

Review of stir casting technique and technical challenges for ceramic reinforcement particulate and aluminium matrix composites

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Abstract

Ceramic metal composites are promising advanced materials compared to conventional materials due to special properties such as: low weight, low cost, wear resistance, corrosion resistance, and high strength, etc. Stir casting is one of the lowest costs and simplest ways of making aluminium matrix composites. The main limitations of stir casting are poor distribution with combination of the reinforcement ceramic particles (agglomerations) in the metal matrix, porosities in composites during fabrication, and wettability of ceramic particles with molten metal's. Enhancement of stir casting parameters for Ceramic-Metals Matrix Composites (CMMCs) is the main objective for many studies. In this paper, the stir casting process will be discussed in detail with parameters affecting the homogeneous distribution of reinforcements, porosities in composites during fabrication, and the mechanical properties of the ceramic metal matrix composites.

Keywords: stir casting, ceramic reinforcement, aluminium matrix composites

Kulcsszavak: keveréses öntés, kerámia megerősítés, aluminium matrix kompozitok

1. Introduction

A composite material can be defined as a combination of the best properties of each of the component materials; each material retains its separate chemical, physical, and mechanical properties. The three major composites are: ceramic matrix composite (CMMC), metal matrix composite (MMC), and polymer matrix composite (PMC). The three composites have a different properties and production methods that portrays specific behavior and capabilities. The main advantages of composite materials are their high strength and stiffness, combined with low density, fatigue life, and high corrosion resistance. The reinforcing stage provides the strength and stiffness. In most cases, the reinforcement is harder, stronger, and stiffer than the matrix. The reinforcement is usually a fiber or a particulate with regular or irregular shape. Particulate reinforced composites usually contain less reinforcement (up to 40 to 50 volume percent) due to processing difficulties and brittleness [1]. There are several fabrication techniques available in manufacturing the CMMC materials. Fabrication methods can be divided into three types. These are solid phase processes, liquid phase process, and semi-solid fabrication process. Liquid phase process includes stir casting, liquid metal infiltration, squeeze casting, and spray code position [2,3]. Ceramics particles are good candidate as reinforcement materials such as oxides, carbides, and nitrides which are characterized by their strength and stiffness at ambient and elevated temperature. Choosing the manufacturing process for any MMCs is based on several factors such as the: maintenance of reinforcement strength, minimization of reinforcement damage, promotion of wetting and bonding between the

matrix and reinforcement, ability to achieve the spacing and orientation of reinforcement with the matrix, and cost. With these several fabrication techniques, there are however problems associated with homogeneous distribution of reinforcement, and porosity in composites during fabrication, essential for optimum mechanical properties of MMC [4-10]. Literature survey indicate that various parameters of stir casting process such as: stirring speed and time, stirring blade angle, pouring temperature and solidification rate, reinforcement's percentage and size have major effect on fabrication of MMC. Enhancement of parameters of stir casting process for CMC is the main objective for many studies. Few of these works are concerned with parameters that are affected by homogeneous distribution of reinforcement, and porosities in composites during fabrication which are the essential for optimum mechanical properties of MMC [11].

2. Stir casting

Stir casting is currently the most popular commercial method of producing aluminum-based composites. Stir casting of MMCs was initiated in 1968 [12,13]. In this process, powder form as reinforcing phases are usually distributed into molten metal's by mechanical stirring as shown in *Fig. 1*. Non-uniform distribution, and porosity in casted CMMCs consider main disadvantages for stir casting process. Generally, the difference in density is between the liquid metal and the reinforcement and the consequent tendency to reinforce the sink or float, resulting in nonuniform distribution of the reinforcement in the solidified composite.

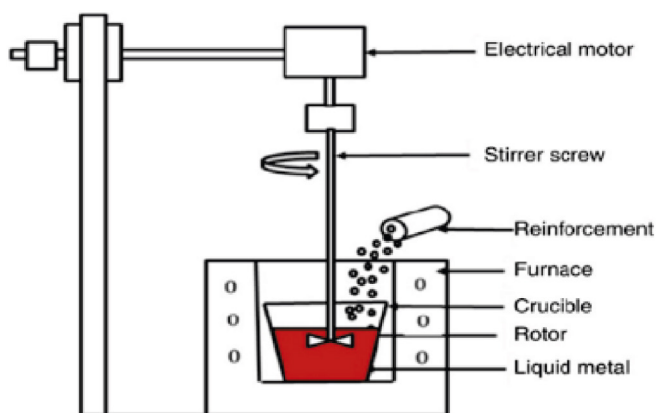


Fig. 1 Mechanical stirring
1. ábra Mechanikus keverés

3. Effect of stirring speed and time on distribution of particles and porosities in casted CMMCs

For most applications, a homogeneous distribution of the particles is desirable in order to maximize the mechanical properties. Prabu *et al.* [14] reported by microstructure analysis that during lower speed and lower stir time particle clustering occurred in some places, and some places were identified without SiC inclusion. By increasing the stirring speed and stirring time better homogeneous distribution of SiC in the Al matrix were found. Better distributions of SiC were found at 600 rpm and 10 min stirring time condition as shown in Fig. 2.

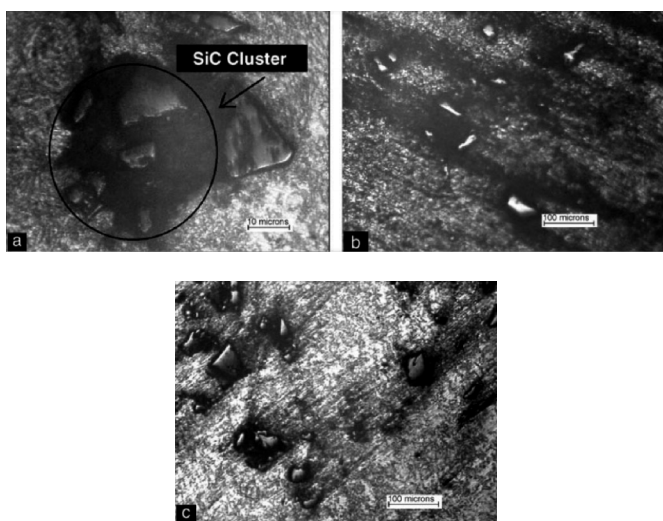


Fig. 2 Microstructure of Al-10%SiCp MMC fabricated at 600 rpm: (a) 5 min stirring; (b) 10 min stirring; (c) 15 min stirring

2. ábra 600 fordulat/perc sebességen készített Al-10%SiCp MMC mikroszerkezete: (a) 5 perc keverés után; (b) 10 perc keverés után; (c) 15 perc keverés után

Also, they reported that with higher speeds (700 rpm), more porosity has been observed in the microstructure which lead to minimize the mechanical properties. From Fig. 3 Adetayo *et al.* [15] explained the influence of stirring speed on stir casting synthesis of 15 wt% silicon carbide particle reinforced aluminium alloy (SiCp-6061 Al) composite.

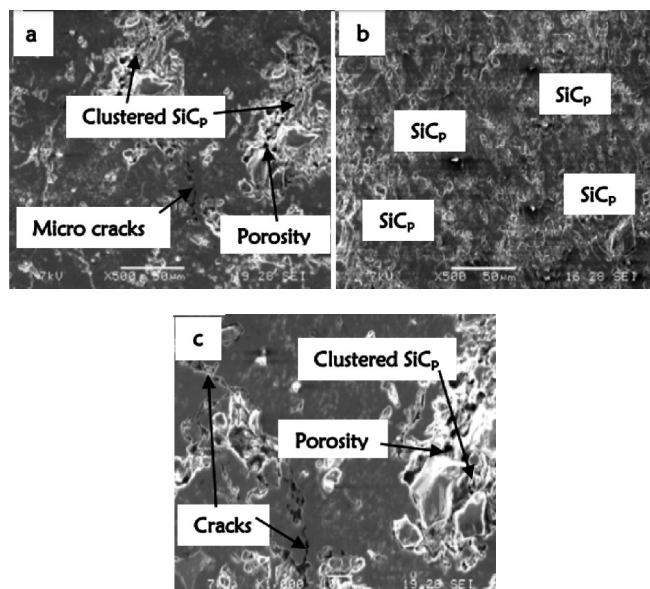


Fig. 3 Microstructure of 15 wt% SiCp Al composite processed at (a) 300 rpm (b) 500 rpm and (c) 700 rpm. The formation of composites, porosity, and micro cracks are indicated

3. ábra 15 wt% SiCp Al kompozit mikroszerkezete különböző fordulatszám esetén: (a) 300 (b) 500 és (c) 700 fordulat/perc. A kompozitok kialakulásának, repedéseknek és pórusok helye az ábrán jelezve

They reported that at 300 rpm, it is observed from the micrograph that regions of clustering and micro porosity are detected. Moreover, the distribution of SiC is not uniformly dispersed. This indicates that 300 rpm is insufficient to achieve homogenous distribution of SiCp in the Al alloy matrix. With higher stirring speed of 500 rpm, an improved distribution of the SiCp is achieved. Moreover, vortex formation is found to be minimized at 500 rpm stirring speed thereby stabilizing centrifugation which may lead to minimal stirring efficiency and potentially severe air entrainment at higher stirring condition. At higher stirring speed of 700 rpm, the porosity in the microstructure is more pronounced. This condition is attributed to the vigorous vortex formation due to high stirring speed which enables oxide skins, gases and contaminants to be entrained in the melt. Furthermore, the distribution of the SiCp is not effective enough due to the formation of undesirable conditions such as large porosity and gas entrapment. Also, Aqida *et al.* [16] explained that low rpm of the stirrer applies less shearing force on the matrix metal and there is no space for the reinforcement particles (dispersed phase) to distribute uniformly throughout the matrix. Moreover, the dispersed phase has the tendency to agglomerate and form clusters. This happens due to the absence of the required force to resist it. At higher speeds of the stirrer the shearing force applied on the matrix metal is higher which creates the passage for the dispersed phase to move inside through the vortex created by stirring. The energy supplied by high speed rotation of the stirrer is strong enough to disperse the particles of the dispersed phase which causes uniform distribution of the dispersed phase into the matrix. It was also founded out by the researchers that on increased stirrer speeds there is chance for the gas particles to move inside the matrix and increase the porosity [16]. Hashim *et al.* [17] reported that it has also been indicated that the reinforcement particles occupy inter dendritic and secondary

dendrite arm spacing; therefore, the finer the spacing or the finer the matrix grain size, the better is the particle distribution. Also, the processing temperature effects the viscosity of the melt. The particle distribution is subjective to the viscosity change. So, the stirring speed is considered as a crucial factor in the fabrication of MMCs. The stirring action should be slow to prevent the formation of vortex at the surface of the melt, and care must be taken not to break the surface too often, which could contaminate the bath with dross. Use of a slowly rotating, propeller like mechanical stirrer is preferred by some foundries. In fact, results of laboratory studies indicate that the mechanical property of the casting are maximized by continuous stirring versus intermittent (hand) stirring. When induction melting, the furnace's natural eddy current stirring action usually is sufficient to disperse the particles, although supplementary hand stirring (with the power off) also is recommended to ensure that no particles have congregated in potential "dead" zones [18]. According to R. S. Rana *et al.* [19] porosity is a casting defect and is undesirable as far as Aluminium matrix composite castings are concerned. However, the process parameters of holding times, stirring speed, and the position of the impeller affect the development of porosity. It has also been reported by Vaibhav Ingle *et al.* [20] that the structural defects during casting like porosity are a result of unsatisfactory casting technology. Hashimet *et al.* [21] reported that the occurrence of porosity cannot be ruled out however, it can definitely be minimized. Porosity formation is caused by:

- i. Gas entrapment during vigorous stirring,
- ii. Air bubbles entering the slurry either independently or as an air envelope to the reinforcement particles,
- iii. Water vapor (H_2O) on the surface of the particles,
- iv. Hydrogen evolution, and
- v. Shrinkage during solidification.

Generally, this non uniformity and porosity are generated due to, difference in density between the liquid metal and the reinforcement, oxide skins, and formation of gases. Therefore, and optimum stirring speed and time are required in order to achieve uniform distribution in the matrix with less porosity. Also uniform distribution in the matrix with less porosity can be improved by: keep the viscosity within the allowed limit, alloys with minimum reactivity to the reinforcement must be used, covering the melt with an inert gas atmosphere to reduce the oxidation, giving heat treatment to the reinforcement particles to remove gas layer around the particle surface which impedes wetting between the particles and molten metal's, and stirring of the melt to minimize the settling of particles due to density difference [22-25]. Based on the studies highlighted, the stirring speed is recognized as an important process parameter for processing aluminum composite [26-29].

4. Effect of stirring blade number with angle on distribution of particles and porosities in casted CMMCs

The blade angle (Fig. 4) and number of blades are prominent factor which formed the vortex by the stirring on solid-liquid

mixing to transfers reinforcements particles into the melt from the liquid surface and lead to uniform distribution. Therefore, selection of a suitable blade angle, and numbers of blades are crucial to acquire good level of axial flow and shearing action [30].

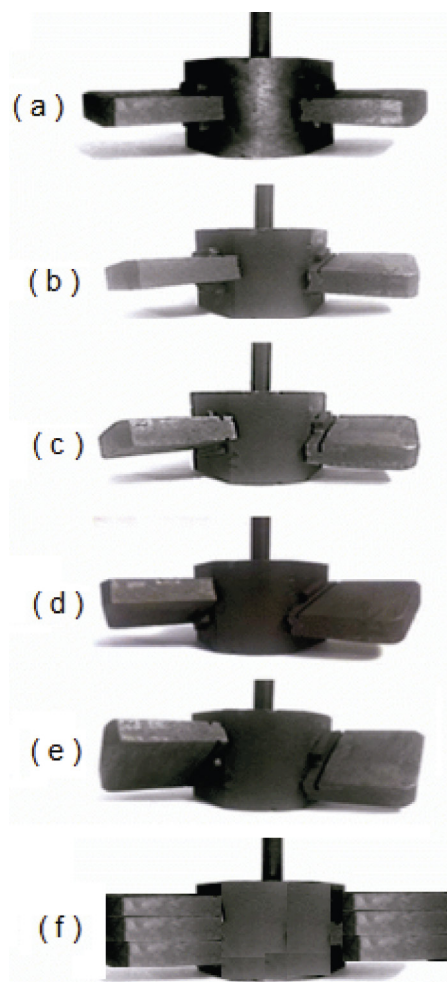


Fig. 4 Three blades stirrer, showing different blade angles (a) 0°, (b) 30°, (c) 45°, (d) 60°, (e) 75°, and (f) 90°

4. ábra Három pengés keverők, kiemelve azok különböző penge dőlési szögét: (a) 0°, (b) 30°, (c) 45°, (d) 60°, (e) 75° és (f) 90°

To investigate the effect of blade angle, researchers used water model and CFD model. They selected blade angle as 15, 30, 45, 60 and 90°. In a water model Ravi *et al.* [31] investigated the effect of impeller blade angle over the distribution of solid particles in the liquid. They found at low angle ($\alpha=15^\circ$) particles are dispersed below the stirrer. Impeller with blade angle ($\alpha=30^\circ$) performed well and shows uniform dispersion without concentration of particles. Whereas, impeller with high blade angle ($\alpha>30^\circ$), most of the solid particles concentrate at just below the tip of the impeller blade which results more radial variation. Thus, 30° was concluded as optimal value of blade angle with respect to stirrer axis which is in good agreement with FEM Model by Sahu and Lu. They attempted to reduce stagnant and dead zones in the flow pattern with blade angle 30, 45, 60 and 90° with respect to the impeller axis. Inactive zone in the cylindrical portion and bottom portion of the crucible are said stagnant zone and dead

zone respectively [32, 33]. Also S. Naher, D. Brabazon, L. *et al.* [34] observed that at 100 rpm and with 0 and 30 degree blade angles no uniform dispersion resulted, but with 45 and 60 degree blade angles there was full particulate dispersion. It is further observed for all stirring speeds that dispersion rates increase with increasing blade angle. The turbine blade also produces dispersion times similar to the best found for the flat bladed stirrers (Naher). They founded the uniform dispersion time for 10% SiC particles for different stirrer types and stirring speeds in water of viscosity 1 mPas. Whereas no dispersion occurred for the higher viscosity glycerol/water mixtures below 150 rpm. it was found that for most cases the 60 degree angle produced the lowest dispersion times. The turbine stirrer again produced the lowest dispersion time. Very similar results were observed for the higher viscosity (300, 500, 800 and 1000 mPas) glycerol/water mixtures tested. High blade angle ($\alpha > 90^\circ$) lead to high level of shearing flow and consume high power as well. Shearing action ensure the solid particle suspension in the melt but without axial suction pressure it is difficult to suck solid particles into the melt. The axial flow can be increased by decreasing the blade angle and significant axial flow was seen close to the liquid surface when the blade angle decreased to 30° [32, 33, 34]. Moreover, stirring time plays an important role over the distribution of solid particles and power consumption by the stirring motor. Kevin Kurian Paul and Sijo MT [28] reported that the Al-20 wt.% SiC composite samples by stir casting with 4 Blade Stirrer have high tendency to form particle cluster than 3, and 2 Blade Stirrer due to the homogeneity in mixing Sic additions to the composite which acts as a reinforcement for the aluminium matrix. Also, they confirmed that mechanical properties show greater strength and hardness for four blade stirrers than two blade and five blades. Many researchers [35,38] reported that the increasing vortex height as shown in Fig. 5 depend on stirring speed and viscosities of mixtures. Much greater vortex height observed in high stirring speeds and low mixtures viscosities.

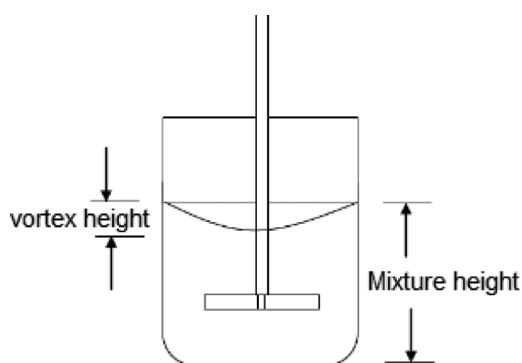


Fig. 5 Vortex and mixture heights
5. ábra Örvény- és keverékmagasság

Skibo *et al.* [37] proved that vigorously stirring in the melt so as to mix the reinforcement particles incorporated in the melt introduces a greater proportion of gas into the slurry. High velocity of slurry, due to higher stirring speeds forms a vortex on the surface of the slurry. The formation of a vortex on the surface was quite helpful in the movement of ceramic particles into the slurry of alloy and reinforcements. This was

attributed to the pressure difference created between the inner and the outer surface of melt, which pulls the ceramic particles into the melt. This has been reiterated by Ghosh and Ray [38] that the extent of porosity in a cast composite depends on the state of agitation and it can be reduced by the control of certain process variables. A vortex created during the stirring can suck the air or gas bubbles in to the liquid metal. As the results, the particles were attached with air bubbles to form the particles cluster in the matrix. At higher temperature ($>800^\circ\text{C}$), more particles cluster are found in the composite bar [39].

5. Effect of solidification rate on distribution of particles and porosities in casted CMMCs

In general, the solidification rate effect on distribution of reinforcement particles, grains size of metals matrix, and porosity which are essential to achieve optimum mechanical properties. The solidification rate is one of the most important factors that affects the reinforcement distribution in composites fabricated by gravity casting and has been investigated in depth both theoretically and experimentally. When the cooling rate is higher than the critical rate, the reinforcement distributes homogeneously in the composite. To improve the properties of composite, should reduce the stirring temperature, and solidify the liquid metal rapidly, or add alloying elements into the matrix alloy [40,41]. Muthazhagan *et al.* [42] observed by micro structure results of Al-B4C-Graphite composite revealed uniform distribution of reinforcements at a medium cooling rate of solidification whereas solidification at a slow cooling rate resulted in settlement of reinforcement at the bottom of the composite due to density variation of boron carbide, graphite and aluminium. Also, there is enough time for settling down of reinforcement particles at the bottom. Solidification at faster cooling rates resulted in entrapment of particles at the top of the composite. Solidification at faster cooling rates after a homogeneous distribution of the particles in matrix with minimum porosity formation is required to achieve optimum mechanical properties. Also A.Labib *et al.* [43] reported that the result of Al/Si-10 vol.% SiC composite properties are basically controlled by the solidification rate. Higher solidification rates promote homogeneous distribution of the SiC particles. Also M. Makhlouf *et al.* [44] confirmed that the cooling rate has a marked effect on the grains size, morphology, and distribution of all the microstructural constituents. Increasing cooling rate refines all microstructural features in size, changes the morphology of some reinforcement particles, and decreases the size of all intermetallic compounds regardless of their type. The rate of solidification in Al/Si composite depends on a balance between the rate of heat flow from the liquid to the solid through the interface and the latent heat of fusion released during solidification. The thermal conductivities of Al and Si in their pure form are 205 and 83 W/mK respectively, and their latent heats of fusion are 396 and 1411 J/g respectively. Since the difference between the magnitude of the thermal conductivity of pure Al and pure Si and the difference between the magnitude of the latent heat of fusion of pure Al and pure Si are large, Al will solidify and shrinkage much faster than Si as shown in Fig. 6(a).

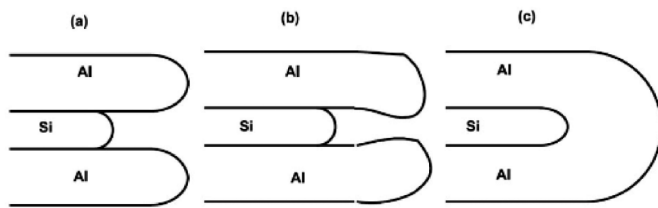


Fig. 6. Solidification in cast Al-Si alloys [53]

6. ábra Al-Si ötvözetek szilárdulási folyamata [53]

By fast cooling the different in cooling rate between Al and Si decreased which lead to solidified the Al completely over Si particle as in Fig. 3(b) and (c).

Pradeep Rohatgi *et al.* [45] also reported that the thermal conductivity and heat diffusivity of particles are generally less than those of the melt, and during the cooling process, the temperature of the particles will be higher than that of the melt. In such cases, it is difficult for the primary phase to nucleate at the particle surfaces. Thermal analysis showed that the unreinforced alloys exhibited undercooling for primary-phase nucleation, whereas the composites generally did not show any significant undercooling. The grain size of the composites is often smaller than that of the unreinforced alloy under identical casting conditions. Solute diffusion is impeded during growth due to the barrier effects of particles [46]. Solidification at faster cooling rates resulted in entrapment of porosity throw-out the composite whereas slow cooling rate form composite with less porosity due to enough time for releasing air bubbles during solidification. Generally, this non uniformity and porosity are generated due to, difference in density between the liquid metal and the reinforcement, oxide skins, and formation of gases. Also, uniform distribution in the matrix with less porosity can be improved by: keep the viscosity within the allowed limit, alloys with minimum reactivity to the reinforcement must be used, covering the melt with an inert gas atmosphere to reduce the oxidation [47].

6. Effect of reinforcement's weight percentage, particles size and on distribution of particles and porosities in casted CMMCs

The volume fraction, and particle size also influence the composite particle distribution. Anjan *et al.* [48] was prepared Al-SiC composites containing 5%, 10% and 15% weight fractions of silicon carbide particles by stir casting technique. The effects of volume fraction of SiC particles and its dispersion on the properties of Al/SiC composites were investigated. Anjan *et al.* Reported based on experimental evaluation that tensile strength and hardness were significantly improved by the addition of SiC particles, and clustering of silicon carbide particles in aluminum matrix were observed in microstructure and porosity level increased with increase in SiC Content. Also, Khalid Mahmood [49] Reported that percentage of SiC should be selected is in line with the information comprehensively reviewed. Also, 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 [50]. By decreasing

alumina particle size from micrometer to nanometer, more frequent interactions occur between Al and hard particles. Moreover, decreasing alumina particle size from micrometer to nanometer led to the reduction of alumina inter-particles distance. Decreasing the distance between alumina particles will increase required tension for dislocation movement between alumina particles and, consequently, enhancement of composite strength [50]. Microstructural analysis of the developed composites indicates that coarse size garnet mineral particles are uniformly distributed in the matrix of LM13 alloy compared to fine size particles. However, particle clustering is observed for fine size reinforced composites [51]. With higher percentage of reinforcements which were stirred for relatively longer time during their processing, have an increased amount of air bubbles sucked into the molten metal vortex. It was found that there is a positive correlation between the particle volume percentage incorporated in a composite and the porosity content of that composite. According to Surrappa [52], in cast metal matrix composites the occurrence of porosity can be attributed invariably to the amount of H₂ gas present in the melt, oxide film on the surface of the ceramic particle, which is drawn into the molten metal at the time of stirring. Vigorously stirred melt or vortex tends to entrap gas into the molten mixture. Nripjit *et al.* [53] also found that the porosity of the reinforced composite is more as compared to unreinforced alloys and goes on increasing with the increase in the volume fraction of the reinforcements in aluminium alloy matrices. In general, with increasing reinforcement weight percentage, and decreasing particles size a significant improvement in the mechanical properties were observed. On the other hand, a sharp reduction in the mechanical properties were observed which was finer particulate and high mass fraction addition level due to high possibility of agglomeration and porosity [54]. Wettability is another significant problem when producing cast metal matrix composites. Wettability can be defined as the ability of a liquid to spread on a solid surface to improve wetting of ceramic particles are:

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 particle matrix interface.

The proper dispersion of reinforcement materials was affected by pouring rate, pouring temperature and gating systems. This paper provides a comprehensive factor that effect on distribution of particles and porosities in casted CMMCs. several authors reported that uniform distribution of the reinforcement particles with less porosity is necessary for the improvement in the properties of MMCs like hardness, toughness, tensile strength etc. [55-58].

7. Conclusions

Stir casting is currently the most popular commercial method of producing aluminum-based composites. In this process, powder form as reinforcing phases are usually distributed into molten metal's by mechanical stirring. Non-uniform distribution, and porosity in casted CMMCs consider main disadvantages for stir casting process.

- During lower speed and lower stir time particle clustering occurred in some places, and some places were identified without inclusion.
- By increasing the stirring speed and stirring time better homogeneous distribution of SiC in the Al matrix were found.
- At higher stirring speed of 700 rpm, the porosity in the microstructure is more pronounced. This condition is attributed to the vigorous vortex formation due to high stirring speed which enables oxide skins, gases and contaminants to be entrained in the melt.
- Optimum stirring speed and time are required in order to achieve uniform distribution in the matrix with less porosity. Also uniform distribution in the matrix with less porosity can be improved by: keep the viscosity within the allowed limit, alloys with minimum reactivity to the reinforcement must be used, covering the melt with an inert gas atmosphere to reduce the oxidation, giving heat treatment to the reinforcement particles to remove gas layer around the particle surface which impedes wetting between the particles and molten metal's, and stirring of the melt to minimize the settling of particles due to density difference.
- Selection of a suitable blade angle, and numbers of blades are crucial to acquire good level of axial flow and shearing action.
- With 45- and 60-degree blade angles there was full particulate dispersion. It is further observed for all stirring speeds that dispersion rates increase with increasing blade angle.
- Dispersion rates increase with increasing blade angle, whereas no dispersion occurred for the higher viscosity glycerol/water mixtures below 150 rpm.
- Most cases the 60-degree angle produced the lowest dispersion times.
- High blade angle ($\alpha > 90^\circ$) lead to high level of shearing flow and consume high power as well. Shearing action ensure the solid particle suspension in the melt but without axial suction pressure it is difficult to suck solid particles into the melt.
- The axial flow can be increased by decreasing the blade angle and significant axial flow was seen close to the liquid surface when the blade angle decreased to 30° [39, 40, 41].
- Solidification at faster cooling rates after a homogeneous distribution of the particles in matrix with minimum porosity formation is required to achieve optimum mechanical properties.
- Solidification at faster cooling rates resulted in entrapment of particles at the top of the composite in some cases.
- Solidification at faster cooling rates resulted in entrapment of porosity throw-out the composite whereas slow cooling rate form composite with less porosity due to density and the enough time for releasing air bubbles during solidification.
- Solidification at a slow cooling rate resulted in settlement of reinforcement at the bottom of the composite due to density variation of boron carbide, graphite and aluminium.
- With increasing reinforcement weight percentage, and decreasing particles size a significant improvement in the mechanical properties were observed. On the other hand, a sharp reduction in the mechanical properties were observed which was finer particulate and high mass fraction addition level due to high possibility of agglomeration and porosity.

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