Role of Stir Casting in development of Aluminium Metal Matrix Composite (AMC): An Overview

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Abstract
Aluminium matrix composites (AMCs) have evolved itself in recent times as a source material for automotive applications, spacecraft applications, electronics applications and sports accessories applications. The reason for these numerous applications is their alterable mechanical properties such as good strength-weight ratio, better stiffness, excellent resistance to wear, precise coefficient of thermal expansion, improved resistance to fatigue, and better immutability at elevated temperature conditions. All these properties are fully dependent on processing/manufacturing methods and their processing conditions. In comparison to other composite development techniques, Stir casting is an adequate method as well as it is greatly acceptable in industries. Such wide acceptability of stir casting process is by the virtue of its adaptability, cost benefits and its superiority for mass production. Therefore, this review paper compiles the details of AMC and their manufacturing methods. Among various manufacturing methods, stir casting method is described in details along with its various parameters, such as size of impeller, impeller blade angle, and position of impeller Stirring speed and stirring time for the homogeneous distribution of reinforcing material. It is still a tough task for AMCs production firms and researchers to investigate the effects of stirring process variables on the particle distribution and also adequate selection of these variables. This review encloses the study of rigorous and specific attempts made so far to investigate the consequences of stirring variables in stir casting method. Additionally for AMCs production firms and researchers, Optimized levels of stirring variables are proposed for obtaining better mechanical characteristics.

Keywords: AMCs, stir casting, stirring parameters, aluminium matrix composites, optimization, distribution.

1. Introduction
Metal matrix composites (MMCs) are composite materials, which are improved in terms of properties as compared to the base material. The base materials in MMCs are known as matrix. The main role of enhancing the properties of base material is of reinforcement and the processing methods/parameters [1–6]. The reinforcement may be of metals, ceramics or organic compounds. Industries related to automobiles, spacecraft’s, and electronics are the vital application areas of MMCs, wherein aluminium matrix based composites (AMCs), copper matrix based composites etc. are mostly used. Aluminium matrix based composites are used due to their unique properties with comparatively at low cost [7–9]. In case of aluminium matrix composite, aluminium or aluminium alloy called as matrix material and reinforcing agents are mostly non-metals. The addition of reinforcing material in
aluminium matrix may of various shapes such particulates, whiskers or fibers with different weight %
or volume % [10]. The microscopic views of composite materials having various forms of reinforcing
agents are shown in Figure 1.

![Microscopic views of reinforcing agents](image)

**Figure 1:** Microscopic views of reinforcing agents; (a) top view of fibres, (b) whiskers, and (c) particulates [11]

Thus, obtained AMCs have unique characteristics such as good strength-weight ratio, better stiffness,
excellent resistance to wear, precise co-efficient of thermal expansion, improved resistance to fatigue.
One of the property, which make AMCs more demanding in spacecraft, automotive and structural
application is better immutability at higher temperature. The better immutability at higher temperature
is due to the reinforcing of particulate material. Wide range of certain modern applications which
requires properties like great electrical and thermal conductivity contained by AMCs makes them
advantageous over traditional metals and alloys [12,13]. But, the main role in enhancing or altering
the properties of AMCs is the methodology adopted for processing of composites [14,15]. The AMCs
can be prepared by any one of the method such as Powder metallurgy, Molten metal methods, Mixing
methods (Stirring Casting), Semisolid casting, Pressure infiltration, Pressure-less infiltration, Spray
deposition and XDTM process [16]. In case of mass production and cost effective, the best suited
method for development of AMCs is Stir casting [17]. This process proceeds with aluminium melting
as primary step. Under this melting, a thin lamina of aluminum oxide ($\text{Al}_2\text{O}_3$) develops due to reaction
between molten alumina and environmental moist, that can be understood by Eq. (1). This lamina
behaves as shielding agent and prevents furthermore reactions of molten metal [18].

$$2\text{Al} + 3\text{H}_2\text{O} = \text{Al}_2\text{O}_3 + 6\text{H}$$  \hspace{1cm} (1)

Uninterrupted oxidation of molten aluminium occurs due to continuous stirring and exposure of
molten aluminium to outer environment. Consequently the particulate reinforced particles maintained
in undiluted form due to which there will be reduction in the wettability of the aluminium. An inert
atmosphere is required to be developed for stopping this oxidation procedure, this includes huge of
difficulties. The extensively used method in AMCs development to overcome this difficulty is the
addition of wetting agents like TiK$_2$F$_6$, borax and magnesium [19,20]. One more problem with the
process is the uniform distribution of particulates in the molten aluminium that can be manipulated by
stirring variables. That is the reason behind importance of properly chosen stirring variables [21]. The
major variables which influence the distribution of reinforcing material are size of impeller, impeller
blade angle, position of impeller Stirring speed and stirring time. Thus, it is most important to know
the influence of each process variable on the AMCs development. Several investigations have been
reported on above variable for aluminium metal matrix composites [21–30].
Naher et al. [8] established a stirring set-up to understand the effect of various processing variable during stir casting. They used a liquid mixture (water and glycerine) as and matrix material by using matrix material analogous to aluminium alloy in a transparent molten pot to recognised a photographic flow pattern during the stir casting process. They found best suited stirring speed for regular distributions of particles is 100 rpm and 200 rpm for water and glycerol/water-SiC mix respectively. It was also reported by them that the pattern of regular distributions reduces with high impeller blade angles. Rajan et al. [14] used step by step various methods to develop the AMCs. They employed compocasting cum squeeze casting and liquid melt stirring. In development of their composite material, Al356 aluminium alloy was utilized as matrix material whereas the reinforcing agent choose were fly ash particles (13 µm APS). Density of 2.486 g/cc was decided to be picked for both solid and hollow spheres of fly ash. SiO₂ (59.46%), Al₂O₃ (26.05%), Fe₂O₃ (6.41%), Na₂O (1.21%), CaO (0.5%) and ZnO (0.1%) were the main compositional elements of fly ash. They concluded that reinforcing particle distribution is more regular in molten melt stir casting as compared to compocasting cum squeeze casting.

Nai et al. [21] developed aluminium based composite by using AA1050 (99.5 wt.% Al) matrix material along with SiC as reinforcing material having particulate size of 34.4 µm. Their investigation was aimed to find out the influences of speed of stirring on particulate distribution in composite which is based on functionally gradient materials (FGM) and proceeded using the gradient slurry disintegration and deposition (GSDD) process. The study concluded that the regularity in distribution of particles increases as a function of speed of stirring. Additionally, they reported that the refinement of grains of matrix material occurred due to the increase in amount (% wt.) of reinforcing particulates (i.e. SiC).

Hashim et al. [22] conducted the experiment to know the effect of process variables i.e. speed of stirring impeller and position of impeller, with respect to molten pot. Moreover, they also wanted to know efficient flow in molten mix, so that a regular distribution of reinforcing particulate could be achieved. Along with the physical experiment, they also conducted the process analysis using finite element method to optimize the parameters. It was concluded at the end that level of particle distribution, as better as will be the fine sized matrix material will be used, decreases as the level of gas entrapped in molten mix and influenced by particle volume, shape, size, density. Su et al. [23] executed their experiment to study the consequences on flow behaviour and the properties of aluminium matrix composite of varying stirring variables such as impeller blade angle, speed of stirring, size of impeller, and the shape configurations. The methodology employed for the study was based on finite element with CFD modelling. The study showed that particle gathered regions in stirring molten pot can be reduced by using stirrer with higher rotating speeds and also with multi stage stirring. Stirrer with multi blade equipped with blades of angle 30°, of size 0.55D, stirring at 1000 rpm results in regular particulate distributions.

Sahu and Sahu [24] employed the Taguchi approach to examine the fluid pattern pretended for finding best suited stirring variables such as blade angle, size of impeller, speed of stirring. They reported that the stirring speed of 550 rpm, stirring impeller size 0.5D, stirring impeller blade angle 30°, are to be best suited stirring variables. Prabu et al. [29] conducted the experiment employing microstructural analysis and hardness test on the samples for finding out the consequences of speed of stirring, stirring
duration on the development of composite having A384 aluminium alloy as matrix material and SiC (60 μm) as a reinforcing material. They used stirring impeller speed range 500-700 rpm and the stirring duration of 5, 10 and 15 minutes. They reported from their study that the molten melt containing the regions of staggered particulates and no particulates while stirring at lower speed, but the best distribution of particulates were found at 600 rpm with stirring duration of 10 minutes.

Thus various process variables have been considered during the development of AMCs composites. The present papers aims to construct a concise review on each process variable of stir casting process related to AMCs. In the next sections, detailed description of stir casting, followed by their process variables one by one.

2. Stir casting process

Stir casting is one of the methods of casting that involves mixing of reinforcing agent into base matrix material with the help of a mechanically operated stirrer. The process is adopted in MMCs development because of its economic rationality, mass production capability, ease in process and better regulations on structural behaviour of composite [25].

Schematic arrangements of stir casting are depicted in Figure 2. Stir casting process comprises a furnace, mechanically operated stirrer and reinforcement dispenser. The melting of the base material is done in furnace by heating. Bottom pouring furnace is more adequate for stir casting process because it does not provide enough time for molten mixture to stabilize at bottom of molten pot. Bottom poring method provides instant feeding of molten mixture in to molds. The proper mixing of molten matrix material and reinforcing material is required for generation of isotropic mechanical properties. This mixing is done with a stirrer, equipped with a stirrer rod and blades. The rotary motion of the stirrer produce swirls in the mixture which leads to proper mixing of molten mixture.

These mechanical stirrer can also be categorizes on the basis of geometrical shape and the counting of impeller blades. Among all stirrers, favourable is one whose impeller consists three flat type blades. It is due to the development of axial flow along with reduced consumption of power [24]. The speed of the stirrer can be controlled with the regulatory speed motor connected to stirrer for providing rotary motion. For feeding the reinforcing material, a feeder is also located along with furnace. The slurry can be poured to any of mold and it can of any type such as sand, permanent or an investment.

The series of different activities consisted in stir casting process are depicted in Figure 3. The procedure starts by keeping the matrix material in furnace equipped with lower feeding mechanism. Before feeding, the reinforcing agent must be preheated for preventing moist, and contaminants etc. A separate furnace is required simultaneously for preheating of reinforcing material [22]. After attaining a desired temperature based on the matrix material, mechanically operated stirrer is started to form swirl. Along the axis of this swirl the reinforcing agent allowed to fall through feeder with steady rate in the molten matrix material until the mixing of desired amount of reinforcing material.

![Figure 2: Schematic arrangements of various components of stir casting process.](image-url)
As mixing of reinforcing material into matrix material is over for desired duration, the state and colour of mixture is in liquid red hot form. The liquid red hot mixture is then poured into a preheated mold and left in it for cooling/solidification. The obtained casting of new MMCs are then taken for material characterisation as well as for various mechanical testing. Further, alteration in properties can be done by heat treatment, forging, extrusion and/or rolling.

2.1. Melting of matrix material
The fusion and mixing of matrix material with reinforcing material is usually done in a melting furnace. The furnace quipped with bottom feeding mechanism is utilized in stir casting process for the development of AMCs. The bottom feeding melting furnaces used in stir casting process are classified on the basis of attachment of molding equipment. Different bottom feeding melting furnaces equipped

![Flow diagram showing the procedure of stir casting technique](image-url)
in stir casting process are vacuum die casting type, squeeze casting type, rotary centrifugal casting type and extrusion type [22]. These classifications are utilizes in different applications according to required shape and geometry of cast object. The immediate feeding of mix is done by these mechanized bottom feeding furnaces. Lost wax casting or investment castings are the major application areas of bottom feeding mechanism, wherein the mold shells are created with slurry and feed through a pin hole from bottom of the furnace [26]. Stir casting involves melting and keeping the matrix material in furnace for duration of 2 to 3 hours. According to the instance of requirement, this molten mix can be fed to the molds through the attachments provided to bottom feeding furnaces. The reinforcing particulates are added in these molten matrix materials for development of composites [31]. Once the matrix material melts completely impeller of stirrer is started to develop swirl in mix.

2.2. Mechanical stirring

In stir casting technique, the stirring is an important parameter for proper mixing of reinforcing material into the metal matrix. It is performed by the mechanically operated impeller and its rotary motion. The rotatory motion required to mix the reinforcing material is provided by regulatory speed motor. The speed of impellor can be control using regulatory speed motor. The stirring process actually done by the impeller can be executed in several manner i.e. Single blade stirring, double blade stirring and multiple blade stirring [27]. Due to the economic affectivity by eliminating excessive swirl development, single impeller stirrer is mostly adopted for development of AMCs. However, double impeller and multi impeller stirrers are adopted for chemical production sectors [23,24]. In Figure 4, different kinds of stirring are shown. However, Figure 5 is showing particle distribution patterns using different kinds of stirring.

![Figure 4: Schematic diagram of: (a) Single blade stirring, (b) double blade stirring and (c) multiple blade stirring](image-url)
As the distribution of reinforcing agent is depends on the process of stirring, consequently it will affect the microstructural behaviour and mechanical behaviour of the newly developed AMC. The most common difficulty which occurs in various AMCs developing techniques as well as in stir casting, is the regular distribution of reinforcing agents [22,28]. Though, such difficulty can be resolved up to an extent by proper settling down of stirring variables. Matrix material, reinforcing material and their percentage, stirring speed, duration of stirring and feed rate are the important parameters, which affect the quality of developed composite. The optimized values of these variables are summarised in Table 1 for specific Al alloys with different reinforcing material. As per the Table 1, different and specific variables are chosen by the various researchers in the development of AMCs. From the Table 1, it also clear that the range of optimized values of stirring speed is 450–700 rpm, stirring time is 5 and 15 min and feed rate is 0.9–1.5 g/s.

Hence, the regular distribution of reinforcing material cannot be accomplished by random picking of process variables during stirring. It will lead the poor and non-homogeneous mechanical properties in the developed composite. Thus, it is challenging to predict the consequences of each and every variable of stirring and get the optimised variable and values for the development of any composite. The consequences of different stirring variables along with best suited values are proposed in next section.

2.3. Consequence and optimization of stirring process variables
Stirrer size (i.e. diameter of blade), stirring speed, duration of stirring, blade angle and feed rate of reinforcements are some process variables which greatly affects the distribution of reinforcing agent. Development of swirls in the mixture is the main motive of stirring by which the distribution of reinforcing agent is done. The equipped stirrer must consume less power and offer enough extent of axial flow, makes the process economical and best suited [22,27,28]. The effect of above mentioned process variables are described in next sub-sections.
Table 1: Different stirring parameters used in stir casting of different aluminium alloys

| S. N. | Matrix material | Reinforcing material | Reinforcing material % | Stirring speed (rpm) | Stirring time (min) | Feed rate (g/s) | Reference |
|-------|----------------|----------------------|------------------------|----------------------|---------------------|----------------|-----------|
| 1     | AA6061         | SiC/Fly ash          | 7.5-10 wt.%, 7.5 wt. % | 350                  | 10                  | 1.2-1.6       | [14]      |
| 2     | AA1050         | SiC                  | 18 wt.%                | 470, 380, 294        | 15                  | -             | [21]      |
| 3     | Al7075         | B$_4$C/Fly ash       | -                      | 500, 550, 600        | -                   | -             | [24]      |
| 4     | Al7075         | Basalt               | -                      | 600                  | 10                  | -             | [25]      |
| 5     | AA6061         | TiC                  | 3-7 wt. %              | Manual               | -                   | -             | [31]      |
| 6     | A384           | SiC                  | 10 wt. %               | 500, 600, 700        | 5, 10, 15           | -             | [29]      |
| 7     | Cast Al–Ti–Zr  | B$_4$C               | 5 Vol. %               | 600, 700             | 5, 10               | 1/60%         | [30]      |
| 8     | Al7075         | TiC/Graphite         | 5 wt. %/1-4 wt. %      | 550                  | 15                  | 0.9-1.5       | [32]      |
| 9     | A384           | Nano sized Al$_2$O$_3$ | 1, 2, 3, 5 wt. %     | 200, 300, 450        | 10                  | -             | [33]      |

2.3.1. Stirring speed

In development of matrix metal composite, distribution of reinforcing material largely affected by stirring speed. In this context, Prabu et al. [29] conducted a stir casting experiment to know the effect of stirring speed and stirring time on the hardness of casted SiC reinforcing based AMC. They have chosen three different speed of stirring as 500, 600 and 700 rpm as well as three different time duration of stirring i.e. 5, 10 and 15 min. They reported that the stirring speed as 600 rpm and duration of stirring for 10 min is the superior match for undeviating hardness value. Additionally, at these parameters, the distributions of SiC particulates are regular in the matrix of aluminium.

Raei et al. [30] used B$_4$C particulates as reinforcing material at two different stirring speed and found similar particle distribution. But the properties and ability of distribution of reinforcing agent of composite stirred at 700 rpm were more refined as compared to stirred at 600 rpm, which may also a
result of more B$_4$C content. Nai et al. [21] developed AMC by using AA1050 matrix material along with SiC reinforcing particles. The investigation was based on functionally gradient materials (FGM) and proceeded using the gradient slurry disintegration and deposition (GSDD). Stirring was performed at three speeds 470, 380, and 294 rpm and their effect on particle distribution were observed. In context of stirring speed, it reported that lower rotation speed (380, 394 rpm) did not provided enough swirl force to get regular distribution, whereas stirring speed of 470 rpm was found satisfactory for particle distribution. Sajjadi et al. [33] investigated the effect of amount of reinforcing particle (wt.%) and the stirring speed on distribution of particles in composite material. Al$_2$O$_3$ was selected as reinforcing particles added in different wt.% in matrix material and stirring was performed at various speeds 200, 300, and 450 rpm. Effects of these inputs were recognised using scanning electron microscopy (SEM), optical microscope (OM) equipped with image analyzer, energy dispersive spectroscopy (EDS) and X-ray diffraction (XRD). It was reported that among all stirring speeds 300 rpm was found satisfactory. Sahu and Sahu [24] employed FEM based computational fluid dynamics (CFD) methodology for study the consequences of various stirring variables on flow characteristics of molten mixture. Stirring was performed at three different speeds 500, 550, 600 rpm. Optimization of stirring variables was done by Grey Taguchi method. The particle distribution in molten mixture was observed by identifying particle gathered regions and particle dead regions in mixture developed with various stirring speeds. It was reported that least number of such regions developed with 550 rpm stirring speed. Therefore stirring speed of 550 rpm was found better for particle distribution.

Thus, to make the process more effective, economic, lowering the power consumption and increasing the flow characteristic can be achieved through a fundamental geometrical feature of impeller i.e. the blade angle of impeller. The details of blade angle of impeller are discussed in next section.

2.3.2. Impeller blade angle

The regular/homogeneous distribution of reinforcing particles in molten matrix material is achieved due to the developed swirls in the mixture by rotary motion of stirring blades. The axial forces produced in the swirls are the result of stirring speed, number of blades attached to the stirrer spindle and blade angle. Initially, the reinforcing particles starts floating on the surface of molten mixture, are pulled into molten bath by the swirls forces developed due to the rotation of stirrer. Additionally, swirls forces provides a shearing action on the reinforcing particles, in results aggregation of these reinforcing particles at a particular location is rectified. In shearing action of reinforcing particles, impeller blade angle have shown a significant role in distribution of reinforcing particles.

Thus, proper mixing of molten material and reinforcing particle is essential to attain desirable homogeneous properties of composites. A schematic representation of an impeller blade angle is shown in Figure 6, wherein the angle of blades to shaft are clearly mentioned with stirring axis. Several investigations have been done by different researchers so far, to investigate the effect of impeller blade angle. In study of these investigations, some researchers have adopted computation modelling. In computational modelling, computational fluid dynamics (CFD) model was used, wherein study was done on water as fluid. Various blade angles were chosen by the researchers in the range of 15°, 30°, 45°, 60° and 90° [7,8,21,23,24,34].
Ravi et al. [7] performed the experiment to understand the effect of impeller blade angle on distribution of reinforcing material in mixture. During their experiment, a water model was utilized for study which contains the water in molten pot analogous to molten matrix material. They reported that the stirring with impeller blades having short angle ($\alpha = 15^\circ$), distributes the reinforcing particles only in region below of stirrer. Further, if the blade angle increased to moderate value ($\alpha = 30^\circ$), the homogeneous distribution was observed throughout the all regions of molten pot. But, as on increasing the blade angle ($\alpha > 30^\circ$), it was reported that the most of the reinforcing particles try to gathered right under the impeller. Such gathering of reinforcing particles produces radial variations. Therefore, stirring with impeller blade having 30$^\circ$ of angle is an optimized value to get uniform reinforcing particles distribution. Sahu and Sahu [24], used CFD based model (FEM based) to investigate the effect of different blade angles (i.e. 30$^\circ$, 45$^\circ$, 60$^\circ$ and 90$^\circ$) on the distribution of reinforcing particles. It was observed in their study that if the impeller is equipped with very high angle blades ($\alpha > 90$), requires high power consumption and provides extraordinary shearing of reinforcing particles. High power consumption makes the process uneconomical. It was observed that high blade angle produces extraordinary shearing which results in better dispersion of reinforcing particles but along with this a axial pulling force is also required to pull the reinforcing particles inside of molten mixture being stirred. Therefore, conclusively it was proposed that blade angle of 30$^\circ$ results in generation of moderate amount of both axial pull as well as shearing action. Along with impeller angle, another variable which affects the distribution of solid particulates is duration of stirring.

Naher et al. [8] performed the experiment to find the effect of impeller blade angle on particle distribution by utilizing water, transparent glycerol/water solution analogous to matrix material and SiC as reinforcing particle. The investigation was based on the pictures clicked during stirring by a camera whose shutter speeds were varied from 1/15 to 1/2000 second, while the aperture was automatically controlled. Stirring was performed at various speeds 100, 15, 200, 250, 300 rpm with various blade angles 0$^\circ$, 30$^\circ$, 45$^\circ$, 60$^\circ$, 90$^\circ$. They reported in their result that as the impeller blade angle increases the particles rapidly distributed in to mixture. Su et al. [23] executed their experiment to study the consequences on flow behaviour and the properties of aluminium matrix composite of varying stirring variables. The methodology employed for the study was based on finite element with CFD modelling. Stirring was executed by employing three turbine blade impellers with four different
blade angles 30°, 45°, 60°, and 90°. Particle distribution patterns in transverse section of molten pot using different blade angles at constant stirring speed of 500 rpm is shown in Figure 7. It was reported that shearing action increases with increment in blade angle but for forcing particle in to mixture a lower angle blade will be beneficial. Therefore, it was proposed that stirring at 1000 rpm with stirrer of size 0.55D with blade angle 30° will be appropriate.

![Figure 7: Particle distribution patterns in transverse section of molten pot using different blade angles at constant stirring speed of 500 rpm; a) 90°, b) 60°, c) 45° and d) 30° [23]](image)

Rohatgi et al. [34] used a transparent model system containing water as matrix material and SiC as reinforcing particle. The investigation was based on gravimetric technique through which the uniformity of particles was identified. Conclusively, it was reported that the distribution of particles improves as the angle of impeller increases but with the expenditure of high power consumption i.e. the power required for homogeneous mixing, increases with blade angle from 20° to 60°.

2.3.3. Stirring Duration

Duration of Stirring is also a crucial variable of stir casting. It is observed that stirring the molten mixture for only few minutes produces bunching of reinforcing particles and gathered regions of reinforcing particles. This results in unregularly distribution of reinforcing particles and thus non-homogenous mechanical properties of composite. On other hand, if the stirring is done for longer duration, this result in the plastic deformation of stainless steel impeller blades due to stresses developed on blade material reaches their yield limit. Particle distribution patterns in molten at different stirring speeds using multiple blade stirring is shown in Figure 8. Certain particulates like B$_4$C are mixed with their aluminium matrix material at great elevated temperature of range 850–950°C. Stirring at such high temperature with high blade angle may results in deformation of the impeller [26]. Prabu et al. [29] investigated the fabrication of aluminium metal composite (AMC), composed of SiC as reinforcing particles. In their experiment, they examined the variation in hardness as well as the microstructural behaviours as an effect of varying stirring duration. They reported that the 10 min duration is an optimised duration of stirring for getting refined regular distribution of reinforcing particulates. This regular distribution leads homogeneous hardness all over the composite. Raei et al. [30] utilized B$_4$C as reinforcing particles in cast Al–Ti–Zr matrix material in development of AMC. For assessing the distribution status, reflected light microscopy (RLM) and field emission scanning electron microscopy (FESEM) equipped with EDX were adopted. Stirring was performed in two sets of duration and rpm: 5 min with 700 rpm and 10 min for 600 rpm. It was reported that in cast
samples, microstructures that 5 min stirring results in gathered regions of particles. However, the samples of 10 min stirring showed few gathered regions and better distribution. Akbari et al. [35] conducted the experiment based on field emission scanning electron microscope (FESEM) in development of A356/nano-Al2O3 composite. In composite development stirring was done at uniform speed 450 rpm and in four different stages of 4, 8, 12, 16 minutes durations. It was reported that the increment of stirring duration results in increment in mating surfaces of aluminium and nanoparticles which causes porosity in composite structure. Guan et al. [36] reported in their study that increasing in stirring duration may results in homogeneous particle distribution. Their experiment was based on electron microscopy of cast samples developed by stir casting of 5% ABO and 15% SiC particles in matrix material of Al6061. In Composite fabrication the stirring was performed at various temperatures 680°C, 650°C, 640°C and 630°C, along with different stirring durations for 10, 20, 30 minutes. It was stated conclusively that stirring duration of 30 min with stirring temperature of 640 °C is optimum for proper particle distribution. Singh et al. [37] proposed in their investigation that the feeding high wt/vol./% of reinforcing particle in matrix material, may result in to bunching/gathering of particles. Therefore, they recommended more duration for stirring.

**Figure 8:** Particle distribution patterns in molten pot at different stirring speeds using multiple blade stirring; a) 300 rpm, b) 600 rpm and (c) 1000 rpm [23].

It is also concluded from various investigations that undesired stirring of the molten mix is matter of huge power intake. This makes the stirring process uneconomical. So in order to make the process efficient and economical it is required to choose optimized duration of stirring. In addition to stirring duration, impeller blade size also influence the reinforcing particle distribution at a great extent, which is discussed in further section.

2.3.4. Impeller blade size

In the stirring process, the stirring impeller may equipped with single, double or multi blades. The size of these blades also has their significant effect on particle distribution and to develop the composite properties. Basically, the diameter of the blades attached to impeller is referred as the impeller size. The size of impeller blades (d) are given in proportion of the melting pot diameter (D). A schematic representation of diameter of impeller blade and melting pot is shown in **Figure 9**. It has been reported that stirring with very small sized impeller provides the deficiency of the reinforcing
particles in the central vicinity of the molten pot [18,24,38]. Such, phenomenon are observed due to suspension of most of the particles at the edges of the molten pot. However, if the impeller size is too large, the reinforcing particles gathered at bottom of the central portion of the molten pot [23,24,38–40]. Particle distribution patterns in molten pot by using different sized impeller with multiple blade stirring is shown in Figure 10. So conclusively, the best suited size of impeller is that which enables the distribution of reinforcing particles uniformly to central position as well as at edges of the molten pot. The impeller size (d) for the molten pot built with even plain baseline, equipped with single blade and stirring at 550 rpm, is proposed to be 0.5 times of melting pot diameter (D) [24,30]. However, for the molten pot built with semi spherical baseline, equipped with multi blade, stirring at 1000 rpm is proposed to be 0.55 times of melting pot diameter (D) [23]. Though, the width of impeller blade (b) is proposed 0.1–0.2 times of melting pot diameter (D) [22].

![Schematic diagram of impeller and molten pot along with their diameter](image)

**Figure 9:** Schematic diagram of impeller and molten pot along with their diameter

Thus, it has been investigated by several researchers that employing suitable stirring process variables such as stirring speed, impeller blade angle, stirring duration, impeller blade size, and feed rate, may result in effective and efficient stirring of the mixture. As a consequence the bunching/gathering of particles eliminated and stirring enables the distribution of reinforcing particles uniformly to central position as well as at edges of the molten pot. The particles which are distributed to central position along the axis of the molten pot are due to dispersion mechanism [36]. Further, it was noticed that the dispersion mechanism is the only reason of axial distribution of particles. It is reported that at the initial stage of stirring process the reinforcing particles get lifted from the bottom of molten pot towards its top.
Figure 10: Particle distribution patterns in molten pot by using different sized (d/D): a) 0.25, b) 0.5 and c) 0.55 using impeller having multiple blades [23]

The lifting of the reinforcing particles can be understood by a concept of Ekman boundary layer [22,23,41]. According to Ekman boundary layer theory, there will be a generation of secondary flow in axial direction of fluid when the momentum in the fluid if forced from higher to lower momentum sections through the Ekman layer. For Ekman boundary layer developed in single-phase fluids, the relation between duration of stirring (t) and the velocity character (Ve) are depicted in Eqs. (3) and (4) respectively.

\[ t = \left( \frac{E \Omega^2}{2} \right)^{-1/2} \]  

\[ V_e = \frac{H_0}{t} \]  

Here E is the Ekman number, \( \Omega \) is container’s angular velocity and \( H_0 \) is the height of melt. The Ekman boundary layer theory have described that the lifting of particles swirling in a rotating fluid can be related to other fluid flow variables with a parameter known as particulate dispersion number (PDN). The particulate dispersion number (PDN) defined as the ratio of specific velocity in Ekman boundary to the terminal velocity. As the value of PDN exceeds to unity, the secondary flow velocity in the axial direction of swirl becomes larger as compared to the settling velocity. In results, particles are forced towards top of the melt. But, if the PDN number remains under unity particles tends to persist towards bottom of the melt. The PDN number for the fluid swirling in a cylindrical container rotating coaxially is given by Eq. 5 [41,42].

\[ PDN = \left[ \frac{H_0 (\mu \omega)^{1/2}}{r_t^{1/2} d^{3/4} V_t} \right]^{1/2} \]  

Here, \( H_0 \) is the melt height, \( \mu \) the viscosity of the mixture developed, \( \omega \) is the container’s angular velocity, \( r_t \) is the radius of the inner cylinder, \( d \) is the radial distance between outer and inner cylinders, \( V_t \) is the settling velocity of particulates. The reinforcing particles may form bunches or gathered in several location in molten mixture during stirring process. It is investigated that this gathering can be eliminated by proper feeding rate of reinforcing particles during stirring. The effect of feed rate of reinforcing particles on particle distribution in mixture is discussed in section ahead.
2.3.5. Particle feed rate

The stirring process begins with the rotation of impeller and its blades to rotate the molten matrix material. This results in development of swirls in molten matrix material. As soon as these swirls start to develop, the feeding of reinforcing particles is done along the axis of these developed swirls. A continuous feeding of particles through the feeder is required to achieve regular distribution in molten mixture. The distribution of particles greatly affects by the feed rate by which these are fed to rotating molten mixture. Investigations done so far in stir casting proposed that the feeding of reinforcing particles in to rotating mixture should be done at constant feed rate. If feed rate vary it may lead to clustering of particles in mixture [43–46]. It is studied that feeding particles with lower feed rate results in formation of solid lumps of particles [32,47]. On the other hand, feeding with higher feed rate results into bunching/gathering of particles in the molten mixture [33] and may result in interfacial reactions between reinforcing particle and matrix material [48].

Kumara et al. [32] performed the experiment to observe the consequences of change in wt. % (1-5), feed rate (0.9-1.5 g/s) of particles on the hardness, tensile and wear strength of final material. Stir casting was adopted in fabrication of Al7075 matrix material based composites with TiC and Graphite reinforcing particles. From their results, it was reported that lower wt. % of reinforcing particle addition in to rotating mixture at higher feed rate results porous microstructure, non-homogeneity and clustering of particles. Additionally, feed rate of reinforcing particles should be accordingly with wt. % or vol. % of reinforcing particle being used in AMC fabrication.

Tahamtan et al. [48] employed the microscopic method to examine the effect of addition of reinforcing particles with A206 matrix material in two different forms. Al₂O₃ particulates and milled particulates of alumina, Al and Mg. in 5vol.% were used. Particles were feed to rotating mixture with respect to time over a period of 15-30 min. During this duration of feeding several samples were taken out. Microstructure of these samples was studied and reported that increasing feeding time lead to the interfacial reactions between alumina (reinforcing material) and molten alloy (matrix material).

Canakci et al. [47] executed the microstructural study of AMC samples using developed using B₄C reinforcing particle in AA2024 matrix. B₄C particles were added in different sizes (29, 71 μm) and in different volume fractions (3, 5, 7, 10 vol. %) with feed rate of 5-10 g/min. The observation made it highlighted that the uniform distribution of coarser grains of particles even at such low feed rate however, finer grains result in to segregated particle lumps with porosities. Thus, the selection of proper fee rate is a significant job in order to achieve regular distribution. It is reported from investigations performed by researchers that it is difficult to attain the feed rate under the value 0.8 g/s and attaining the value over 1.5 g/s causes particulate gathering. Therefore, it is found that the acceptable range of feed rate for elimination of gathering and to attain regular distribution of reinforcing particle all over the composite is 0.8–1.5 g/s [14,22,30,32,43,45,46,49].

3. Applications

Aluminium matrix composites (AMCs) are having their extensive applications in automotive production sector, spacecraft production sector, electronics production sector and also in sports accessories production due to their unique features. In automotive production sector AMCs are widely
Figure 11: Pictorial representation of various components used in automotive applications; (a) Fibre reinforced metal diesel piston, (b) Car brake disc of particle reinforced AMC, (c) Particle reinforced bearing assembled at ends of connecting rod and (d) Reinforced light weighted material casing [50,51].

Figure 12: Pictorial representation of Sports tool applications made up of AMCs; (a) Prosthetic limbs (b) Bicycle frame and (c) Golf stick [50,51]

utilized in production of automotive parts of engines, suspension system, driveline, housings of gears and brakes. In automotive applications, AMCs are also used for making the body structure and constructing mechanical parts like brakes, in disk brake rotors, pistons, piston rings and callipers etc. Various components made up from AMCs and used in automobile sectors are shown in Figure 11.

Applications in spacecraft production sector are propeller of jet engine, solar reflector based satellite and missile vanes. Table 2 depicting the applications of aluminium matrix composites in various sectors such as automotive production sector, spacecraft production sector, electronics production sector, in sports accessories production and also in military equipment productions. AMCs
are also having applications in naval crafts constructions due to the their unique properties i.e. light weight, highly anticorrosive, good fatigue and impact strength etc. Some of the pictorial representation of sport tool applications made up of AMCs are shown in Fig. 12. Along with pictorial representation of AMCs products, the wide-range information about the applications is discussed here in tabular form (See Table 2).

**Table 2:** Various applications of aluminium matrix composites AMCs [50–52].

| Market sector | Components | Property requirement | Type of AMC/ MMC being used |
|---------------|------------|----------------------|-----------------------------|
| Aircraft      | Engines    | Improved high temperature strength, creep resistance, stiffness. | Nextel/Al, Cu–Nb, Cu–Nb, Sn |
|               | Airframe   | Improved strength and stiffness | B/Al                        |
| Defence       | Tank tracks| Lower density, higher wear resistance. | SiC/Al                      |
|               | Missiles   | Better high temperature strength, higher modulus. | Nextel/Al, Cu–Nb, Cu–Nb, Sn |
|               | Armour     | Complex high rate properties | Bn / Steel                  |
|               | Torpedoes  | Higher modulus and strength | Nextel/Al                   |
| Automotive    | Engines    | Improved high temperature strength, fatigue and wear Better Match to CTE of steel in certain components | SiC/Al, SiC/Al, SiC Mg, Al2O3/Al, TiC/Al, etc. |
|               | Brake callipers | Stiffness | SiCp/Al |
|               | Ring groove reinforced piston | Light weight, wear resistance at high Temperature | Al2O3/ Al-alloy |
|               | Shock absorber cylinder | Light weight, wear resistance, thermal Diffusivity | SiC / Al-alloy |
|               | Diesel engine piston | Light weight, wear resistance | SiC Al-alloy |
|               | Sprockets, pulleys, and covers Piston ring Piston crown | Reduced weight, high strength and stiffness, Wear resistance, high running temperature | Aluminum–aluminum oxide (short fibers) |
| Electronics | Substrates | Matched CTE of ceramic at low Density | Al/B, Al/SiC, Al/graphite foam, Etc |
|-------------|------------|-------------------------------------|----------------------------------|
| Satellites  | Lower (zero) CIE, higher stiffness, self-damping characteristics | B/Al |
| Space panels| Higher strength at temperature and low density. | Gr/Al, SiC /Al |
| SDI         | Higher thermal conductivity with high temperature strength. | Gr/Al |
| Sporting goods | Various | Higher stiffness, strength and high tech image | Al/SiC |

### 4. Conclusion

According to present scenario of necessities of different applications concerned to various production sectors and industries, this study highlights the reputation of various stirring process variables and identifies the prominent effect of these variables on the properties of aluminium matrix composites (AMCs) developed with stir casting technique. Lower cost of material, dominant strength, and light in weight etc., these are some essential properties of composite materials. This review also demonstrates the roadmap for attaining these essential properties of composites along with the proper selection of various stir casting variables in the development of aluminium matrix composites (AMCs). Therefore, presented review covers the consequences of tuning the process variables and their best suited values for getting optimum properties in developed AMCs through stir casting process. The study of consequences of stirring speed, impeller blade angle, stirring duration, impeller blade size and feed rate of particle was done and following conclusion were drained out:

1. In stir casting, the speed of stirring could be in the range of 200-1000 rpm. The higher speed of stirring creates turbulence in mixture. Therefore, the optimised speed of single stage stirring to be 550 rpm and for multi stage stirring is 1000 rpm.

2. The homogeneous particles distribution can be obtained by a proper combination of axial flow development and shearing of particle phenomenon. To achieve homogeneous particles distribution, best suited impeller blade angle must be of 30°. It also lowers the power expenditure of the process.

3. The regular distribution of particles along with prevention from the deformation of stirrer blades, the stirring duration variable also debated and proposed to be 10 minutes.
4. The size of impeller which, would lead to decrease counts of gathered and dead regions, designated through the diameter of the blades is proposed to be in a range of 50–55% of the diameter of the melting pot.

5. To eliminate the gathering of reinforcing particles during stirring, the feed rate of reinforcing particle in to molten matrix material should be in the range of 0.8–1.5 g/s.

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