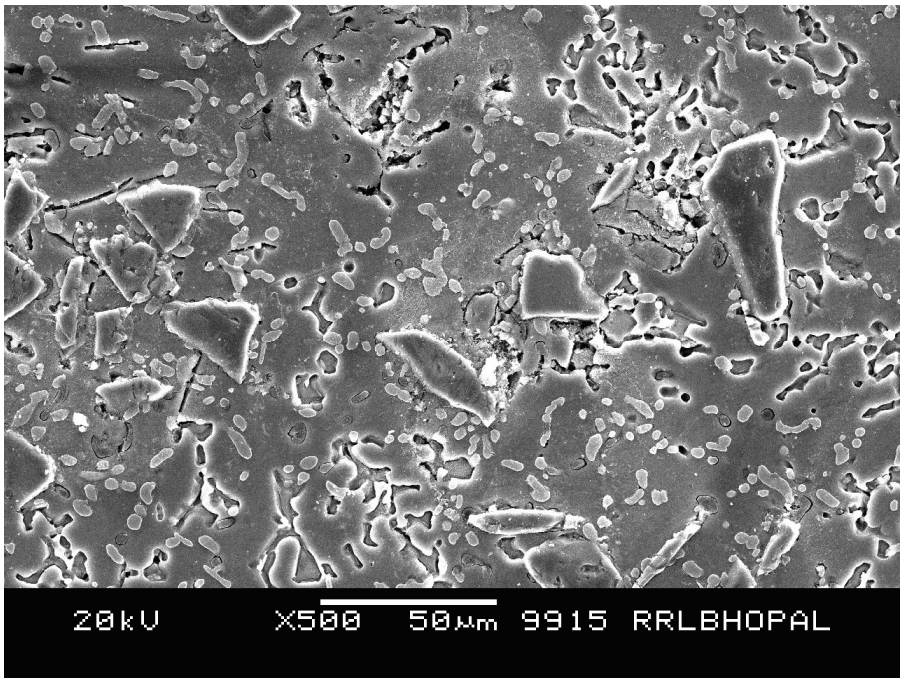

Fig 3.8 SEM micrograph showing distribution of SiC particles in heat treated (aged at 175 C) aluminum composite and spherical shaped eutectic silicon

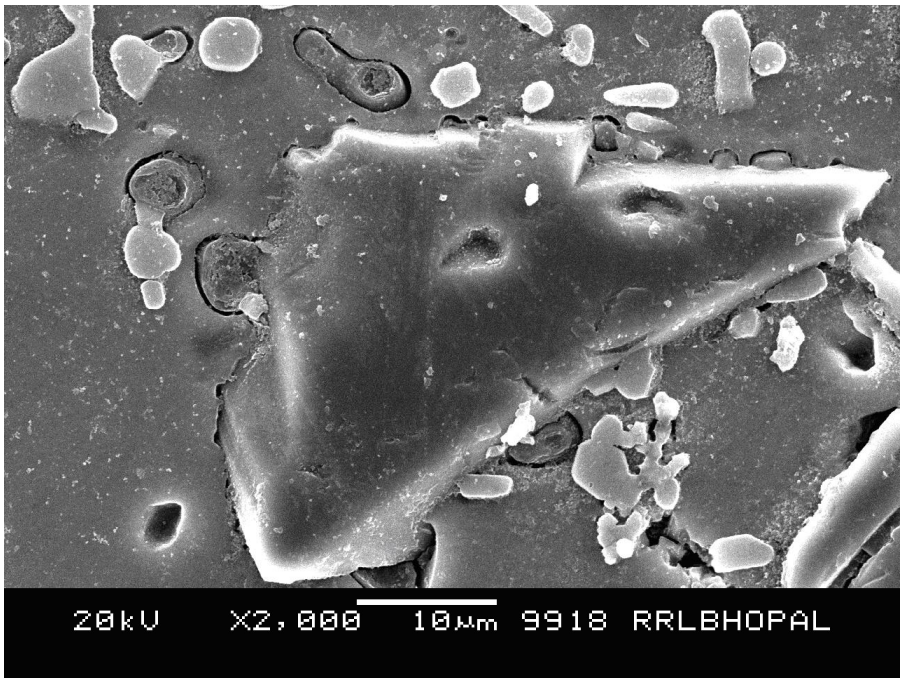

Fig 3.9 SEM micrograph showing the interphase of SiC particles and aluminum matrix. The spherical shaped eutectic silicon can also be seen at the interphase

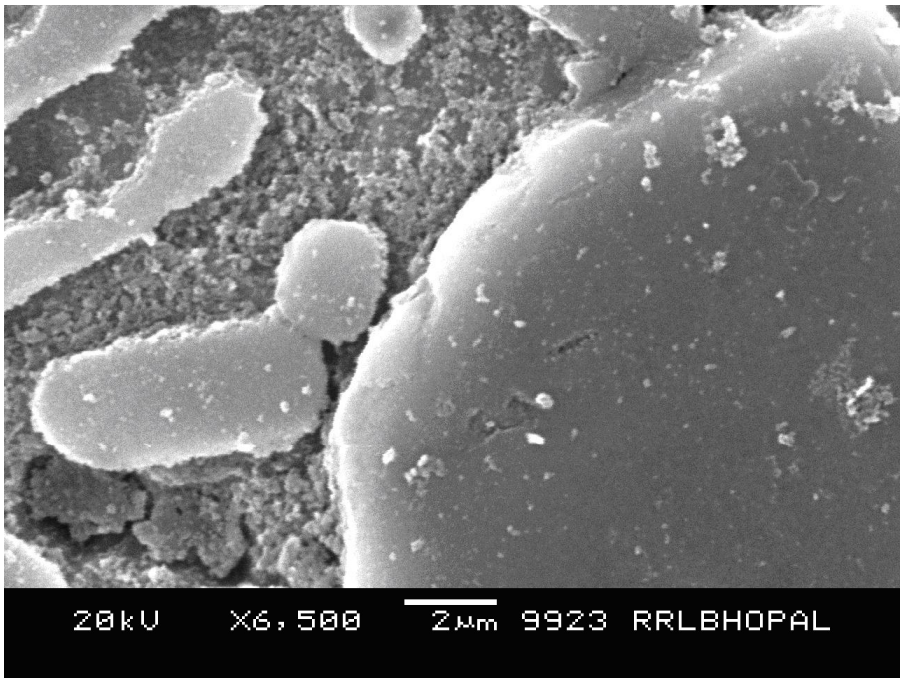

Fig 3.10 A higher magnification micrograph showing interphase of SiC particles and heat treated composite.

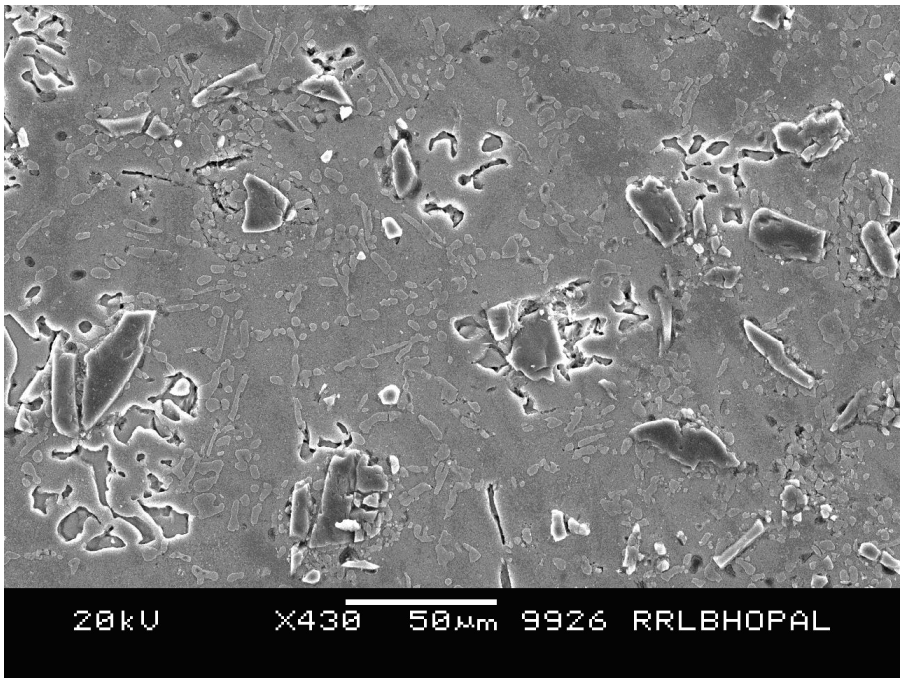

Fig 3.11 SEM micrograph of heat treated (aged at 240 C) composite showing cracking of the matrix

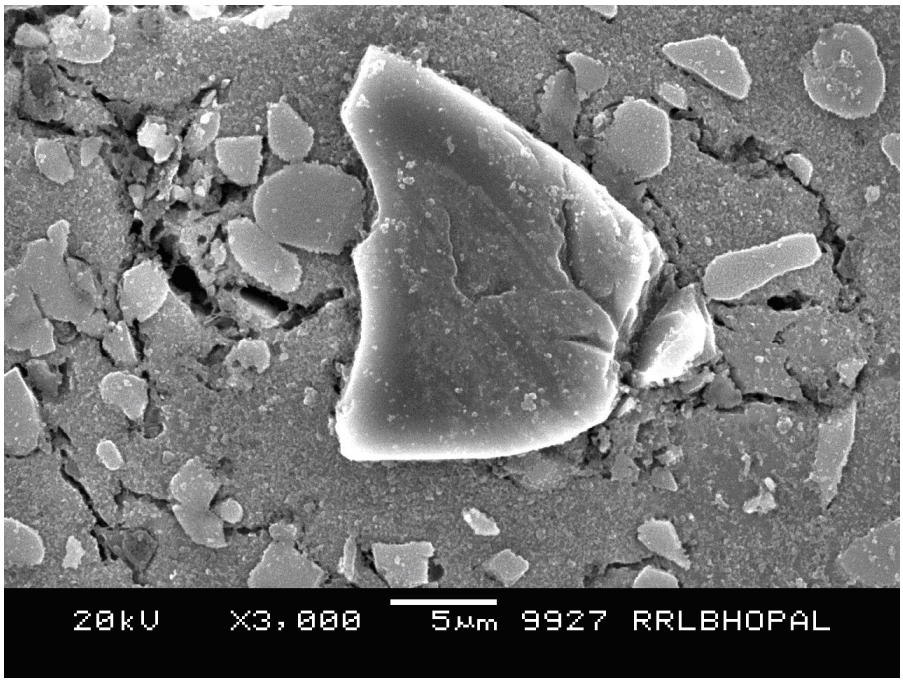

Fig 3.12 A higher magnification micrograph of heat treated (aged at 240 C) composite showing cracking of the matrix

Fracture Surface Study

The fracture surface study was done to ascertain the type of fracture taking place in the composite. The study reveals the inter-granular fracture and SiC particle embedded on the surface. In case of composites the fracture may take place by decohesion of particle matrix interphase or it may be due to particle fracture. By careful observation of fracture surface it is depicted that particle decohesion and fracture both are occurring simultaneously in tensile fracture (fig 3.13). In some instances the segregation of particle in aluminum matrix is observed which is seen in the micrograph (fig 3.14). Heat treatment of the composite shows similar fracture surface as that of cast one. (Fig 3.15) shows a typical fractograph of ADC12 – 10 % SiC composite in heat treated condition (aged at 175 C).

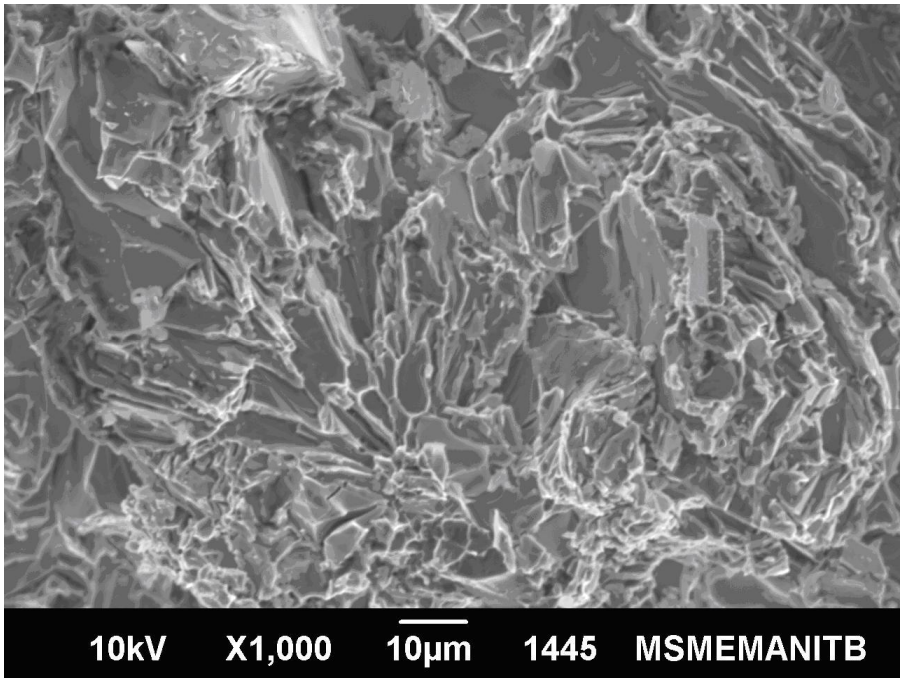

Fig 3.13 SEM micrograph showing particle decohesion and fracture of particle

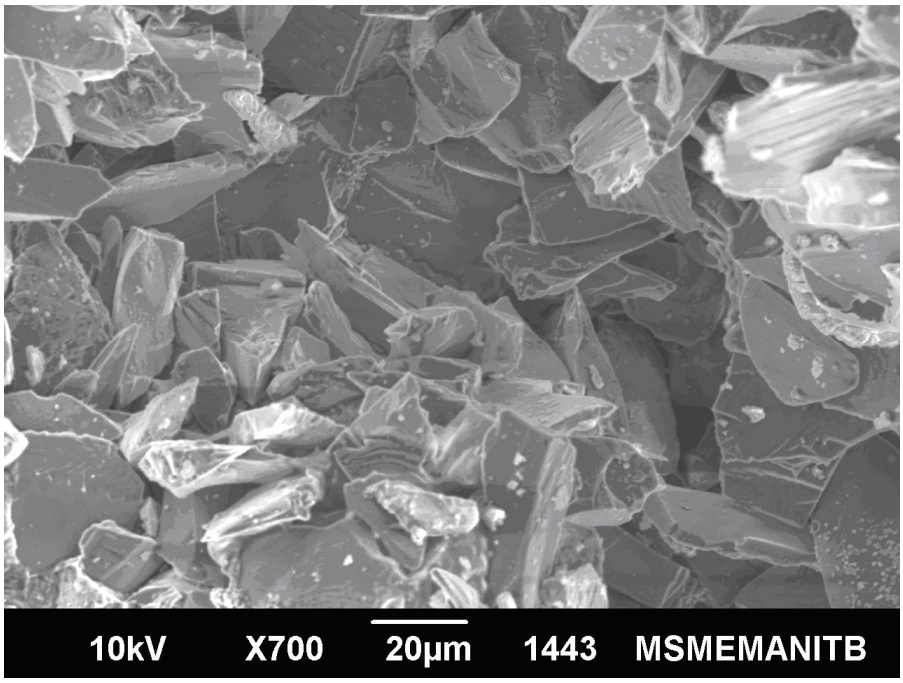

Fig 3.14 SEM micrograph showing segregation of particle in aluminum matrix

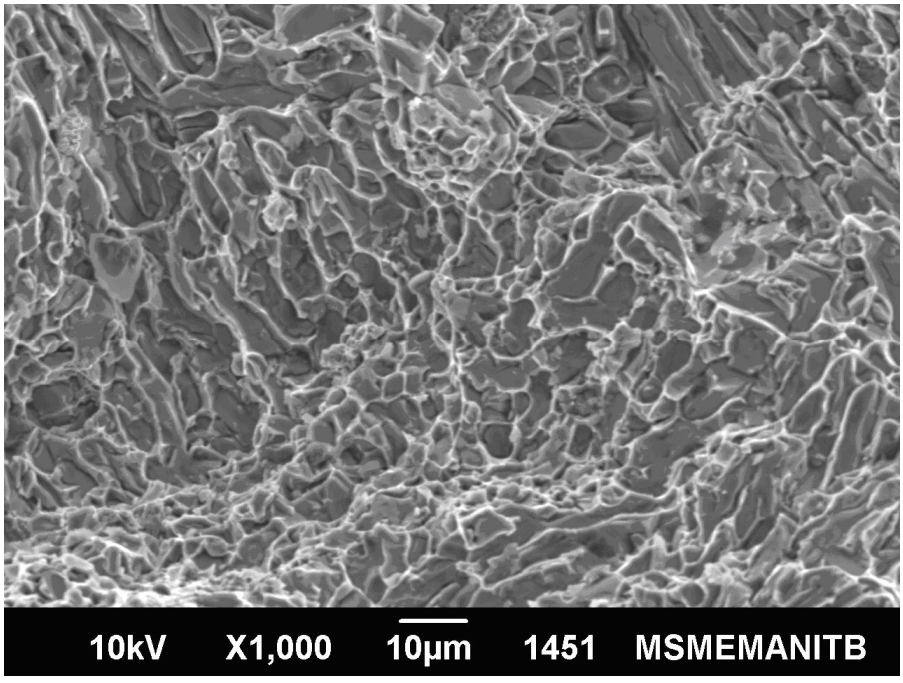

Fig 3.15 SEM micrograph showing fracture of composite in heat treated condition (aged at 175 C)

4. CONCLUSIONS:

1. There is an improvement of around 36% in the tensile strength at peak age temperature (aged at 175 C) as compared to as cast composite because of formation of coherent precipitates.
2. There is an improvement of nearly 56% in 0.2% proof stress value due to heat treatment.
3. There is an improvement of around 38% in the hardness due to heat treatment. The reason being a good interface between the SiC and aluminium matrix which always give rise to higher hardness value.
4. The impact strength increases initially with aging temperature and thereafter it remains almost constant with increase in aging temperature.
5. The micro structure of the composite in as cast condition shows secondary aluminum dendrites and eutectic silicon in the dendretic spacing and around the dendrites. The SiC particles are seen distributed in the matrix. The microstructure also shows faceted or plate shaped eutectic silicon at the interphase of SiC particle and aluminum matrix. In case of heat treated composite the eutectic silicon has become spherical shaped. At high temperature aging, in some instances, cracking of the matrix is observed.
6. Fracture study reveals that particle decohesion and fracture both are occurring simultaneously. The composite is fracturing by brittle fracture.

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