Recent development and challenges in processing of ceramics reinforced Al matrix composite through stir casting process: A Review

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Abstract— **Use of Composites are increasing day by day because they offers advantages such as low weight, corrosion resistance, high fatigue strength, faster assembly, etc. MMCs posses significantly improved properties including high specific strength, specific modulus, damping capacity and good wear resistance compared to the unreinforced alloys. It is durable and highly efficient for automobile or aircraft. It exhibits higher competence for machining complex shapes with greater accuracy. Homogenous Continuous reinforcements can result in dramatic improvements in MMCs properties, consist of lightweight metal alloys, but cost remains high. Cost reduction can be achieved by cheaper reinforcements, simpler fabrication methods. It is possible to tailor their properties as per the requirement of various industrial applications by suitable combinations of matrix, reinforcement and fabrication method. This paper presents an up-to-date review of progress and benefits of different routes for fabrication and machining of composites. The purpose of this review to provide a reliable scientific basis for the researchers planning to synthesize particulate reinforcement, Wettability, porosity MMC in the stir casting.**

Index Terms— **MMCs, Stir casting etc.**

I. Introduction

The development of metal matrix composites (MMCs) has been one of the major innovations in materials in past 20 years. Several issues and requirement in liquid processing (Casting) of particle metal matrix composite are involved**.** Metal matrix composites (MMCs) are under consideration as potential candidate materials for a variety of structural applications such as those in the aeronautical/ aerospace, transportation, defence and sports industries because of the range of mechanical properties they possess. There is however problems associated with the production of reinforced composites, one of significance being the difficulty of achieving a homogeneous distribution of reinforcement in the matrix, essential for optimum mechanical properties. This problem is common to most production routes, including the stir casting process which, using particulate reinforcement, offers the possibility of producing relatively complex shaped composites.

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Metal-matrix composites (MMCs) are combinations of two or more materials (one of which is a metal) where tailored properties are achieved by systematic combinations of different constituents. Conventional monolithic materials have limitations in respect to achievable combinations of strength, stiffness and density [1]. Particle-reinforced MMCs generally exhibited wide engineering applications due to their enhanced hardness, better wear, and corrosion resistance when compared to pure metal or alloy.

The aim is designing metal matrix composite materials is to combine the desirable attributes of metals and ceramics. MMCs consisting of continuous or discontinuous fibres, whiskers, or particles in a metal achieve combinations of very high specific strength and specific modulus. The addition of high strength, a high modulus refractory particle to a ductile metal matrix produces a material whose mechanical properties are intermediate between the matrix alloy and the ceramic reinforcement [2].

The potential for extensive application of cast composites is very large in India, especially in the areas of transportation, energy and electromechanical machinery; the extensive use of composites can lead to large savings in materials and energy, and in several instances, reduce environmental pollution [1]. There are a num significantly better hardness, and somewhat better of niche applications in aerospace structure stiffness and strength (MMC).

The ultimate objectives in design of MMCs can be to produce Homogenous, isotropic, good manufacturability and eco friendly to environment by using different processing methods, reinforcement (Particle size and shape), machining, testing and analysis.

Table 1 lists the other proven applications of some MMCs in the automotive industry.

Table 1: Some proven Application of Al Matrix composites

Manufacturer	**Composite**	**Component**
Duralcan, Martin Marietta, Lanxide	Al/SiCp	Pistons
Duralcan, Lanxide	Al/SiCp	Brake rotors, calipers, liners
GKN, Duralcan	Al/SiCp	Propeller shaft
Nissan	Al/SiCw	Connecting rod
Dow Chemical	Mg/SiCp	Sprockets, pulleys, covers
Toyota	Al/Al2O3	Piston rings, (saffil) &Al/Boriaw
Dupont, Chrysler	Al/Al2O3	Connecting rods
Hitachi	Cu/graphite	Current collectors
Martin Marietta	Al/TiCp	Pistons,

		connecting rods
Zollner	Al/fiberfrax	Pistons
Honda	Al/Al2O3-Cf	Engine blocks
Lotus Elise, Volkswagon	Al/SiCp	Brake rotors
Chrysler	Al/SiCp	Brake rotors
GM	Al/SiCp	Rear brake drum for EV-1, driveshaft, engine cradle
MC-21, Dia-Compe, Manitou	Al/SiCp	Bicycle fork brace and disk brake Rotors
3M	Al/Nextelf	Missile fins, aircraft electrical ac door
Knorr-Bremse; Kobenhavn,	SiC/Al	Brake disc on ICE bogies
Alcoa Innometalx	Al/SiCp	Multichip electronic module
Lanxide	Al/SiCp	PCB Heat sinks
Cercast	Al/graphite foam	Electronic packages
Textron Specialty Materials	Al/B	PCB heat sinks

II. Metal Matrix Composites

MMCs are a class of materials with potential for a wide Varity of structural and thermal management application. Metal matrix composites are capable of providing higher-temperature operating limits than their base metal counterparts, and they can be tailored to give improved properties. Metal matrix composites can be characterized by the method of reinforcement, that is continuous reinforcement and discontinuous reinforcement [3,9]. There are two types of discontinuous reinforcement for MMCs: particulate and whiskers. The most common types of particulate are alumina, boron carbide, silicon carbide (SiC), titanium carbide, and tungsten carbide. The most common type of whisker is silicon carbide, but whiskers of alumina and silicon nitride have also been produced. In fibre reinforcement, by far the most common kind of continuous reinforcement, many types of fibres are used; most of them are carbon or ceramic. Carbon types are referred to as graphite and are based on pitch or polyacrylonitrile (PAN) precursor. Ceramic types include alumina, silica, boron, alumina-silica, alumina-boria silica, zirconia, magnesia, mullite, boron nitride, TiB_2, Sic, and boron carbide. All of these fibers are brittle, flaw-sensitive materials. Aluminium is the most popular matrix for the metal matrix composites (MMCs). The Al alloys are quite attractive due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, high thermal and electrical conductivity, and their high damping capacity.

Hybrid metal matrix composites (HMMCs) are second-generation composites, wherein more than one type, shape, and size of reinforcements are used to obtain better properties.

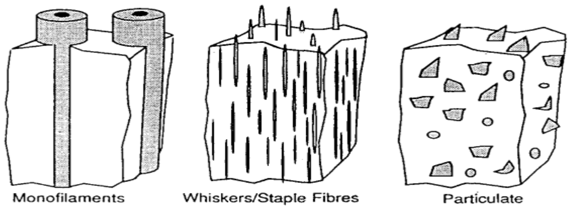

Figure 1. Schematic presentation of various types of metal matrix composites [4].

III. Processing Technique for Particulate Reinforced MMCs

Because MMC technology is hardly beyond the stage of R&D at present, costs for all methods of producing MMCs are still high. Manufacturing methods must ensure good bonding between matrix and reinforcement, and must not result in undesirable matrix/fiber interracial reactions. MMC production processes can be dividing into primary and secondary processing methods. In primary solid state processing include powder metallurgy and liquid metallurgy technique include squeeze casting, spray deposition, compocasting, Infiltration, Spray casting, Stir casting.

For processing particle-reinforced MMCs several researches prefer to employ ex-situ route, mainly the stir casting technique. Melt Stir casting is an attractive processing method since it is relatively simple, flexible applicable to large volume production, offers a wide selection of materials and processing conditions and the most economical method and allows very large sized components to be fabricated [4]. In conventional stir casting method, hard ceramic reinforcements are introduced into the vortex of the melt and are transferred to permanent mould after stirring [5]. This involves incorporation of ceramic particulate into liquid aluminium melt and allowing the mixture to solidify. Here, the crucial thing is to create good wetting between the particulate reinforcement and the liquid aluminium alloy melt. The simplest and most commercially used technique is known as vortex technique or stir-casting technique. The vortex technique involves the introduction of pre-treated ceramic particles into the vortex of molten alloy created by the rotating impeller. Lloyd [15] reports that vortex-mixing technique for the preparation of ceramic particle dispersed aluminium matrix composites was originally developed by Surappa & Rohatgi (1981) at the Indian Institute of Science. Subsequently several aluminium companies further refined and modified the process which are currently employed to manufacture a variety of AMCs on commercial scale. Microstructural inhomogeneties can cause notably particle agglomeration and sedimentation in the melt and subsequently during solidification. Inhomogeneity in reinforcement distribution in these cast composites could also be a problem as a result of interaction between suspended ceramic particles and moving solid-liquid interface during solidification. Generally it is possible to incorporate upto 30% ceramic particles in the size range 5 to 100 mm in a variety of molten aluminium alloys. The melt–ceramic particle slurry 11 may be transferred directly to a shaped mould prior to complete solidification or it may be allowed to Solidify in billet or rod shape so that it can be reheated to the slurry form for further processing by technique such as die casting, and investment casting. The process is not suitable for the incorporation of sub-micron size ceramic particles or whiskers. Another variant of stir casting process is compo-casting. Here, ceramic particles are incorporated into the alloy in the semi solid state.

In the preparing metal matrix composites by the stir casting method, there are several factors that need considerable attention, including the difficulty of achieving a uniform of the reinforcement material, wettabilty between the matrix and reinforcement, porosity in the cast metal matrix composites, and chemical reaction between the reinforcement materials and the matrix alloy.

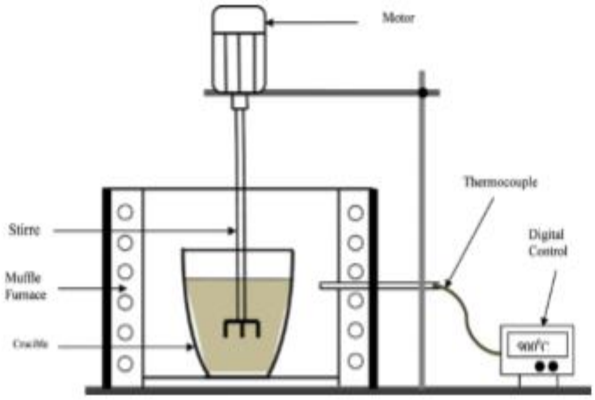

Figure 2. Schematic view of setup for stir casting (color figure available online).

The investigation of Hashim et al. [2] reported that in preparing metal matrix composites by the stir casting method, there are several factors that need considerable attention, including

1. The difficulty of achieving a uniform distribution of the reinforcement material;
2. wettability between the two main substances;
3. porosity in the cast metal matrix composites; and
4. chemical reactions between the reinforcement material and the matrix alloy.

In order to achieve the optimum properties of the metal matrix composite, the distribution of the reinforcement material in the matrix alloy must be uniform, and the wettability or bonding between these substances should be optimised. The porosity levels need to be minimised, and chemical reactions between the reinforcement materials and the matrix alloy must be avoided.

Accordingly, to fabricate high quality particulate-reinforced MMCs with desirable mechanical properties through stir casting technique substantial attention should be given to important factors such as (1) type, size, and weight fraction of reinforcement particles; (2) design, position and speed of stirrer; (3) working and holding temperature; (4) preheating temperature and time for reinforcement particles, molds, and stirrer; (5) material of mold, crucible, and stirrer; (6) method of particle addition; (7) solidification behavior during casting, etc. [7].

A. Factors affecting the uniform Distribution of reinforcement particles

Achieving a uniform distribution of reinforcement within the matrix is one of the technical challenges in the stir casting technology which affects directly the properties and quality of composites material. Uniformity of distribution of particulates is a major factor in determining the in-service properties of engineering components made of MMC. So far several experimental studies have done to investigate this subject. All agree that particle distribution in the matrix material depends strongly on the stirring speed, stirring time, viscosity of slurry, heating temperature, particle wetting, solidification rate, and minimizing of gas entrapment [5].

D.J. Lloyd [15] explained that the reinforcing size effects on the incorporation coarser particle into melt whereas large size particles are more susceptible to gravity settling and can result in a heavily segregated casting. The volume fraction should be low <10 vol%. On that mechanical property which is always significantly increased by the addition of reinforcement is the elastic modulus. S. Naher et. al.[7] reported that particle distribution in MMC during the melt stage of the casting process depends strongly on the viscosity of the slurry, particle wetting, reinforcement particle influence settling rate, the effectiveness of the mixing and breaking up of agglomerates, and the minimizing of gas entrapment. The vortex method for particulate entrapment was the most frequently used in previous studies since any stirring of melt naturally results in formation of vortex. Hashim et al. [2] reported that it has also been indicated that the reinforcement particles occupy interdendritic and secondary dendrite arm spacings; therefore, the finer the spacing or the finer the matrix grain size, the better is the particle distribution. M. K. Surappa [11] presented results that composites generally contain equiaxed ceramic reinforcements with an aspect ratio less than about 5. Ceramic reinforcements are generally oxides or carbides or borides (Al_2O_3 or SiC or TiB2) and present in volume fraction less than 30% when used for structural and wear resistance applications. However, in electronic packaging applications reinforcement volume fraction could be as high as 70%.

Stirrer is used to mix the SiC particles in molten aluminium. Stirrers in the existing system stir the SiC particles by providing minimum amount of stirring force, which is inefficient. So the stirrer is modified in the following two ways to increase the strength of Aluminium MMC. (i) Modified geometry to make various flow patterns to achieve uniform distribution of SiC (ii) Modified dimensions 36 mm ×65 mm to increase the stirring force which cluster can reduce formation Stirrer has two blade assemblies, which are namely upper blade assembly and lower blade assembly. This two-blade assembly placed in anti parallel manner. This geometry makes molten aluminium to form various flow patterns. This complex flow patterns makes the SiC particles to mix uniformly and reduces the formation of cluster. The area of the blade is increased. So stirring force is increased. This increase in stirring force reduces the attraction force between SiC particles and reduces the cluster formation. The blades of 18 mm width and 25 mm breadth are twisted 45^0 from vertical; this geometry makes the molten metal flow above the blade and optimizes the required mechanical force. Two blades assembly is used because in order to make the flow pattern which increases the distribution of SiC particles in the molten Aluminium [6]. The investigation of Prabu et al. [12] revealed that the effect of stirring speed on the distribution of the particle is considerable. Homogeneous distribution of the particle has been achieved by higher stirring speeds. It is also understood that increase the stirring speed alone will not distribute the particles the stirring time should also optimized. Similarly, D.J. Lloyd et al. [15] have reported that the distribution of the reinforcement is a function of the solidification rate; in general the higher the solidification rate the more uniform is the distribution. Indumati B. et al. explained that in stir casting, process parameters such as furnace temperature, stirring speed, time of stirring, holding, and solidification are influenced on the soundness of the casting. Flow and solidification characteristics during casting are the key factors affecting the uniformity of the particles distribution in the matrix.

B. Wettability between the reinforcement particles and Matrix Alloy

In MMCs the primary function of the reinforcements is to support most of the applied load while that of the matrix is to bind the reinforcement's together and to transmit and distributes the external loads to the individual reinforcements. Good wetting is needed to provide high level of mechanical properties.

J. Hashim and L. Looney [14] were experimented on to find the weattability of the reinforcing by the matrix alloy is one aspect of the process that must be optimized. To improve the weattability in this paper there is gap is fundamental of wetting of solid particles and the practice of preparation of MMCs. Good wetting leads to a strong bond between reinforcing particles and matrix. However contamination, the presence of gas layer or on the formation of an oxide layer on the melt can be detrimental wetting.As per study K.M. Shorowordi et al. [13] reported that good wettability of B_4C in the aluminium has been found in air due to the formation of boron oxide film around the particles. Particles distribution was found to be better in Al- B_4C composites as compared to Al-SiC and Al- Al_2O_3 composites. Bharath V. et al. explained that the reinforcement particles were preheated to a temperature of 200^0C and then dispersed in steps of three into the vortex of molten Al6061 alloy to improve wettability and distribution. Micro structural characterization was carried out for the above prepared composites by taking specimens from central portion of the casting to ensure homogeneous distribution of particles.

Hashim et al. [2] performed experimental work on modified stir casting route to produce cast DRMMC had discovered the reinforcement preheating technique to enhance the wettability between the matrix alloy and reinforcement material as well as to reduce the porosity formation in stir cast DRMMC. Normally, the mechanical mixing at high stirring speed is employed to disperse the reinforcing particle uniformly. As per the well-known sessile drop experiment, the tendency of the matrix melt to spread over the surface of a reinforcement substrate forming a low ($<90^0$c) contact angle. The boundary between wetting and non wetting conditions is generally taken as h¼ 90^0 C. Wetting occurs when h$<90^0$ c, while h$>90^0$ c represents a non wetting condition. However, a contact angle of less than 90^0 is not sufficient enough to lead to spontaneous entry of the particles but a 0^0 contact angle (total spreading condition) is required. To enhance the wettability of reinforcement particles in the liquid matrix, earlier investigators have suggested several techniques. For example Hashim et al. [14] reported that the wettability can be improved by (1) increasing the surface energies of the solid; (2) decreasing the surface tension of the liquid matrix alloy; and (3) decreasing the solid-liquid interfacial energy at the particles-matrix interface. According to the wettability test result of heating silicon carbide particles to 90^0C assists in removing surface impurities, desorption of gases, and altering the surface composition due to the formation of an oxide layer on the surface. String in a semi-solid state did help to promote wettability between SiC particles and Al-Si alloy. It has also been observed that use of magnesium enhances the wettability. However, increasing the Mg content above 1wt% increases the viscosity of the slurry which causes the wettability to decreases. Increasing the volume percentage of SiC particles in the matrix alloy also decreases the wettability.

C. Causes of Formation of Porosity on MMCs

One of the major problems associated with cast MMCs is formation of porosity. For stir cast MMCs porosities may form at the interface between reinforcement particles and the matrix alloy. The volume fraction of porosity and its size and distribution in a cast MMC play an important role in controlling the material's mechanical properties. Some of the defects occur in MMCs due to the presence of porosity are: failures initiated from the pores within the matrix material, particle fracture in the reinforcement-matrix interface due to voids coalescence, and reduction of ductility. This kind of a composite defect can also be detrimental to the surface finish and corrosion resistance of the casting. Therefore, porosity levels must be kept as minimum as possible [8].

Ahmad and Hashim et al. [8] was findings of porosity effects on the mechanical properties of cast discontinuous reinforced metal matrix composite. Aluminium silicon alloy composite specimen are produced by the stir casting method with varied content of reinforcing silicon carbide (SiC) particles for metallographic study, porosity and tensile and fatigue testing. D.J. Lloyd was investigated the factors for porosity occurrence in cast DRMMC were gas entrapment during vigorous stirring, air bubbles entering the slurry either independently or as an air envelope to the reinforcement particles, presence of water vapour on the reinforcement particles surface, and hydrogen evolution and solubility. Referring to a previous experimental work, applying vigorous stirring in the stir casting method to distribute the particles had resulted in difficulties in achieving a clean and low gas content melt.

The formation of turbulence due to the stirring action had entrapped gas and water vapour from the atmosphere in the melt. Concurrently, water vapour is also present at the particle surface due to high humidity level. The entrapped gas and water vapour diffuse into the surface of the molten matrix alloy and react with it besides the atmosphere; water vapour is sourced from the hydrogen evolution process. As the liquid Aluminium attracts oxygen, water vapour is formed when hydrogen which readily dissolves in Aluminium reacts with oxygen. The presence of water vapour enhances the hydrogen content in casting and promotes porosity. The gas porosity in Aluminium casting is caused by hydrogen, which penetrates into the liquid alloy by the reaction of aluminium with water vapour. At an elevated temperature, specifically above the liquidus temperature, the solubility of hydrogen gas in molten aluminium is high. However, the gas solubility decreases as the temperature drops. When the aluminium solidifies, the hydrogen dissolved in molten Aluminium alloy gets trapped, which produces gas porosity. Based on the previous works of Hashim, Ghosh and Ray, and Moustafa porosity formation in cast DRMMC is due to the reinforcing particles, and casting parameters. The porosity content increased with particle added, and reinforcement particles appeared to have a significant stress-raising effect on the formation of slip bands and cracks as there were micro pores formed during solidification. These micro pores were preferred nucleation sites for fatigue cracks. The occurrence of porosity as discontinuities in cast DRMMC had interrupted the balance and thus, reduced its mechanical properties. In metal-based cast composites, the ductility and tensile strength are influenced by void presence and nucleation. The commonly encountered and analyzed gas porosity is observed to originate stress concentration and thus lead to failure. Porosity tended to develop strain of a particular region when stress was applied. In unreinforced alloys, porosity had caused decrease in tensile strength. Porosity formation in the stir-cast discontinuous rein- forced MMC has been addressed by several authors and most of them agrees that, porosity arises from four causes: (1) gas entrapment during mixing; (2) hydrogen evolution; (3) shrinkage during solidification and (4) process parameters such as holding time, stirring speed, and the size and position of the impeller.

A vortex created during stirring can suck in even non-wetting particles and also bubbles into a molten alloy. Particles often attached to the bubbles, counteracting the buoyancy which would normally help them to float out of the melt. As a result, it has been observed that porosity content in a stir cast composite varies almost linearly with particle content [5]. It is necessary to create turbulence during stirring, but it should be only in the bottom region of the fluid [2].

Hashim et al. [2] also reported that processing variables such as holding temperature, stirring speed, size of the impeller, and the position of the impeller in the melt are among the important factors to be considered in the production of cast MMCs, as these have an impact on mechanical properties. The microanalysis observation of Prabu et al. [12] revealed that, the porosity formation is due to the solidification rate and metal feeding. These are determined by the reinforcement content, its distribution, the level of the intimate contact of the wetting with the matrix materials, and the porosity content.

D. Techniques used to control the Interfacial reaction

As per the study of P. Gurusamy [12] the contact interface between mould and casting plays a major role in a metallic mould, an interfacial thermal resistance develops between the casting and the mould. This thermal resistance usually varies with time. The thermal resistance is due to imperfect contact between the casting and mould, and in some cases, the formation of air gaps between the casting and mould. The interface becomes significant when an air gap is formed due to the casting shrinkage away from the mould and the mould expanding away from the casting.

One of the major concerns with the use of HT-MMC is the issue of interface/ interphase. Interface is the boundary separating the fiber and the matrix whereas interphase is a layer of finite thickness separating the fiber and matrix. The existence of the interphase is usually attributed to the chemical reaction that takes place between fiber and matrix during the cool-down phase of the fabrication process. However, sometimes a layer is intentionally introduced primarily to prevent chemical reaction between fiber and matrix. Often this layer also serves as a compliant layer which helps to reduce the thermal residual stresses due to the cool-down phase of the fabrication process. The thermal residual stresses develop due to the mismatch of thermal expansion coefficients between fiber and matrix. These are further accentuated by the difference between the use and the processing temperatures. B.S. Yigezu et al. [5] have done experimental study on interfacial reaction causes deterioration of the mechanical properties of the composite. Sozhamannan et al. have informed that the rate of chemical reaction between liquid aluminium and SiC increases with increase in temperature. Al4C3 reaction rate also depends upon the prolonged contact between liquid aluminium and SiC particles. It has also been reported that, to avoid formation of Al4C3, the SiC particulate can be pre-treated before being added to molten solution by baking in a 700 to 1,200^{0}C furnace for several hours. SiO2 film is formed on the surface of the particles which can enhance wetting between particles and molten solution and the formation of Al_4C_3 (s) is avoided.

IV. CONCLUSION

This article presents a brief review of literatures related to the main characteristics of a stir cast particle-reinforced Aluminium based composites. In general, the reviewed work can be summarized as follows:

1. Cost reductions can be achieved by using cheaper reinforcements, simpler fabrication methods, and higher production volume. Particulate reinforcements are relatively cheaper and easily available. Also, stir casting is the most economical processing method. Uneven distribution, poor wettability, interfacial reactions, porosity are the major processing issues in the stir casting process.
2. Particle distribution in the matrix material depends strongly on the stirring speed, stirring time, viscosity of slurry, heating temperature, particle wetting solidification rate, and minimizing of gas entrapment. Rapidly solidified structures, gives a better distribution of the particles due to finer dendrite size as well as due to a limited setting of the particles resulting from the reduced time. The vortex method is one of the better known approaches used to create and maintain a good distribution of the reinforcement materials in the matrix alloy.
3. The problem of the wetting of the ceramic by molten metal is one of surface chemistry and surface tension. A mechanical force can usually be used to overcome surface tension to improve wettability. Wettability can be improved by reinforcement and the molten alloys have been achieved using various metallic coating on the reinforcement. Some of the coating techniques are also complicated and expensive.
4. Porosity cannot be fully avoided during the casting process, but it can be controlled. The process parameters of Holding times, Stirring speed, Size and position of the impeller will influence the development of porosity. To minimize porosity we can use extensive inert gas bubbling through the melt, casting under pressure, compressing and extruding or rolling the after casting to close the pores.
5. The rate of chemical reaction between liquid aluminium and SiC increases with increase in temperature. Al4C3 reaction rate also depends upon the prolonged contact between liquid aluminium and SiC particles. To avoid formation of Al4C3, the SiC particulate can be pre-treated

before being added to molten solution by baking in a 700 to 1,200^{0}C furnace for several hours.

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