Synthesis and Characterization of Al/SiC Composite Made by Stir Casting Method

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Abstract

Ceramics contain a distinctive property of completely absence of slip planes and have least probability of deforming by the application of force. Among these ceramics, the silicon carbide occupies a competent place to be used as a reinforcing agent for aluminum or its alloys. It has the density close to aluminum and is best for making composite having good strength and good heat conductivity. Stir casting has been used to synthesize Al/SiC MMCs by reinforcing silicon carbide particles into aluminum matrix. The reason for using stir casting is to develop technology for the development of MMCs at affordable cost. The selection of SiC as reinforcement and Al as matrix is because of their easy availability. The practical data acquired, analyzed and optimized will be interpreted in the light of information available in the literature and be shared with the relevant industries. The present work was mainly carried out to characterize the SiC/Al composite which was produced by reinforcing the various proportions of SiC (5, 10, 15, 25 and 30%) in aluminum matrix using stir casting technique. Mechanical properties of test specimens made from stir-casted Aluminum-Silicon Carbide composites have been studied using metallographic and mechanical testing techniques. It was observed that as the volume fraction of SiC in the composite is gradually increased, the hardness and toughness increase. However, beyond a level of 25-30 percent SiC, the results are not very consistent, and depend largely on the uniformity of distribution of SiC in the aluminum matrix

Key Words: stir casting, uniform distribution, toughness, matrix

1. Introduction

Metal Matrix Composites (MMCs) are manufactured by various methods such as casting, diffusion bonding and powder metallurgy. In case of continuous fiber composites, powder metallurgy techniques cannot be used because of difficulties in achieving correct alignment in fibers, although problems relating to connectivity and continuity also exist [1-3]. The other types of MMCs like discontinuous and particle reinforced can be made by the powder metallurgy; however, casting techniques may also be employed. The stir casting process is carried out by first liquefying the metal, then introducing the ceramic particles in the melt by different processes and at the end letting it to solidify on its own or by using controlled solidification mechanism. In this process of manufacturing the composites, the main emphasize is upon the wetting of the particles by the liquid metal otherwise there are potential areas which could lead to fatal deterioration of the material [4-6]. There are different ways to enhance the wetting of the particles which include the surface coating of the particles before their introduction into the liquid melt. In this way the coating not only minimizes the interfacial energy but also the chances of the chemical interaction between the particles are reduced [7,8]. Using of wetting agents could be another choice in this direction. The other factors which improve the wettability are high surface area of the particles, decreasing the surface tension of the alloy by heating at higher temperature and reduction of interfacial energy at the surface of the particles [9].

In stir casting process, the major difficulty is the settling of fine reinforcement particles during the formation of composite. This results in a non uniform distribution of the reinforcement, which affects mechanical and chemical (corrosion) properties [10,11]. The distribution of ceramic phase can be improved if matrix phase is in semi - solid condition. The greater thickness of the melt prevents the ceramic phase to settle down in the bottom of the pan [12-15]. The distribution of reinforcement is also achieved by temperature of the melt, the mechanical stirrer speed, way of stirring, the particles size and their density and surface area. The other variables may include design of the mold, proper gating system and temperature of mold before pouring.

The present work employed manual and mechanical stirring to achieve as much as possible uniform and homogenous distribution of reinforcing phase in aluminum matrix. There are tremendous advantages of MMCs over other materials because of improved properties of principal interest and weight saving [16]. MMCs are produced by various processes such as diffusion bonding, preform infiltration and powder metallurgy. The processes to produce MMCs are difficult to implement as compared to conventional low cost processes [17]. Present study mainly focuses upon stir casting, a low cost process to produce MMCs. Steps to process once documented in the form of SOP and thereafter implemented for optimized conditions for one component stays valid for subsequently produced one million components for instance. It is an applied research and the technology developed will be shared with small and medium enterprises in the automotive sector.

The process of stir casting which has been selected to produce samples of MMCs for characterization seems to be the opposite process carried out for the refinement of materials but in this case reinforcement is carried out with the material of known composition. Commercial grade aluminum is liquefied first and ceramic material is added in the desired manner and magnitude followed by agitation via mechanical means [18]. This liquid suspension is then cast by usual means and thereafter it is mechanically worked to enhance the properties of the composite by introducing the dislocation in the composite. It is basically because of the interaction of dislocations with the particles which increases the strength of the composite as reported by Huang et al [19]. Following features are important to understand the stir casting technology as reported by Tong. C.J. et al [20].

- The magnitude of the dispersed phase should not be higher than 30% in most of the cases.
- Even though it is tried but still the reinforcement phase is not uniform throughout the matrix phase.
  - There are packs of particles which cannot be removed by conventional means.
  - Problem arising because of the difference in densities of the two phases.
- Stir casting is a low cost process.
- Even though it is tried but still the reinforcement phase is not uniform throughout the matrix phase.

The uniform distribution of the phases can be improved if the ceramic phase is inserted in the matrix phase when it is in the semi-solid condition. Processing of the composite in the aforementioned manner is known as rheocasting. The greater thickness of the melt prevents the ceramic phase to settle down in the bottom of the pan as described by Tong C.J. et al [21]. Settling of the fine reinforcement particles during formation of the composite results in the irregular distribution of reinforcement, irregular mechanical and chemical properties as expressed by Tsai M.H. et al [22]. There are several stages where there are chances of irregular distribution of particles in the melt as shared by Chen H.Y. et al [23] is summarized below:

a) At the time of mixing while the melt is being continuously heated and stirred.

b) At the time of pouring into the mold there has been observed irregular flow of the melt.

c) At the time of solidification stirring is impossible in the molds.

Information shared by Yeh J.W and Chim Ann [24] on injection of particles is summarized as under:

i) Inert gas can be used as carrier gas to inject the particles.
ii) While filling the mold particles can be added in the molten stream.
iii) Reciprocating rods can be used to introduce particles into the melt.
iv) By simultaneously spraying molton metal alongwith particles on chosen substrates can be employed in spray casting.
v) Making cast parts via centrifugal casting where continuous motion mixes the particles while the melt in being cast.
vi) First forming pallets of the particles alongwith metal and thereafter redispersing them in the molten metal.
vii) Use of ultrasound energy to continuously stir the melt and concurrently injection of particles into the melt.

The information shared so far is cost intensive. Stir casting being cost effective is being selected to synthesize MMC in the present investigation. The most important consideration while introducing the ceramic into the molten metal is the wettability of the ceramic particles in the liquid metal as summarized by Dieter, G.E. [25]. A comprehensive information shared by Doer F.R. et al mention wettability is like surface tension of the metal which reduces at higher temperatures. The problem associated to this effect is that there are decreased the best distribution chances because of its disability to carry the load at higher temperature [26]. Some authors have reported chemical reaction of the surface with the metal but the same has not been considered in the present investigation [27]. There are different ways to improve wettability but the very basis as reported by Yeh J.W. et al are mentioned below [22].

i) If the surface area of the particles is higher, its wettability is more and hence by making the fine sized reinforcement the level of wettability can be enhanced.
ii) Decreasing the surface tension of the alloy by heating at higher temperature or putting some other metallic element and making it more wettable by reducing the surface tension.

2. Experimental Work

2.1 Raw Material

Commercial Grade Aluminum, Silicon carbide and graphite powder (particle size) less than 10μ were used to produce sample of metal matrix composites for performance evaluation and characterization. Physical data (as reported by the supplier) of the Silicon Carbide powder used as reinforcement is given below:

Composition	96% SiC, 2.3% Al, 1.1% FeO other 0.9%
Bulk Density	3.2-3.4 g/cm^3
True Density	2.97 g/cm^3

2.2 Fabrication Procedure

The stir casting method was applied for the making of composite. Pure aluminum was melted in the laboratory scale induction furnace integrated with the mechanically driven stirrer. Viscosity of the melt was kept optimum merely suitable for stirring and casting. The fine silicon carbide powder (particle size) less than 10μ preheated up to 1000^{o}C and added in the melt when it was possible to manually stir. In mushy state of the melt it was not possible to apply mechanical stirring. After this the temperature of the melt was raised; 50^{o}C upto 15% SiC addition and 75^{o}C up to 30% of the SiC addition and mechanical stirring was done. Burning losses of 5-7% were incorporated of the matrix material. This gives good homogenization of SiC particles in the matrix phase. The melts of various percentages of SiC and matrix as shown in Table 1 were cast as ingots in cylindrical shaped permanent molds. Samples were then cut and machined to size suitable for characterization.

Table: 1 Composition of SiC and Matrix in Ingots

Percentage of SiC Addition	0	5	10	15	20	25	30
Percentage of Matrix	100	95	90	85	80	75	70

3. Mechanical Testing

3.1 Hardness Test

Brinell Hardness Testing using 10mm ball diameter with an applied load of 3000kg for 30 second. Product No. is 341-66750-50, Shimadzu Corporation, Japan was carried out to determine the hardness.

3.2 Impact Test

Charpy impact testing machine of Shimadzu Corporation, load used was 50kgf-m, Product No. is 27090247-1994-11-15 was used to check the impact strength of the composites. Standard ASTM specimens were used having notch of particular dimensions as indicated below; cross section dimensions ±1% or ±0.075mm (0.003 inches), radius of notch : ±0.025 mm (0.001 inches), depth of notch : ±0.025 mm (0.001 inches), finish requirements : 2µ, width : 10mm, depth : 10mm. Scanning electron microscopy was used for micro structural study of the MMC.

4. Results

Figures 1(a) and 1(b) show an X-ray diffraction (XRD) pattern taken from SiC powder to verify its quality and standard SiC XRD pattern respectively. The X-ray diffraction pattern given in Fig. 1(a) shows that only the two highest intensity peaks, *i.e.*, (111) and (220), are distinctly visible. This is believed to be due to low purity of the SiC, as well as due to the preferred orientation in the powder sample along (111) plane.

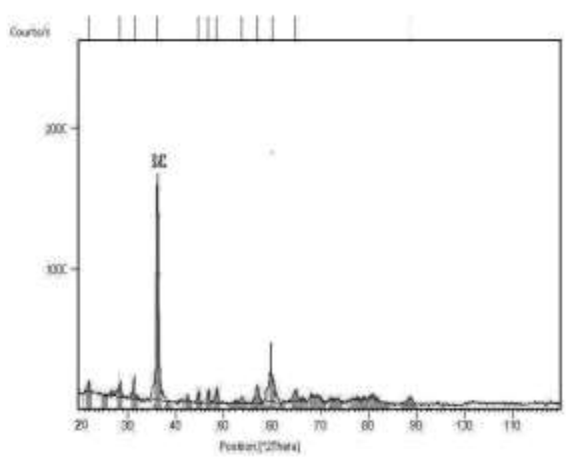


Fig.1(a) X-ray diffraction pattern taken from SiC powder

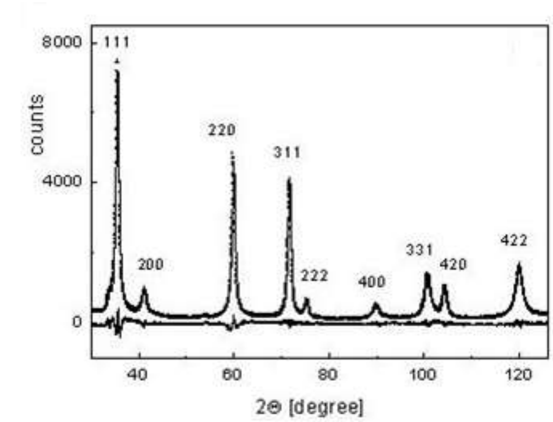


Fig.1(b) Standard SiC X-ray diffraction pattern

The SiC/AI composite was characterized to study the effect of volume fraction of silicon carbide. The following tests were performed to note the variations in mechanical properties.

4.1 Hardness Test

Various compositions of SiC/AI composite having 5, 10, 15, 20, 25 and 30 % of SiC were produced. The average hardness values of the samples were measured using Brinell Hardness Tester (BHN). The hardness values are given in Table-2 and graphically presented in Figure-2.

Table: 2 Outcome of Hardness Tests

Percentage of SiC Addition	0	5	10	15	20	25	30
Hardness (BHN)	31.2	44.5	46.3	47.5	49.8	49.3	47.3

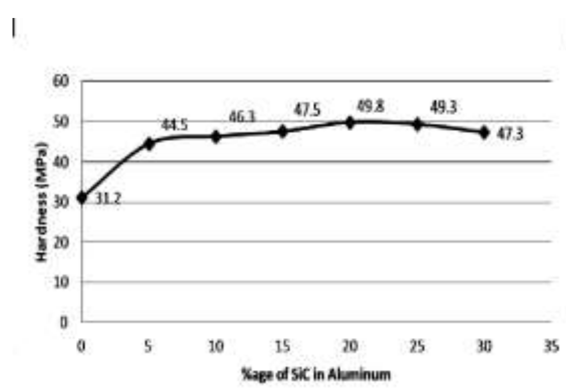


Fig.2 Graph between percentage of SiC and Hardness (in mega Pascal) of the composite.

4.2 Impact Test

Charpy impact testing machine was utilized to check the impact strength of the composite. The values are tabulated in Table 3 and graphically presented in Figure 3 indicating the variations in strength with respect to percentage of SiC volume fraction in aluminum matrix.

Table: 3 Outcome of Impact Tests

Percentage of SiC Addition	0	5	10	15	20	25	30
Impact Strength (Nm)	10	20	23	27	32	35	31

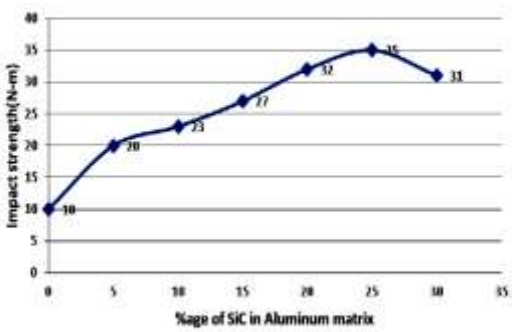


Fig.3 Graph between percentage SiC and impact strength of the composite.

4.3 Microscopy

Electron microscopy of the fractured surface was carried out to know the fracture mechanism of the composite. Figure 4 shows the fracture of the highest strength composite sample (25 percent SiC) which indicates that the mixture was uniform because there was no segregation of SiC particles. Figure 5 shows the fracture of composite sample (30 percent SiC) which indicates the agglomeration of SiC particles resulting in lowering of properties in terms of toughness and hardness. Figure 6 shows that the microstructure of 25 percent SiC is more uniform than with higher %age of silicon carbide (30 percent SiC) as shown in Figure 7.

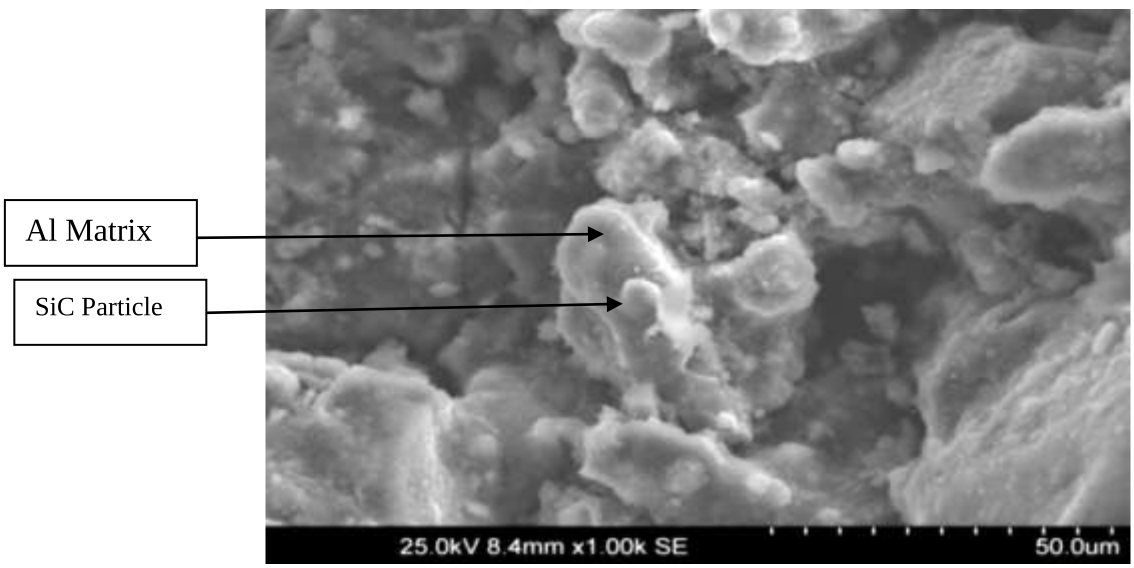


Fig.4. Fractured surface created in impact test of 25%SiC sample

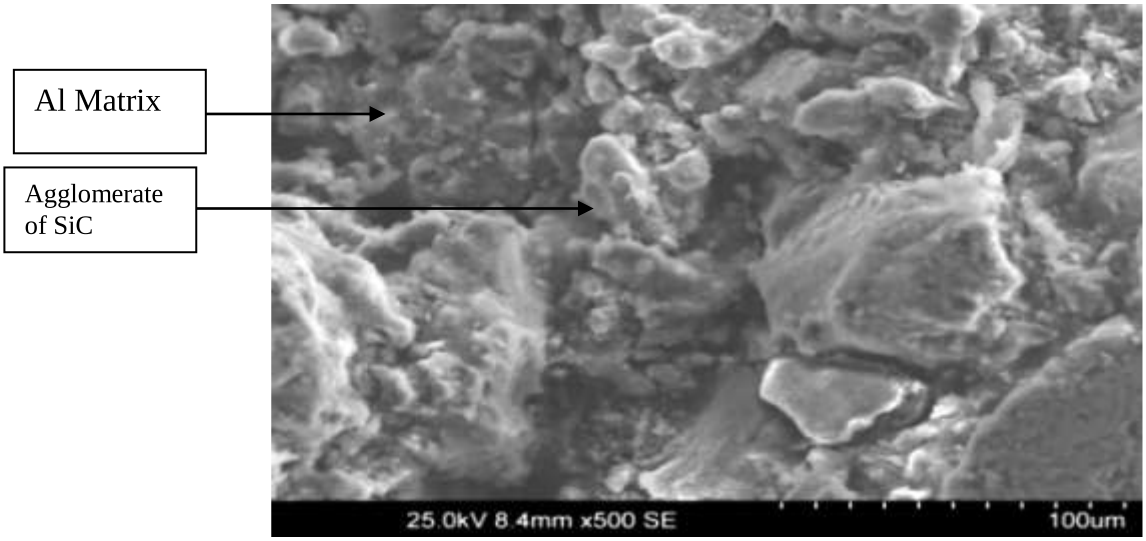


Fig.5 Fractured surface created in impact test of 30%SiC sample

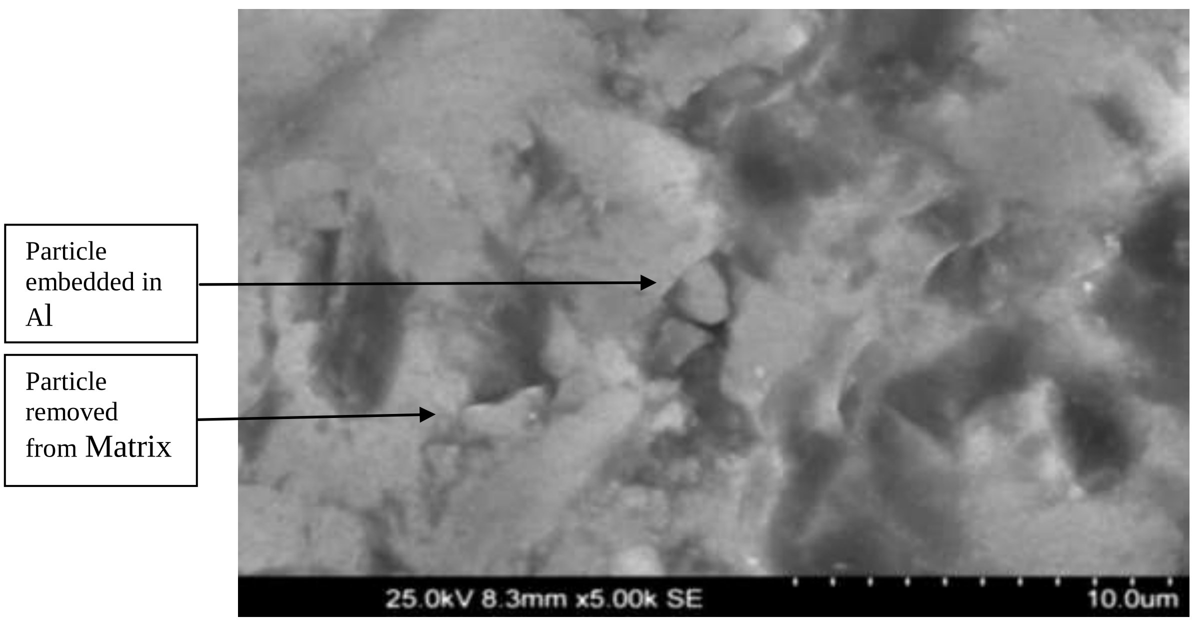
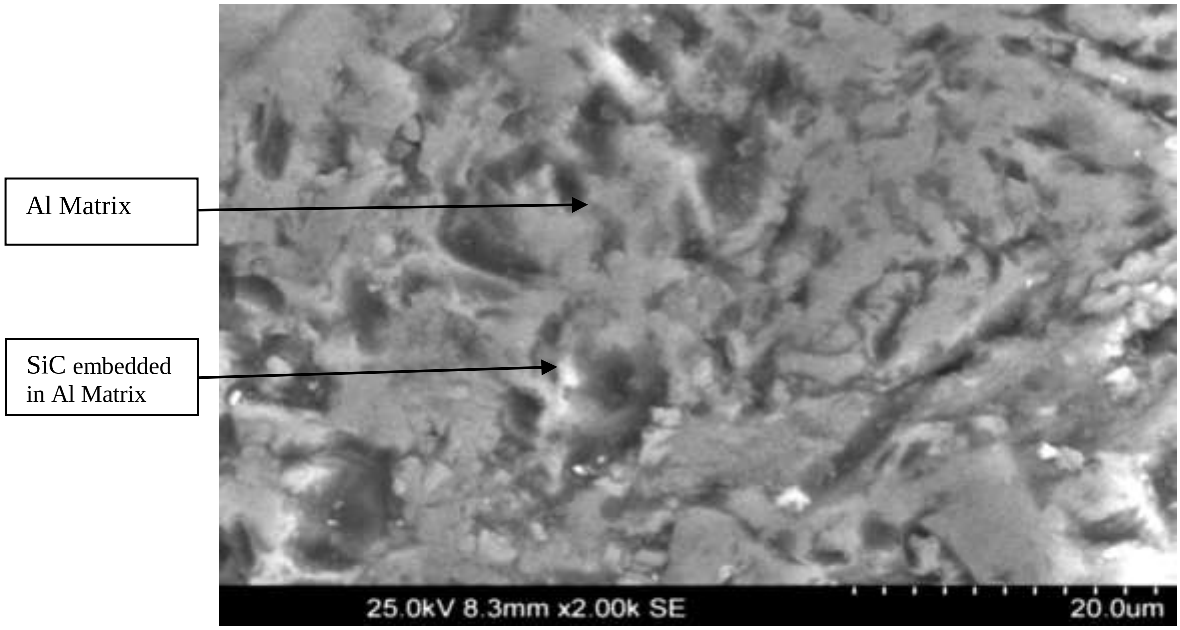


Fig.6 Polished surface of the composite with 25% of silicon carbide



Fig,7 Polished surface of the composite with 30% of silicon carbide.

5. Discussion

The experimental results showed that the composition of the composite for the optimized properties ranges between 70 to 80 percent aluminum and 20 to 30 percent silicon carbide. It is quite evident that deformation in metals is because of the movement of dislocations and if we block these dislocations by some means the strength which is resistance against the applied force of the material, sufficiently increases. There are numerous ways to block these dislocations like increasing the dislocation density, alloying and making composite in such a way that the newly reinforcing phase acts like a barrier against movement of these dislocations.

In the current research work it is evident that as we increase the amount of silicon carbide in aluminum matrix, there is improvement in hardness and the impact properties, these are sufficiently high in the vicinity of mechanical mixture of 25% silicon carbide and 75% aluminum.

The experiments were tried by manual as well as using by the mechanical stirring but the results with the manual stirring were very poor because of the following reasons:

1. Lack of uniformity resulted because in certain sites of the melt, the stirring was higher as compared to others. The particle distributions were different in different areas which resulted in property variation.

2. Potential sites for crack initiation: The accumulations of particles in certain areas of the composites were the potential sites for the crack initiation because in those areas either the particles were quit*e* in the vicinity of each other or totally absent from those sites which resulted in the crack or deformation initiation.

For the samples, made by manual stirring, the results were not even and the samples with same volume fractions had entirely different properties from experimentally calculated because of the aforementioned problems.The mechanical mixing process was more efficient to get the uniform results because in this case, the agitation was more uniform and steadier. The resultant composite gives better results to understand the idea of effect of volume fraction of the reinforcement phase to the Aluminum matrix. Optimum particle size distribution was considered to be very important to avoid concentration gradient of SiC in the matrix.

5.1 Effect of Percentage of SiC on Hardness and Impact strength

As the reinforcement content was added to the aluminum melt, the hardness shoots up from pure aluminum's hardness to 45 BHN only by addition of 5 percent of silicon carbide. The reason of this is that these small reinforcements added offer hindrance to the plastic flow of matrix material and they also lock the grain boundaries which elevate its strength up to maximum level. But as we go on increasing the silicon carbide content we approach to a point above which there appears a decrease in hardness at 20 percent of the reinforcement. This was because of the segregation of the particles of SiC in the matrix. The segregated particles become the potential of the surface energy which is responsible for the initiation of the crack and thus the mechanical properties are affected by this agglomeration of the particles. This effect is obviously clear from the fractured surface with 30 percent SiC reinforcement.

Saturation of the melt which is because of the fact that whenever there is crystal formation it can only accommodate the guest substrate up to its defects capacity and the difference in the size of the host and guest particles. But h ere, because the Silicon carbide particles were not fine up to nano level so the possibility to enter into the crystal because of the size difference is eliminated and the only factor was the defects locations like grain boundaries, triple points and the bigger dislocations which have sufficient size that can contain a macro particle inside these creating a strain field around these. The same strain field also becomes a cause for the blockage of the dislocation movement. This strain field is because of the misfit of particles in little spaces. And because the final composite was solidified under normal conditions so the defect level was not that much. But even then there is every likelyhood that if we do tempering with this higher percentage reinforcement phase, its properties can be improved. The same phenomenon of agglomeration of the particles was responsible for the reduced impact strength of the composite visible from the graphical representation as shown in Fig-3.

5.2 Electron Microscopic Examination

The electron micrographs for the fractured samples reveal that in around the 25 percent of the SiC, particles are more uniformly embedded in the matrix rather at 30 percent which is one of the reasons because of which at 30 percent the strength was lower than at 25 percent. The other micrographs which were polished show deep vallies in them because of the hard ceramic particles which emerged during polishing of the samples.

6. Conclusions

- SiC/Al composites can be made in an open atmosphere by stir casting using fabrication scheme derived from the literature review and mentioned in the experimental.
- The particle size of SiC reinforcement should be finer so that the miss fitting problem can be accommodated accordingly. By using fine particle size, the problem arising from the centrifugal force can also be minimized that produces segregation in the melt due to which the non-uniform properties are attained.
- Percentage of SiC should be selected is in line with the information comprehensively reviewed
- Present research confirms that Optimum use of SiC requires extensive experimentation.

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