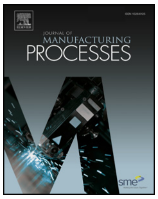
Journal of Manufacturing Processes 42 (2019) 213–245

Contents lists available at ScienceDirect

Journal of Manufacturing Processes

journal homepage: www.elsevier.com/locate/manpro



Review

A review on the production of metal matrix composites through stir casting – Furnace design, properties, challenges, and research opportunities

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ARTICLE INFO

Keywords:
Metal Matrix Composites
Production
Stir casting
Furnace
Squeeze casting
Matrix
Reinforcements
Mechanical properties

ABSTRACT

Stir casting is one of the most suitable processes for producing Metal Matrix Composites (MMCs) because of its simplicity, proven process, lower cost of production and mass production capability. This paper reviews all the significant attributes of stir casting process such as furnace design, properties of the composites, challenges in the production of the composites as well as the potential research opportunities in the production of composites. We have also provided recommendations for the furnace design, selection of matrix and reinforcement materials as well as process parameters and additives, which makes the review novel. In order to provide a background for any reader interested in the production processes for MMCs, we have also discussed the various approaches in the introductory section briefly. Based on the critical assessment of the literature, especially the mechanical properties of the produced MMCs, a bottom tapping stir casting furnace, preferably with electromagnetic and ultrasonic stirrer along with squeeze attachment is recommended for the production of MMCs.

1. Introduction

The composite material is a mixture of two or more materials insoluble in one another, and possess properties which are superior to any of the component materials. Composite materials are more robust and lighter than other common materials, such as steel. In the automobile industry, many of the components in a vehicle are being switched to the composites materials from steel to reduce the weight of the vehicle [1]. The wide range of reinforcing materials provision and the advancement of new processing techniques are drawing attention to composite materials enabling large-scale production. The composite materials are broadly classified into two categories concerning the matrix and reinforcement materials used for production. According to the matrix material, it is classified as Metal Matrix Composites (MMCs), Ceramic Matrix Composites (CMCs), Polymer Matrix Composites (PMCs) and Carbon Matrix composites (referred as carbon composite). Among these, MMCs has an advantage over other composites because of their ability to resist high temperatures, moisture, radiation and zero outgassing at vacuum, thermal and electrical conductivities, enhanced mechanical properties [2]. MMC is a combination of ductile metal or alloy matrix reinforced with other metal, nonmetallic or organic compounds [3]. It is produced by implanting the reinforcements into the metal matrix. MMCs can be produced using a strong reinforcement material which is incorporated into a matrix material to improve its properties such as specific strength, specific stiffness, wear resistance, excellent corrosion resistance and high elastic modulus [4].

Among the available matrix materials (Al, Mg, Cu, Fe, Ti) for MMCs, Al and Mg are the common ones. Magnesium-based composites have fascinated significant attention due to its attractive mechanical properties over monolithic alloy. However, some disadvantages have

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Abbreviations: Al, aluminium; Al_2O_3, aluminum oxide; AMC, aluminium matrix composite; AMMC, aluminium metal matrix composites; ARB, accumulative roll bonding; B_4C, boron carbide; BN, boron nitride; CG, centrifugal casting; CMCs, ceramic matrix composites; CNT, carbon nanotubes; Cu, copper; EMS, electromagnetic stir casting; Fe, iron; GNP, gold nano-particles; GPI, gas pressure infiltration; HB, Brinell Hardness; HEBMMS, high energy ball mill mixing and sintering; HRB, Rockwell Hardness B scale; HPCI, high pressure centrifugal infiltration; Mg, magnesium; MI, melt infiltration; MMCs, metal matrix composites; MS, microwave sintering; PI, pressure infiltration; PM, powder metallurgy; PMCs, polymer matrix composites; RVS, rapid vacuum sintering; SC, stir casting; SD, spray deposition; SE, screw extrusion; SGC, stir gravity casting; Si, silicon; Si_3N_4, silicon nitride; SiC, silicon carbide; SiO_2, silicon dioxide; SPS, spark plasma sintering; SSQ, stir squeeze casting; Ti, titanium; Ti_3SiC_2, titanium silicon carbide; TiB_2, titanium diboride; TiC, titanium carbide; TiN, titanium nitride; TiO_2, titanium dioxide; VGS, vacuum/gas sintering; VI, vapour infiltration; VH, Vickers Hardness; VPI, vacuum pressure infiltration; WS_2, tungsten disulfide; Zn, zinc; ZnO, zinc oxide; Zr, zirconium; ZrB_2, zirconium diboride; ZrO_2, zirconium dioxide

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https://doi.org/10.1016/j.jmapro.2019.04.017
Received 15 September 2018; Received in revised form 17 December 2018; Accepted 18 April 2019

restricted the progress of magnesium usage in automobiles. The primary reason is the low ductility and low resistance to fracture. Mg is very reactive at elevated temperature. However, it can be controlled with surface coatings or its naturally occurring oxide [5]. During the production of Mg-based MMCs, an inert atmosphere should be maintained to avoid oxidation with the environment. A significant disadvantage of using iron as the matrix is its brittleness and less impact strength compared with composites. Therefore, steel-based metal matrix composites show great potential only for wear-resistant applications. It is not suitable for marine environment application [6]. Copper-based MMCs are mainly used for the application where the thermal and electrical conductivity property plays a significant role. For many applications, pure Cu cannot be used as a matrix because of its low strength [7]. Among the several available matrix materials, aluminium and its alloys are widely used to produce MMCs. Some of the attractive properties of aluminium are less weight, economically feasible, easy to process with different techniques and possess the high strength to weight ratio and excellent resistance to corrosion [2].

The reinforcements could be particulates, fibre, layer or even interpenetrating type. According to the reinforcement used, composite can be classified into fibre reinforced composites, laminar composite, flake composite, filled composite and particulate reinforced composite. In this review, the focus is on particulate reinforced composites, since they are readily available, cheaper and easier to disperse it in the matrix and relatively uniformly distributed in the matrix. The selection of reinforcement materials is based on the objectives and applications of the composite. The reinforcement of light metals opens up the possibility of application where weight reduction has priority [8]. Al reinforced with SiC or Al_2O_3 or B_4C is one of the most commonly used MMCs which produce improved mechanical properties at relatively lower production cost. Because of this, many engineers have been attracted to utilize Aluminium Metal Matrix Composites (AMMC) for various applications such as brake rotor, drive shafts, pistons, cylinder liner, etc. [9]. The interfacial bonding in the composite materials is a serious concern during the fabrication of composite materials. If the matrix and reinforcement materials are not appropriately tailored, then it is difficult to get the expected properties from the fabricated composites. Fig. 1 shows the various matrix and reinforcement materials that can be used for the production of MMCs.

The AMMCs properties mostly rely upon the processing method, and so the selection of production process plays an important role to comply with the industrial needs and to provide functional properties [10]. The disadvantage of producing AMMCs, in general, is a higher cost of the reinforcement materials, non (or heterogenous) homogeneous reinforcement distribution in the matrix and higher investment cost in some cases. The cost-effective method for manufacturing composites is essential for expanding their applications [11]. The primary fabrication methods used for bulk AMMCs are stir casting, compo casting, infiltration, a direct melt oxidation process and powder metallurgy [12].

Based on the literature reviewed, especially review papers on MMCs, it is evident that recently there has been no comprehensive review, especially on AMMCs produced through stir casting. Kamyar et al. [13] reported 19 review papers have been published in the area of MMCs since the year 2000 and out of this 10 of them discuss the production techniques. Kaczmar et al. [14] briefly discussed the production processes, and not all liquid state processing are reviewed. The focus of Torralba et al. [15] is the production of MMCs through powder metallurgy route. Mg-based MMCs is the focus of Ye and Liu [16] and only one subsection focusses on the production processes. Again Miracle [17] only discusses the production processes briefly, and the focus is on the MMCs properties that make them suitable for several applications.

Similarly, Qu et al. [18] also focused on MMCs for thermal management applications. Ye et al. [19] focused on MMCs production through a metal injection moulding process. Bakshi et al. [20] and Silvestre [21] have reviewed MMCs reinforced with carbon nanotubes and so very specific and does not cover a broad spectrum of reinforcement particles as well as the production processes.

Similarly, Casati and Vedani [22] focussed on nanoparticles reinforced MMCs. Kala et al. have given mechanical and tribological properties of Al-based MMCs produced by stir casting attention [11]. Therefore, it is quite evident from this review that so far none of the reviews have focused on the primary production process such as stir casting process. There are very few review papers on MMCs that focus on the stir casting process. Kumar and Menghani [23] reviewed stir casting process and its issues, however, the developments in stir casting design and recommendations are not covered. Although the processing

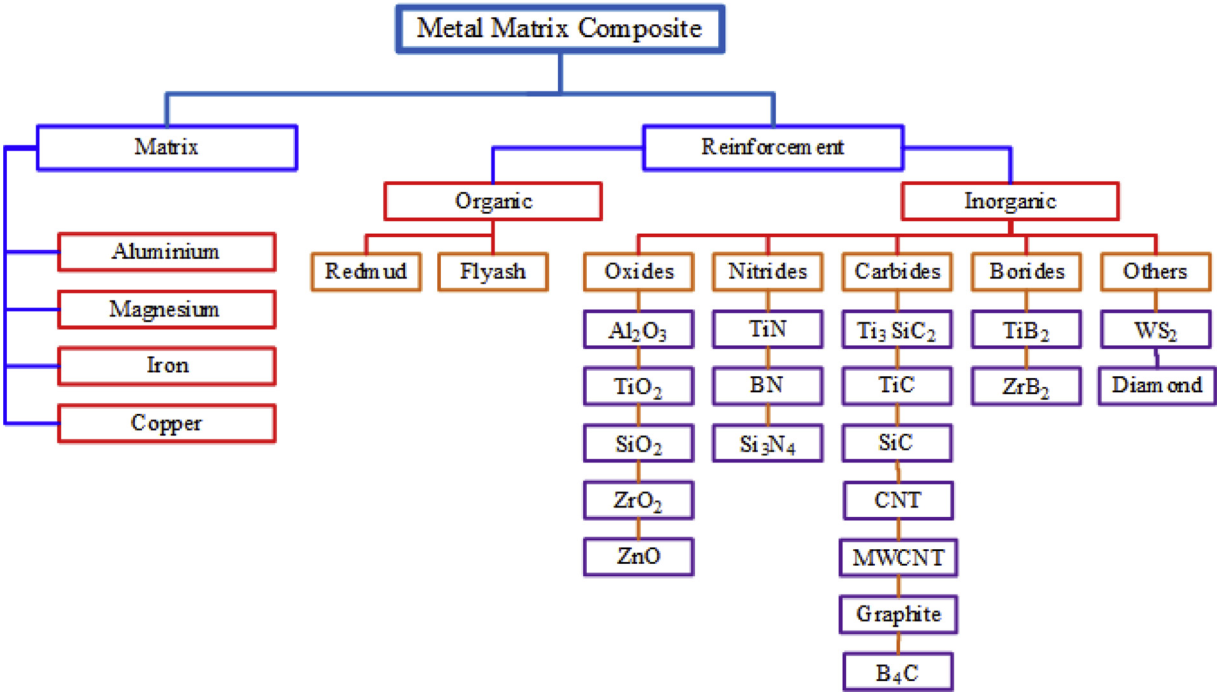


Fig. 1. Various matrix and reinforcement materials used for the production of MMCs.

issues in the production of AMMCs by stir casting is discussed by Suthar and Patel [24], machining and applications of AMMCs are also discussed, and so it is entirely different from this review. Kumar et al. [25] briefly reviewed the fabrication and characteristics of MMCs produced by stir casting. Shabani and Mazahery [26] introduced a new method called semisolid agitation process in the stir casting process, as a result, improved the mechanical properties of the composites.

Similarly, Mistry and Gohil [27] have reviewed the various fabrication processes including stir casting for AMMCs followed by mechanical characterization and applications. Bhaskar et al. [28] also reviewed the manufacturing and technological challenges in the production of MMCs using stir casting process. However, in the latter three reviews, the focus is more on the mechanical characterization and lacks assessment of many stir casting furnace designs. Although challenges are mentioned, they are very brief and not consolidated. None of them discusses the recommendations and research opportunities especially in the production of AMMCs. Stir casting and infiltration processes account for almost 67% by volume of MMCs produced [17], and so this review is the need of the hour. This review is structured as follows:

- First, it describes the various production processes for MMCs by using schematic illustrations.
- Following this, several stir casting furnace designs are discussed again with the help of schematic illustrations. Stir casting is evaluated because of it being an established and economical process to produce AMMCs. The recommended furnace design is also provided in the later section so that the researchers can make an informed decision in choosing a furnace for producing AMMCs that will exhibit the desired properties.
- The next section focuses on AMMCs by discussing and comparing the properties of matrix and reinforcement materials especially Al_2O_3 and SiC. The process parameters that can influence these properties, as well as additives that can enhance these properties, are also discussed.
- Finally, challenges in the production of AMMCs using stir casting and recommendations to overcome the challenges are discussed and concluded by highlighting some of the advanced application for AMMCs and possible research opportunities.

The discussion on recent commercial applications is also updated when compared to published literature. The discussion on challenges in the production of AMMCs is also new, and the recommendation to overcome these challenges is a new contribution to the existing knowledge base on AMMCs. The uniqueness of this review lies in the evaluation of many stir casting furnace design and the recommended one for producing AMMCs for various applications. In summary, this review is not only comprehensive but also structured and presented in a way that allows for clear evaluation by the readers themselves. A framework of this review is illustrated schematically in Fig. 2 using a fishbone diagram. This cause and effect diagram is also unique since it very succinctly captures the factors that influence the quality of the MMCs. To achieve the desirable properties, there are several challenges that could be overcome by using the recommendations including the furnace design that will enable the various applications for AMMCs. The prominent ones for each factor like production process, stir/squeeze parameter, matrix, and reinforcement material and the wetting agent is highlighted in yellow colour. Finally, the research opportunities that could be pursued are also shown in the schematic.

2. Production processes for MMCs

Fig. 3 shows the evolution of the production processes used by researchers worldwide for the production of MMCs. The data is presented chronologically based on a Scopus database search (Search terms: Aluminium Metal Matrix Composites; Production Method Names) conducted on 4th April 2018. The evolution of the stir casting process is highlighted in yellow colour, and the final text box refers to the recommended stir casting furnace design discussed later in Section 6.1.

The production processes for MMCs can be classified according to whether they are based on primary processes such as treating the metal matrix in a liquid or a solid form or others (including semi-solid, in situ and others) as shown in Fig. 4. The production processes have a significant influence on the mechanical properties as well as the cost of production. Particulate-reinforced MMC materials may be produced either through bulk processing or applied as coatings. This section aims to discuss MMCs materials produced only through bulk processing. Each of the process mentioned in the classification is discussed with the help of a schematic. This section gives an overview of the various processes available for the production of MMCs.

2.1. Solid state processing/powder metallurgy

Solid state fabrication of MMCs is the process of bonding matrix material and reinforcements due to mutual diffusion arising between them in solid states at a higher temperature and under pressure. The following section discusses some of the conventional processes used for the production of MMCs.

2.1.1. Spark/plasma sintering

Razavi et al. [57] reported that sintering of Al_2O_3 (Matrix)–SiC (Reinforcement) composite was produced successfully using Spark Plasma Sintering (SPS). The general process of SPS is shown in Fig. 5. SPS increases mould and composite powder's temperature rapidly and the pressure applied during the heating can increase the driving force of process and enable the sintering process. Electrical current can condense the powder in the mould by creating many sparks between particles and creating a plasma environment. The composites obtained exhibited the highest hardness of 324.6 HV with 20 wt% Al_2O_3-SiC. Dash et al. [58] reported that the distribution of alumina particles in the aluminium matrix is homogeneous and uniform in micro composites.

2.1.2. High energy ball mill mixing and sintering

Bhatt et al. used high-energy ball milling and sintering (HEBMS) with the milling speed of 300 rpm to successfully produce a nanostructured metal matrix composite of Al-Mg reinforced with amorphous silica particulate. The general process of HEBMS is shown in Fig. 6. Maximum Hardness values observed from the nano-reinforced composites is 145.2 HV which is comparatively higher than that of micro reinforced composites. They observed that the distribution of reinforcement particle in the aluminium matrix is homogeneous at 20 h [59]. Li et al. produced Al2024-TiN nanocomposite using HEBMS which exhibited a Vickers hardness of 274HV [60]. Han et al. produced advanced Al-Al_2O_3 MMC through HEBM for selective laser melting which offered not only uniform distribution but also good flowability [61].

2.1.3. Vacuum/gas sintering

Vacuum and gas pressure sintering is the most commonly used sintering methods because of its good controllability and large-scale features [62]. The general process of vacuum or gas sintering process is shown in Fig. 7. The process is similar to HEBMS, but the difference lies in vacuum or gas sintering after compacting. Gao et al. noticed that the when sintering temperature increases to a particular temperature the alloys will have the minimum porosity, homogeneous microstructure and best hardness [63]. Zhang et al. [64] concluded based on the experimental result that the microhardness and fracture toughness for dense samples greatly depended on porosity and grain size.

2.1.4. Microwave sintering

Microwave sintering is a process of supplying electromagnetic filed energy directly to the material. By this method express heating is achieved all over the material with a condensed thermal gradient [65].

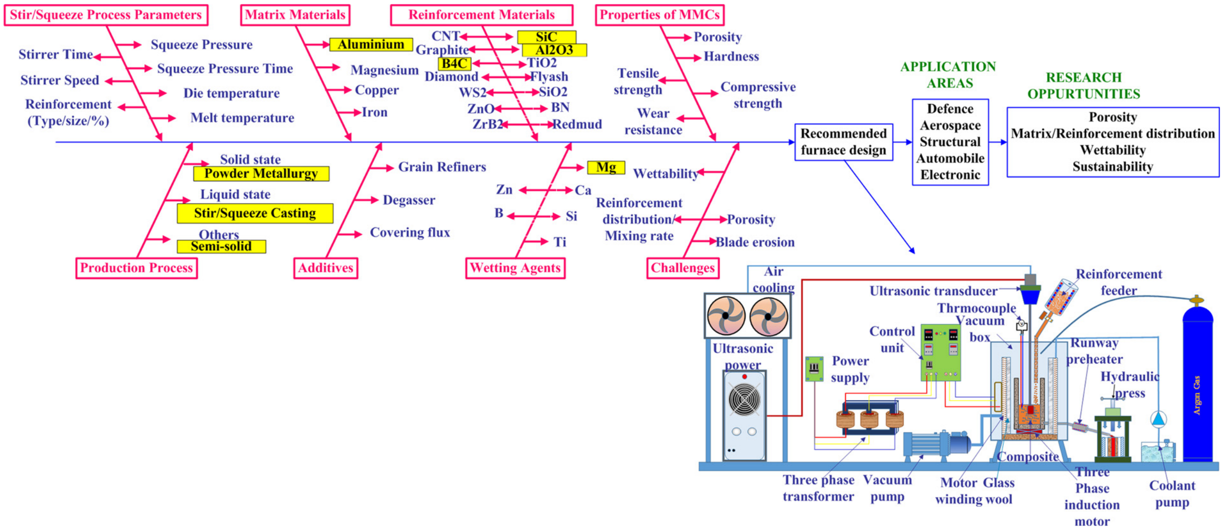


Fig. 2. A framework for producing better quality AMMCs by a stir casting process.

Microwave heating is a process by which the materials absorb the electromagnetic energy volumetrically and transform into heat. The heat generates within the material and dissipates to the entire volume. In microwave sintering, however, the composite materials themselves absorb microwave energy and then transform it into heat within their bodies as shown in Fig. 8. Microwave sintering appears to be an attractive alternative to plasma arc sintering for large specimens [66]. Reddy et al. [67] observed that the ductility of Al-SiC nanocomposites decreases with the increasing volume fraction of SiC. Compared to the other developed nanocomposites the microwave sintered and hot extruded nanocomposites revealed better mechanical and thermal properties. Through this process, the maximum compression and tensile strength achieved were 392 MPa and 178 MPa respectively.

2.2. *Liquid state processing*

Liquid state processing of MMC's is eye-catching to many industries as they are relatively simple and economical. These processes include either the infiltration methods of molten metal into preforms or fibre pack or by the casting methods such as mixing of molten metal with reinforcement particles. Infiltration methods include melt, pressure, gas pressure, vacuum pressure, vapour, high pressure centrifugal and squeeze casting. Casting methods include processes such as stir gravity, stir squeeze, stir vacuum and centrifugal casting.

2.2.1. *Infiltration methods*

Infiltration is a permeation of molten metal into a preform by the infiltration process. The infiltration can be achieved either by melt infiltration otherwise called as pressureless infiltration or by pressure infiltration. In melt infiltration, reinforcements are first placed in the die, and the molten alloy is then penetrated on to it and permitted to solidify without any external pressure. In the pressure infiltration process, external pressure is applied directly or through an inert gas, vacuum pressure, vapour, centrifugal force, and squeeze infiltration.

2.2.1.1. Melt infiltration. Zhou et al. successfully fabricated Al 6061-Ti_3SiC_2 composites by adopting pressureless infiltration method at low temperature with melt-spun Al alloy ribbons [68]. The phase reaction of reinforcements in the matrix material was performed at 950 °C. The maximum hardness and compressive strength achieved were 751 HV and 932 MPa respectively. Fig. 9 shows a typical setup used for melt infiltration. Gecu et al. [69] studied 304 SS chips which were added to the molten A356 alloy through melt infiltration method performed at 730 °C. It was identified that the sufficient preheating temperature improved the tribological properties of the composite.

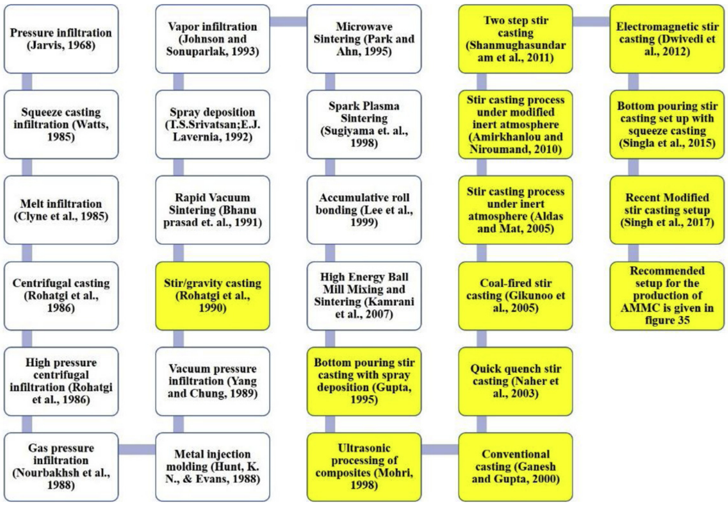


Fig. 3. Evolution of the production process for MMCs (Source: www.scopus.com) [24,29–56].

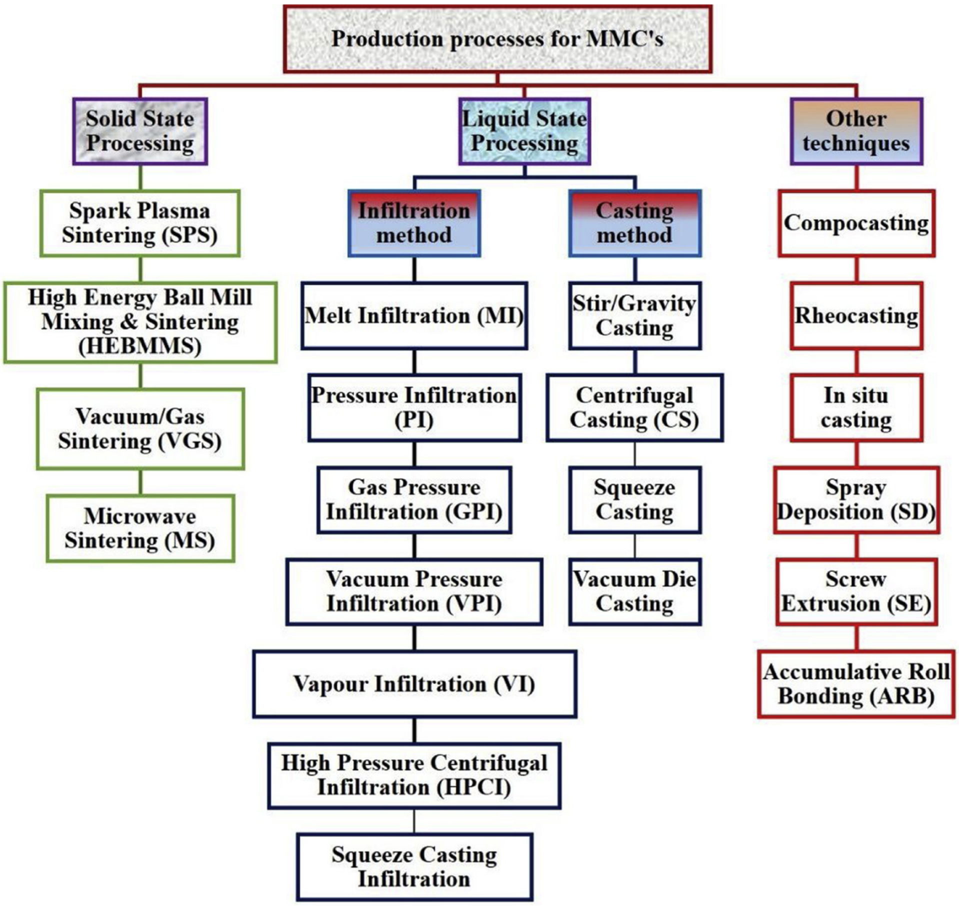


Fig. 4. Classification of the various production process for MMCs.

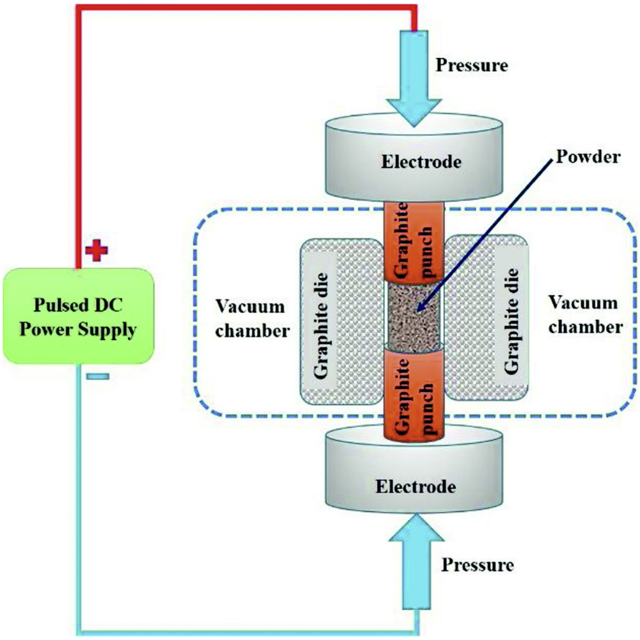


Fig. 5. Spark plasma sintering [Redrawn from [57]].

2.2.1.2. Pressure infiltration. Pressure infiltration process is used for making high reinforcement content in which molten metal or alloy is solidified in a mould packed with a reinforcement material. This process is shown in Fig. 10. Yang et al. [70] investigated graphene nanoplates reinforced pure Al composites by the pressure infiltration method. The work instituted that the pressure infiltration method can be used to produce Al/GNPs composites with excellent mechanical properties such as an increase in yield and tensile strength without the formation of aluminium carbide. Blucher [71] determined that the pressure infiltration method is suitable to produce composite parts economically. Compared to other production techniques, pressure infiltration method offers exceptional quality since the casting does not depend on matrix wetting the reinforcement [72]. Guo et al. [73] revealed that the pressure infiltration method shows better thermal conductivity due to the enhanced interface bonding between diamond/Al-12.2Si composites. Narciso et al. [74] fabricated Al-12Si/graphite composites and obtained good mechanical and thermal properties which are suitable for the production of piston engines.

2.2.1.3. Gas pressure infiltration. Gas pressure infiltration is a forced infiltration method of liquid phase fabrication of MMCs, using a pressurized gas for applying pressure on the molten metal and forging it to penetrate a preformed dispersed phase. This process is shown in Fig. 11. Li et al. [75] successfully prepared Al/diamond composites by gas pressure infiltration in a nitrogen atmosphere, which resulted in avoiding the formation of aluminium carbide and improved thermal conductivity [76].

2.2.1.4. Vacuum pressure infiltration. Vacuum pressure infiltration process is carried out using increased gas pressure. The reinforcing preform is placed in a mould consisting of a metal cylinder. A vacuum pump is connected between the mould and the metal bath. When the vacuum pump is switched on, molten metal is drawn into the preform. This process is shown in Fig. 12. Ma et al. [78] effectively fabricated 2-D carbon fibre reinforced aluminium matrix (C_f/Al) composite by

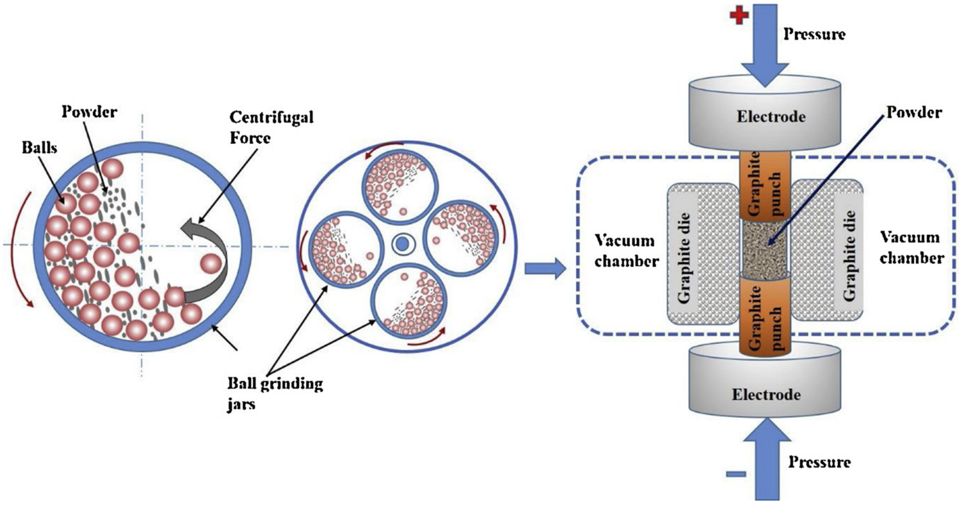


Fig. 6. High-energy ball milling and sintering [Redrawn from [59]].

applying vacuum pressure infiltration technique. The ultimate tensile strength is highly dependent on the appropriate specific pressure applied. The porosity level is considerably reduced in this technique.

2.2.1.5. Vapor infiltration. Vapour infiltration is a process in which matrix material is infiltrated into fibrous preforms with the aid of reactive gases at elevated temperature to form a reinforced composite. Vapour deposition is particularly useful for porous substrates, whereby the solid materials such as carbon, SiC, and other porous materials are infiltrated by matrix material from a mixture of CH_4 in an H_2 carrier gas at the elevated temperature illustrated in Fig. 13. Han et al. [79] prepared porous silicon carbide nanowire/silicon carbide (SiC_{nw}/SiC) composites by chemical vapour infiltration which resulted in excellent mechanical properties and poor microwave absorption properties. Mu et al. [80] fabricated $SiC_f/BN/SiC$ composites which resulted in high flexural strength.

2.2.1.6. High-pressure centrifugal infiltration. High-pressure centrifugal infiltration is a process in which a mould containing packed ceramic preform located at the end of an elongated runner is rotated. By controlling the metal level above the preform in the runner to be higher and constant throughout the infiltration process, significantly higher pressures are obtained. To fabricate MMCs, infiltration can also be achieved by using a high-pressure centrifugal force. Wannasin and Flemings [81] designed and constructed the high-pressure centrifugal infiltration equipment for the fabrication of MMC and is shown in Fig. 14. The primary results proved the new equipment designed and fabricated for this purpose have the potential to become future fabrication process for the production of MMCs.

2.2.1.7. Squeeze casting infiltration. Squeeze casting infiltration method is a process of applying a ram force to the molten metal. Aluminium is in a molten state and infiltrates the preform from the top end to the bottom end under the squeeze pressure. This method is similar to that of a conventional squeeze casting technique. Maj et al. [82] investigated the microstructure, and mechanical properties of $AlSi_{12}/Al_2O_3$ fabricated using squeeze casting infiltration method shown in Fig. 15. They obtained better hardness compared with as-cast material. Alhashmy and Nganbe [83] successfully fabricated carbon fibre reinforced aluminium matrix composites by using squeeze casting infiltration technique which resulted in improving wettability and homogeneous distribution. Squeeze casting assisted pressurization for the infiltration of reinforced particle preforms and prevented the formation of aluminium carbide [84].

2.2.2. Casting methods

Casting is one of the primary and established manufacturing processes that are capable of producing complex shapes in a variety of materials economically. In the casting process, molten metal is poured into a mould or a cavity and allowed to solidify to form a predefined shape. Primary applications include lathe bed, the structure of the milling machine, IC engine components, etc. The casted components generally have high compressive strength. This method is considered as cheapest among all manufacturing processes [86].

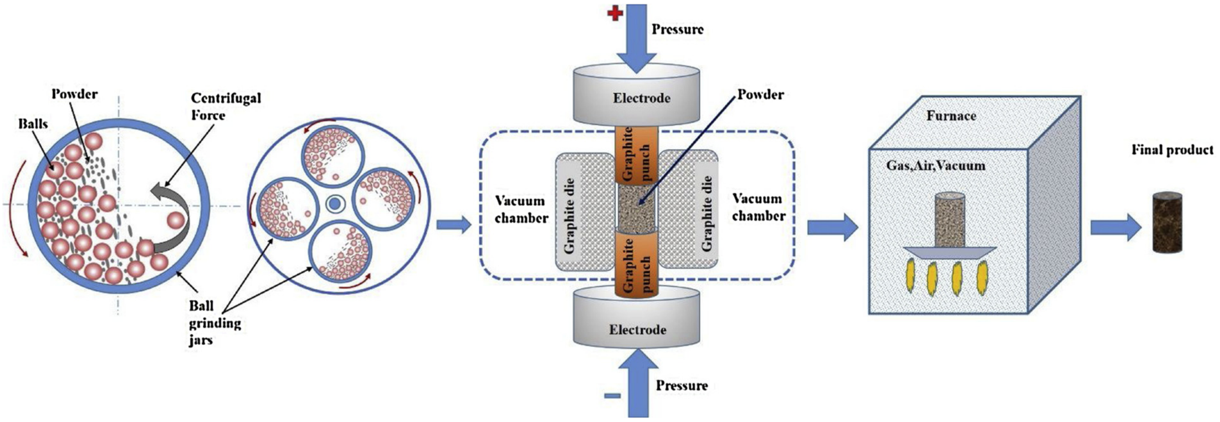


Fig. 7. Vacuum/gas sintering [Redrawn from [62]].

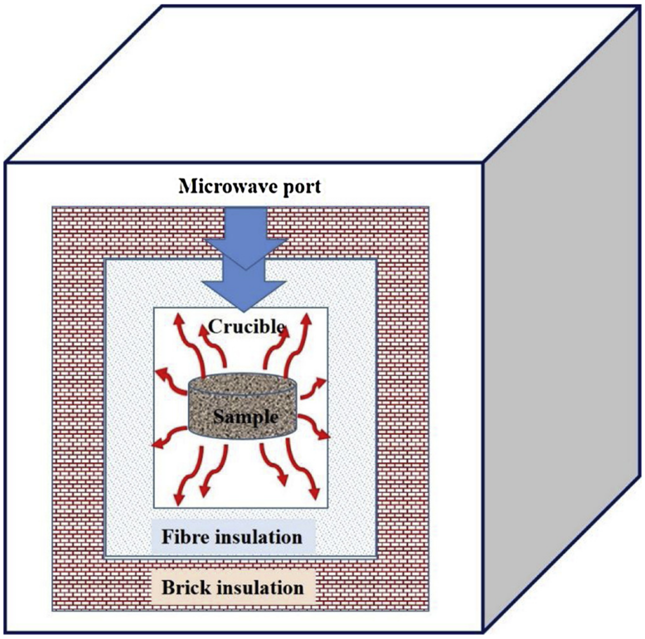


Fig. 8. Microwave sintering [Redrawn from [66]].

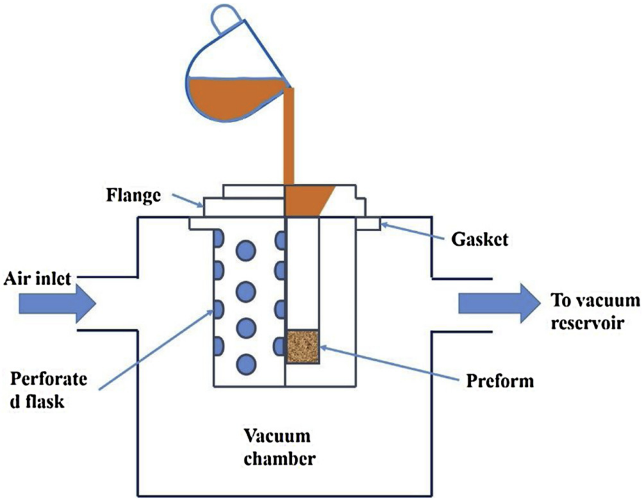


Fig. 9. Melt infiltration [Redrawn from [68]].

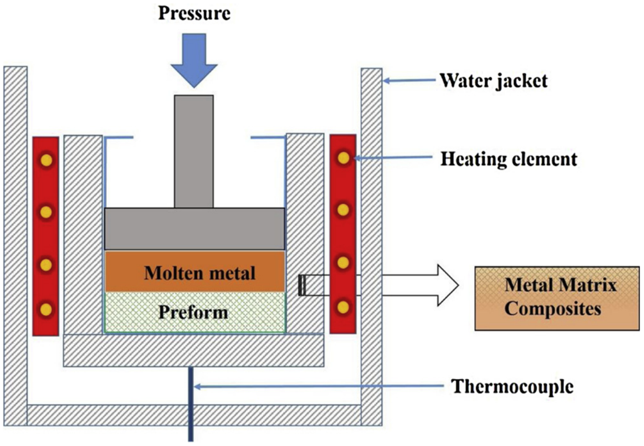


Fig. 10. Pressure infiltration [Redrawn from [70]].

2.2.2.1. *Stir/gravity casting.*

Stir casting is a process of mixing dispersed phase ceramic particles or short fibres with a molten matrix metal using mechanical stirring. Ravikumar et al. [87] fabricated A6063/TiC composite by using stir gravity casting method as shown in Fig. 16 and reported that the addition of reinforcement into the matrix improved the mechanical properties such as hardness and tensile strength. Rohatgi et al. [88] attempted to add fly ash into A356 alloy by using melt stirring furnace and reported that the addition of fly ash could make automobile parts lighter and cheaper.

2.2.2.2. *Centrifugal casting.*

Centrifugal casting is a method of producing cast material by driving the molten metal into a fast rotating mould. Centrifugal casting is a relatively economical process in which the metal is flung out towards the mould surface by centrifugal force under substantial pressure. It is mainly classified into horizontal and vertical axis centrifugal casting. Fig. 17 shows a typical horizontal centrifugal casting machine.

Adelakin and Suárez [89] studied the effect of casting parameters on the fabricated Al–B–Mg composites by using centrifugal casting method. In this method, the centrifugal caster consisted of an articulated free arm connecting a preheated scoop that spins around a vertical axle driven by an electric motor. The centrifugal casting resulted in good mould filling combined with good microstructure control and brilliant mechanical properties. Wang et al. [90] studied the transfer behaviour in the centrifugal casting of SiC/Al composites under centrifugal force. Microstructure result shows most SiC particles drifted to the peripheral region of the castings under the centrifugal action, resulting in non-homogeneous particle distribution. The piston made using centrifugal casting with optimal process parameters shows the best wear resistance behaviour [91].

2.2.2.3. *Squeeze casting.*

Squeeze casting is a combination of casting and hydraulic forging as schematically shown in Fig. 18. In this process, the liquid metal is poured into the die and immediately forged using the hydraulic press at high pressure. The runway is connected between bottom pouring and the mould to transfer molten metal from the furnace to the die. Venkatesan and Anthony Xavior [93] fabricated AA7050 aluminium alloy reinforced with graphene nanoparticles using stir and squeeze casting techniques. 0.3% of Graphene particles with aluminium matrix showed a uniform distribution of particles. The maximum tensile strength of 255 MPa was obtained at 0.3 wt% of graphene particles.

2.2.2.4. *Vacuum die casting.*

In vacuum die casting, the die is kept at a vacuum condition to remove the gases from the melt. The schematic diagram of this process is shown in Fig. 19. The main advantages of this method is reduced porosity in the casting by reducing gasses in the melt. Strength and cast density are increased through this process. Yu Li et al. [94] fabricated large-scale AA6061-31%B_4C through sophisticated stir vacuum casting route. SEM revealed B_4C particles are uniformly distributed and well dispersed within the matrix material. Composite had a tensile strength of 340 MPa which is improved by 112.5% compared with AA1100-31%B_4C.

2.3. *Other processes*

In addition to solid and liquid state processing routes for the production of MMCs, there are other techniques such as semi-solid processes that could also be used but are not that popular when compared to the solid and liquid state processing routes. The following sections discuss some of the prominent ones.

2.3.1. *Compocasting*

Compocasting is a liquid state process in which it involves the addition of preheated [95] reinforcement particles into SSM at a temperature of around 690 °C [96] using strenuous agitation [97]. Fig. 20

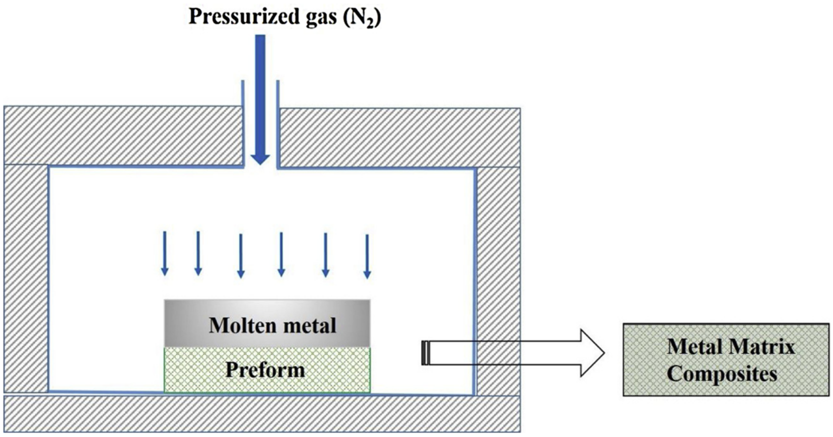


Fig. 11. Gas pressure infiltration [Redrawn from [77]].

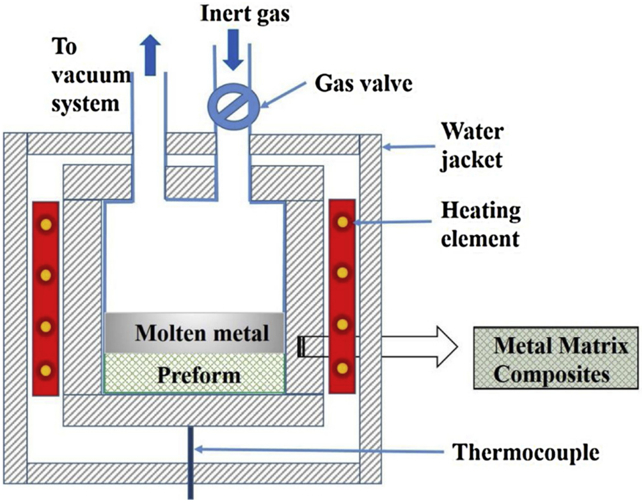


Fig. 12. Vacuum pressure infiltration [Redrawn from [78]].

shows the primary solid particles converted into the semi-solid slurry that is then poured into the die cavity and squeezed during the solidification. The slurry agitation can be made by mechanical vibration, mechanical stirring, electromagnetic stirring (EMS) and cooling slope techniques [98] to distribute the reinforcing particles. The primary solid particles formed in the semi-solid slurry reduce agglomeration or clustering [99] and lead to better distribution of the reinforcement particles [100], grain refinement of the matrix and extremely low porosity than the stir casting process. The primary advantages of compocasting lie in high production cycle time [101], lower processing temperature which helps to extend die life significantly [102]. The wettability is also improved since stirring is carried out within the freezing temperature range of the aluminium alloy [97]. Electromagnetic stirring is one of the common ways to create globular structure in metals. In this method, the desired metal is stirred in the range of semi-solid temperature by rotating Lorentz force resulting from the magnetic field of coils, and consequently, the dendritic cast structure is transformed into a globular structure [98]. Composite produced through compocasting by electromagnetic stirring enhances mechanical properties such as hardness, yield strength, UTS [103] and improved wear properties [104] while the ductility of the aluminium matrix is retained [105]. The application of this technique is still in its early stage, and some brake cylinders and pistons have been manufactured by this process [100]. Soorya Prakash Kumarasamy et al. [96] fabricated Al7075 reinforced with flyash cenosphere and Gr particles by using a two-step compocasting method. This study is exclusively conducted with the possibility of improving the mechanical properties for worm gear production in the aerospace industry. Micrograph confirmed homogenous distribution of reinforcement particles. With the addition of 10% fly ash cenosphere and 2%, Gr the maximum hardness attained was 62 HRB and tensile strength up to 213 MPa.

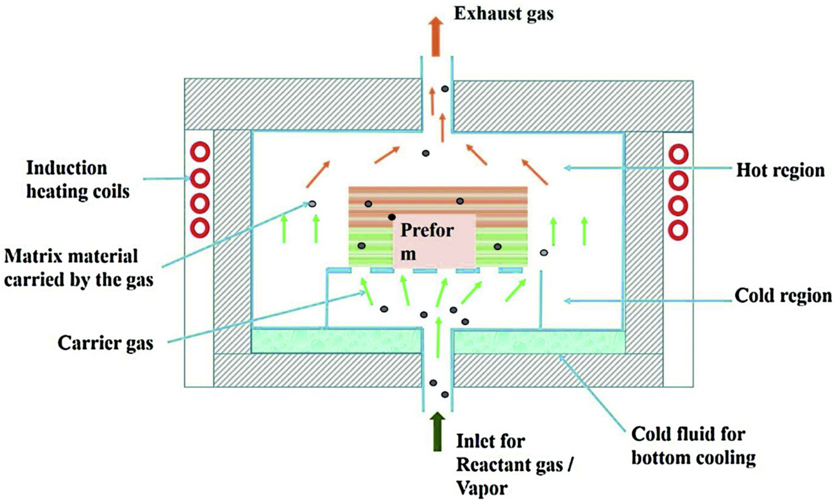


Fig. 13. Vapor infiltration [Redrawn from [61]].

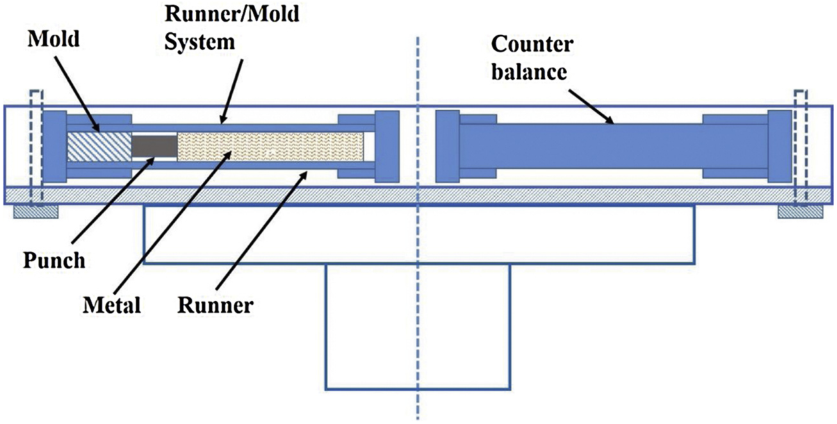


Fig. 14. High-pressure centrifugal infiltration [Redrawn from [81]].

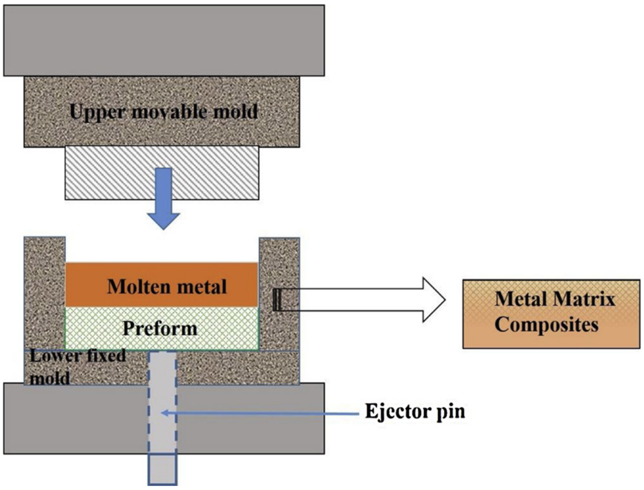


Fig. 15. Squeeze casting infiltration [Redrawn from [85]].

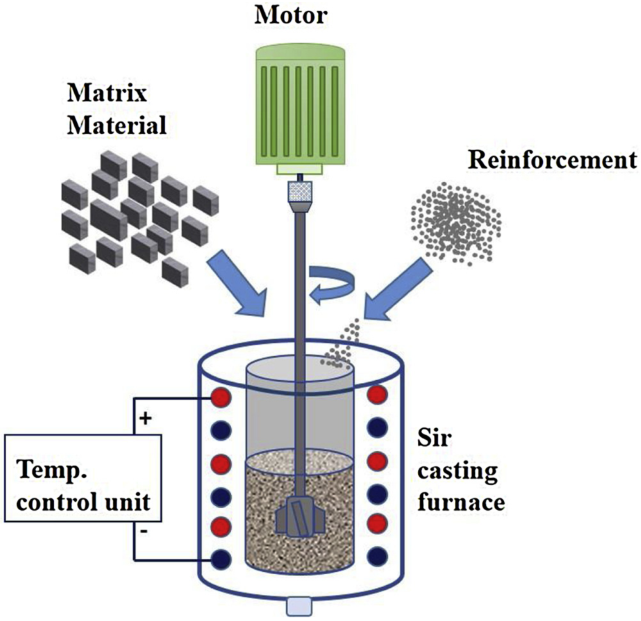


Fig. 16. Gravity casting [Redrawn from [87]].

2.3.2. Rheocasting

The two main routes for producing semisolid aluminium parts are thixocasting and rheocasting. Thixocasting involves a special feed stock material that is later heated into the semisolid range [102]. In a rheocasting process, a semi-solid slurry is prepared from the molten alloy by shearing action, and the reinforcement particles are mechanically entrapped during the solidification process. The prepared slurries are directly transferred to a die for component shaping. Compared to thixocasting, rheocasting possesses many superiorities such as energy saving, in-house scrap recycling, and no special solid billet materials as feed stock required. This process has therefore recently become the preferred manufacturing process due to its cost efficiency and high productivity for producing SSM [107]. The particle distribution of MMC is much improved by intensive shearing, and an excellent microstructure refinement occurs as an effect of the pressure application [108]. Settling of particles or agglomeration can be prevented through this process since the reinforcing particles are added when the alloy is in partially solid condition. In the rheocasting process, the reinforcements should be stable in the given working temperature and non-reactive too. The most commonly used reinforcements are silicon carbide and aluminium oxide. The schematic diagram explaining this process is shown in Fig. 21. High-quality cast components of metal matrix composites such as complex parts, porosity-free, reduced shrinkage, excellent mechanical performance, excellent metal filling, heat treatable and good surface finish can be produced using this method. Rheo-squeeze cast MMC offer superior wear properties as compared to other methods of casting [108]. Rheocast parts exhibit a significant improvement of tensile properties over the gravity cast parts [107]. The main limitation of this process is that the production facilities need a high level of technology and operators to require similar knowledge and training. Curle and Ivanchev [109] successfully fabricated composite plates using rheocast process with the combination of Al 359 reinforced with SiC. They identified that the hardness of the composite material increases from 73 to 93 HRB with an increase in the volume fraction of SiC particles. The wear rate of the composite material attained a maximum of 192 mg min^{-1} when 11% of SiC is added in the matrix.

2.3.3. In situ

In situ fabrication of MMCs is a process, in which dispersed phase is formed in the matrix as a result of precipitation from the melt during its cooling and solidification. Liu et al. fabricated Al (A380) alloy reinforced with TiB_2 particles using in situ process through the chemical reaction of K_2TiF_6 and KBF_4 salt. The microstructural analyses revealed that the alloying elements play a significant role in the formation and growth of the in situ particulate [111]. Ultimate tensile strength of 159.7 MPa was achieved with the addition of TiB_2 particulates. The yield strength is also increased by approximately 65% with the addition of in situ TiB_2 particulates, reaching 66.8 MPa.

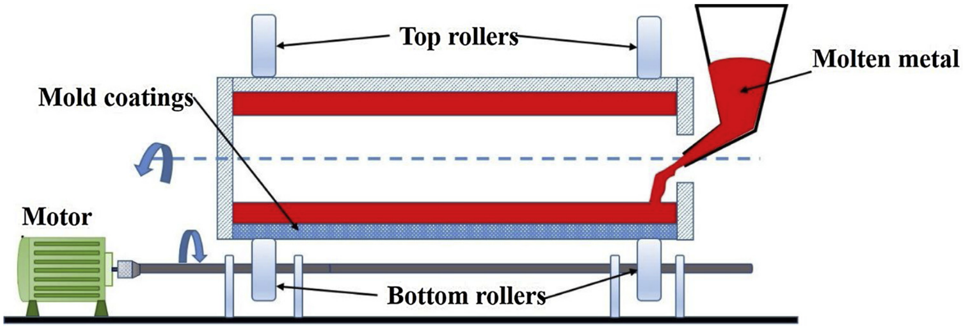


Fig. 17. Centrifugal casting [Redrawn from [92]].

2.3.4. Spray deposition

Spray deposition is a process of atomizing matrix material into a fine diffusion of droplets through pressure controlled inert gas jets into which heated reinforcement particles are injected as shown in Fig. 22. Srivatsan and Lavernia [35] reviewed and discussed various synthesis techniques for producing MMCs through particulate technology and identified that the spray deposition like the one shown in Fig. 23 brings excellent prospect to fabricate good quality MMCs. Mistry and Gohil [27] presented a comprehensive review of diverse types of fabrication processes and mechanical characterization of MMCs and its application in different fields. They identified that Spray deposition process offers higher production rate and lower solidification time that benefits the MMC to achieve minimum reaction of matrix material with reinforcement

2.3.5. Screw extruder

Metal injection moulding or screw extrusion shown in Fig. 24 is a continuous solid-state processing method which can be used to fabricate near net shape MMC's. In this process, fine granules of matrix material are continuously feed through feed hopper. The motor connected to feedscrew pushes the granules forward at a controlled speed through three different zones such as throat cooling zone, a compression zone and melt pumping zone and finally extruded through a die. This method is capable for mass production of any complex shape at a

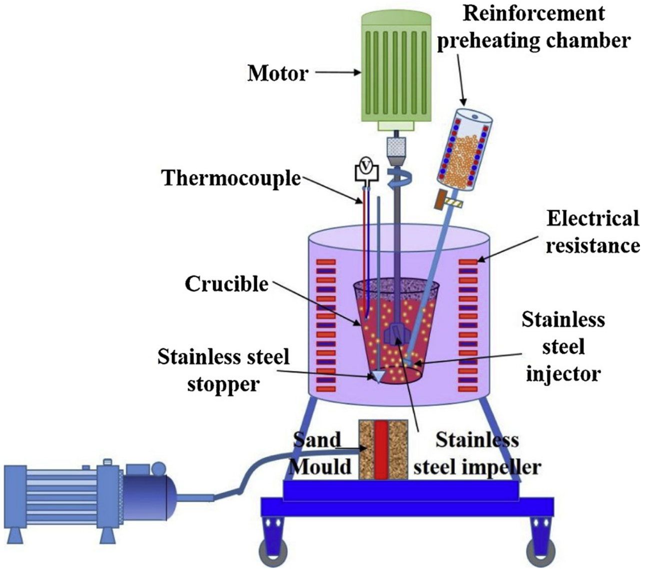


Fig. 19. Vacuum die casting.

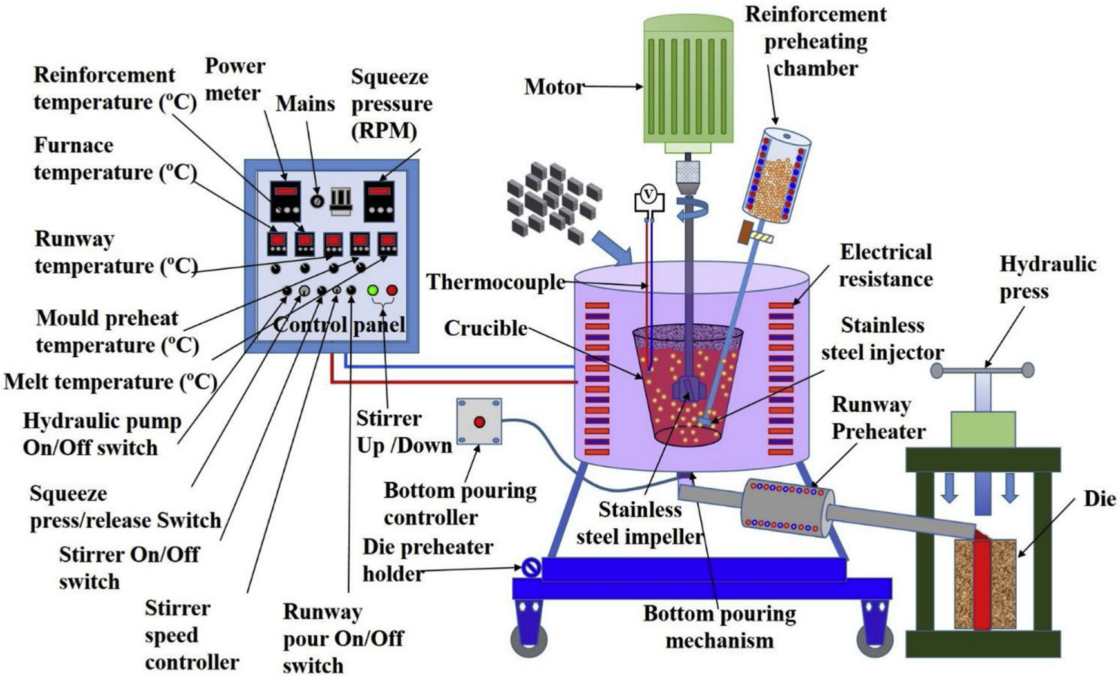


Fig. 18. Squeeze casting.

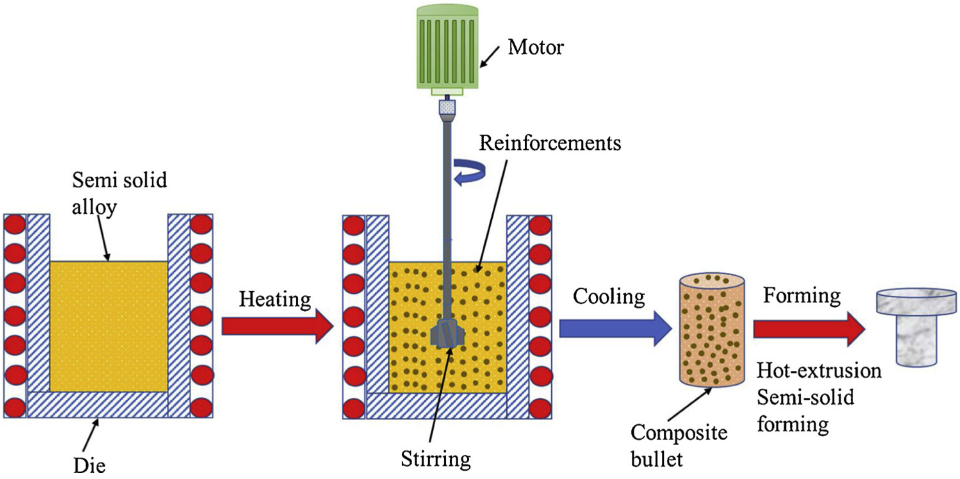


Fig. 20. Compocasting of MMC [Redrawn from [106]].

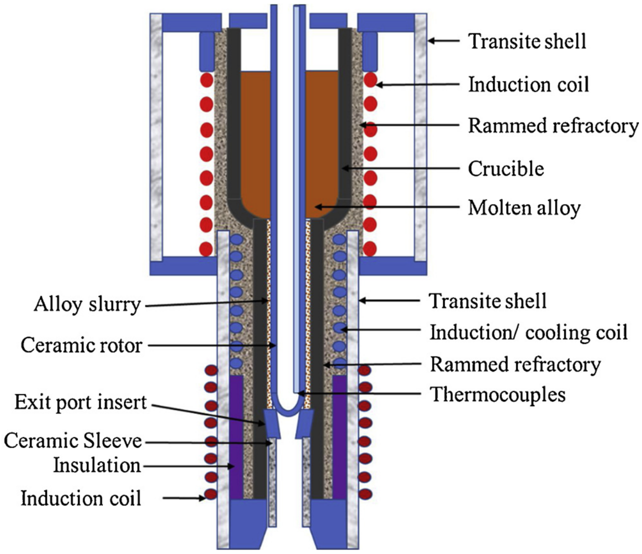


Fig. 21. Rheocasting of MMC [Redrawn from [[110]].

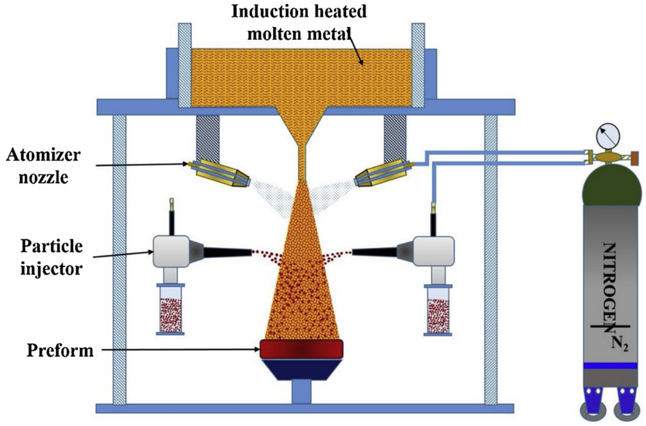


Fig. 22. Spray deposition [Redrawn from [35]].

reasonable production cost. Ye et al. [112] has reviewed extensively on the fabrication of MMC's using metal injection moulding and revelled that this process is economical for the fabrication of tiny, complex parts due to its shaping capabilities.

2.3.6. *Accumulative roll bonding*

Accumulative roll bonding is the process of interfacing two or more alloy strips which are put together by rolling as shown in Fig. 25. To form the perfect bonding between each strip, enough pressure should be applied [113]. Reihanian et al. [114] developed an analytical model to predict the critical strain to obtain a uniform distribution of particles. In the model, the effect of size, volume fraction and initial thickness of reinforcement were considered. The result predicted the composite with well-distributed particles.

2.4. *Comparison of processes used for the production of MMCs*

Table 1 compares the various production processes used in the production of MMCs with their advantages and disadvantages. The properties and applications are more specific to the particular combination of matrix and reinforcement mentioned in the MMCs column and so should not be considered as general. ISO designation for the matrix is included to know the composition of the Al alloy easily.

Solid state processing such as powder metallurgy produces good quality MMCs. Powder metallurgy route involves the homogeneous distribution of reinforcement within the matrix material. SPS is capable of achieving uniform sintering. HEBMS is necessary to assure homogeneous distribution of reinforcement. Rapid Vacuum Sintering can be used for large-scale production with better mechanical properties. Microwave sintering reduces energy consumption and improves the physical and mechanical properties. However, Solid state processing is limited to simple-shaped components with low content of reinforcement.

The stir casting process is simplest, economical and most commercially used technique in liquid state processing. There are some challenges associated with the stir casting process, primarily to maintain wettability (intimate bonding between liquid and solid phase). Secondarily to produce MMC with a homogeneous distribution of the particles, less porosity, and excellent mechanical properties is also a challenge. Unwanted chemical reactions between the matrix and reinforcement and poor wettability of reinforcements with the molten matrix create a nonuniform distribution of particles. Gas entrapment and slag in the melt leads to high porosity and micro defects. These challenges can be overcome using appropriate stir casting design for the production of, especially AMMCs which is discussed thoroughly in the following section. Although these furnaces could be modified to produce Mg or other MMCs, the focus here is on AMMCs because of its more extensive applications and more straightforward production process. The available number of research articles published on the production of AMMCs from 2007-2017 was 12,375 based on Scopus database search (Search Terms: Aluminium Metal Matrix Composites;

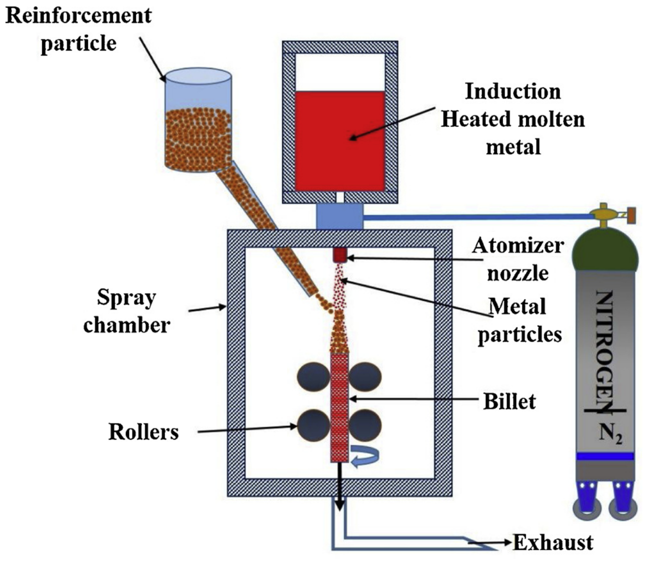


Fig. 23. Spray deposition [Redrawn from [27]].

Production Method Names) conducted on 21st March 2018. The frequently used methods were identified and presented using the pie chart. The number of documents published under the three major topics such as casting, powder metallurgy and infiltration is shown in Fig. 26. It depicts that in the casting process, stir and the combination of a stir with squeeze generated around 2588 documents in a decade. The maximum number of documents published are 620 and 951 in plasma sintering under powder metallurgy and pressure infiltration under infiltration method respectively. Based on this survey, it is concluded that the worldwide research is progressing in the field of casting especially in stir and stir with a squeeze for the production of MMCs.

3. Stir casting furnace design used for the production of AMMCs

Stir casting is a liquid state primary manufacturing process for the production of MMCs. Stir casting is a process of mixing dispersed phase ceramic particles or short fibres in a molten matrix metal using mechanical stirring. Its advantages lie in its simplicity, flexibility, and applicability to large quantity with low-cost production. There are some critical factors to be considered while choosing stir casting methods and are listed below:

1. Achieving a uniform distribution of particles in the cast MMCs.
2. Achieving perfect bonding between matrix and reinforcement materials.
3. Minimizing the percentage of porosity in the cast MMCs.
4. Avoiding chemical reactions between the reinforcement material and matrix alloy.
5. Avoiding the reaction of the melt with the atmospheric element.

Stir casting furnace is broadly classified based on the melting method used and is shown in Fig. 27. The following sub-sections discuss the various stir casting furnaces briefly in each classification with the help of a schematic diagram. The most commonly used is the one based on electrical energy and is discussed elaborately. In the last subsection, all the stir casting furnace discussed are assessed which could be of use to select an appropriate furnace for a specific application.

3.1. Coal-fired stir casting

In this process, the matrix material is melted in a crucible by using a coal-fired furnace. The blower is used to draw heat from the furnace and distribute it throughout the crucible. The stirring is activated using the motor on top of the stirrer. Reinforcement is added to the matrix after stirring the matrix material for a certain amount of time. Annigeri Veeresh Kumar [122] reviewed different methods of producing MMC and the most basic type being the coal-fired furnace shown in Fig. 28. Singh et al. [123] studied the effect of different particle size of SiC and Al_2O_3 reinforcement as hybrid solute on wear properties of aluminium matrix composite (AMC) carried out in a graphite crucible using a coal-fired furnace at 760 °C temperature.

3.2. Electrical stir casting

Stir casting furnace using electrical energy is the most common and among that electrical resistance is the most frequently used technique and is discussed in the following sub-sections.

3.2.1. Stir casting using resistance heating

Conventional resistance stir casting is the process of stirring particles into the alloy melt. The melt is then immediately poured into the sand mould and allowed to solidify. Rohatgi et al. [88] successfully produced Al(A356) with 10% fly ash composite using conventional stir casting shown in Fig. 29, that yielded better tensile strength. Increase in fly ash content improves hardness and wear resistance. Composite can be used for automobile products; house holds items and other products. As a concluding remark, they mentioned that the production of composites using waste or reusable materials would benefit in pollution control and reduced energy consumption. Balasubramanian and Maheswaran [124] investigated the effect of adding SiC particles on the mechanical resistance behaviour of stir-cast AA6063/SiC 0, 5, 10, 15%

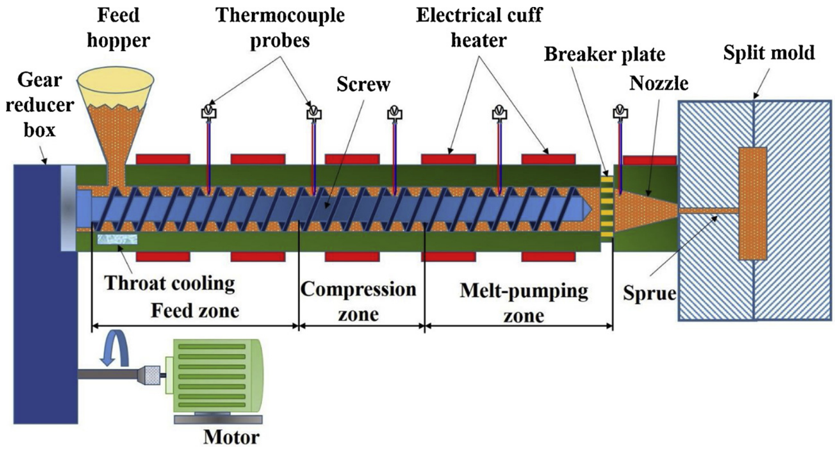


Fig. 24. Screw extruder [Redrawn from [112]].

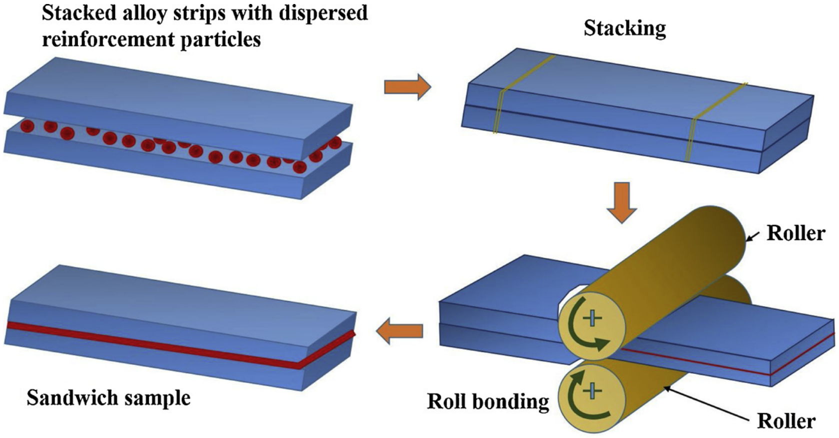


Fig. 25. Accumulative roll bonding [Redrawn from [115]].

composites using conventional stir casting with melt temperature more than 700 °C. The composite had an increase of approximately 50% in hardness and tensile strength when adding appropriate weight percentage of SiC particles [125].

3.2.2. Quick quench stir casting

A quick quenched stir casting process can also be used to produce MMCs. The stir casting furnace was mounted on four legs and attached to a steel table. A screw driven actuator lift was bolted vertically underneath the table. Through this arrangement, the crucible can be easily extracted from the furnace. This process is schematically shown in Fig. 30. Naher et al. [126] developed Al–SiC composite using quick quench stir casting. An actuator connected to the rig enables the stainless steel crucible to be extracted from the furnace immediately after casting for quick solidification that results in uniform distribution of the particles.

3.2.3. Two-step stir casting

Sambathkumar et al. [127] studied mechanical and corrosion behaviour of Al7075 hybrid 0–15 vol% SiC and TiC using two-step stir casting method equipped with a proportional-integral-derivative (PID) controller. In this process, melting was carried out in the furnace equipped with a fire resistant stirring motor and speed regulator that is used for stirring. The produced composite showed higher tensile strength and hardness compared to base alloy. Radhika and Charan et al. [128] fabricated LM 25 with 10% TiC particles through a two-step stir casting route as shown in Fig. 31. Based on the experimental and statistical results they concluded that the increase in load is directly proportional to the wear rate. Particles are well distributed when an optimal 10% reinforcement is used. Pazhouhanfar and Eghbali [129] synthesized Al6061-3, 6, 7% TiB_2 composite using stir casting furnace and studied its mechanical properties along with microstructural characterization. Tensile test result proved there is a significant improvement in the ultimate tensile strength of the fabricated composites (257 MPa) by adding 9 wt% TiB_2 reinforcement particles which are 29.2% higher than that of the virgin alloy.

3.2.4. Stir casting process under an inert atmosphere

Gopalakrishnan and Murugan [130] produced an Al-TiC composite by improved conventional stir casting method by attaching a controlled bottom pouring arrangement under an inert gas atmosphere as shown in Fig. 32. This arrangement helped in avoiding the reaction of molten aluminium with the open atmosphere. Josyula and Narala [131] successfully fabricated Al-5%TiC composite. Throughout the process of composite production, a blanket of argon gas was released around the melt to prevent oxidization reactions. It was observed that there is a drastic reduction in wear rate in the developed composite at a maximum load of 25 N.

3.2.5. Modified stir casting

Singh et al. [133] developed a low-cost production method for the production of MMCs. The stir squeeze casting setup designed mainly for the production of near net shape MMC parts. This setup consists of five processes in one equipment such as melting, stirring, squeezing, bottom pouring, quenching as shown in Fig. 33. Through the simulation and experimentation investigation, they reported that the reinforcements were uniformly distributed in the developed MMCs.

3.2.6. Ultrasonic processing of composites

Srivastava et al. [134] fabricated Al6061 alloy with 1% nano Al_2O_3 composites at different temperatures by using ultrasound solidification technique (UST). The schematic of the production process is shown in Fig. 34. This process consists of an electric resistance furnace, ultrasonic unit, thermocouple, and controlled argon atmosphere. An ultrasonic probe vibrates with an operating frequency of 20 kHz and is inserted into molten metal for approximately 3 min. The result proved exceptional distribution of reinforcement obtained in composite specimens due to ultrasonic treatment. Meanwhile, due to high melt viscosity, some agglomerates of particles are also observed in the composite.

3.2.7. Stir casting process under a modified inert atmosphere

The setup shown in Fig. 35 is similar to the conventional stir casting with bottom pouring arrangement. However, to distribute the reinforcement homogenously and to avoid reaction with atmosphere, an inert gas flow is released to the crucible through reinforcement chamber. The flow of reinforcement can be controlled by adjusting the pressure of the inert gas. Amirkhanlou and Niroumand [47] produced Al 356/5% SiC by injecting ball milled SiC particles through Argon gas as a carrier gas into the molten alloy. This process consists of dual connection from the inert gas source. One connection controls the flow of reinforcement into the melt by adjusting the gas pressure, and the other connection bypasses the reinforcement chamber and supplies the gas directly into the casting chamber. The addition of fine particles to the melt resulted in the homogeneous distribution of particles, improved wettability, improved mechanical properties and decreased the percentage of porosity.

3.2.8. Bottom pouring stir casting set up with squeeze casting attachment

Kannan and Ramanujam [135] produced hybrid AA 7075/4% SiC and 2–4% nano Al_2O_3 composite using stir-squeeze casting arrangement. In this process, the furnace is a typical stir casting with bottom pouring arrangement but has a provision for applying squeeze pressure on the casting during solidification which helps in reducing porosity and improving the mechanical properties. Once the furnace valve is

Table 1
Metal matrix composites production processes and its properties.

Process	MMCs	Properties	Advantages	Disadvantages	Application	References
SPS	Al-Al_2O_3 & Al–SiC	Hardness 324.6 HV	Uniform sintering Compaction and sintering stages are combined in one operation	Only simple symmetrical shapes may be prepared Expensive pulsed DC generator is required Expensive process	Armour, nozzle	[57]
HEBMS	Al-Al_2O_3	Hardness 93.9 $HV_{0.05}$	Homogeneous mixing and uniform distribution Good flowability	High-quality ball mills are potentially expensive	Refractory and structural	[61,116]
RVS	MgO-doped Al_2O_3		Good controllability Large-scale features Large-scale production Minimum porosity Homogeneous microstructure Best hardness	Expensive process	Hard metal tools, micro drills	[64]
MS	Al 5%, Ti 0.5%, SiC	Hardness 65.46 ± 0.58 HR15T Tensile 183.9 MPa	Reduced energy consumption Very rapid heating rates Decreased sintering temperature Improved physical and mechanical properties	Suitable only for specific material which possesses dielectric properties and not suitable for silicon nitride (Si_3N_4) and alumina (Al_2O_3)	Bio medical applications	[66]
MI	Al/Ti_3SiC	Hardness 751 HV, Compressive strength 750 MPa	Improved wear property Cost-effective Ultra-high-temperature capability	Limited temperature and depth causes blockage in infiltration	Space, defense, industrial	[68]
PI	Al/GNPs	Tensile 250 MPa	Improved tribological property Economical for large-scale production	High tooling cost High porosity Not suitable for large casting	Piston engines Wheels Electric motor housing	[70]
GPI	Aluminium alloy AlSi12/ Metallic glass Ni60Nb20Ta20 flakes		Improved thermal conductivity Capable for high melt temperature Possible to produce any combination of matrix and reinforcement For manufacturing large composite parts	Production rate lower than squeeze casting Cost of high pressurized inert gas Slower solidification process	Brake callipers, hydraulic components	[77]
VPI	2D-Cf/Al	Tensile 281.2 MPa	Reduced porosity Improved ultimate tensile strength Near net shaped composite can be obtained	Slower solidification process Lack of wettability Crack formation	Electronic packaging	[78]
VI	SiC_{nw}/SiC		Low residual stress Complex shapes can be produced Improved mechanical properties Minimum fibrous damage	Low production rate Very high porosity level High production and capital cost	Heat exchangers, burner and flame tubes	[79]
HPCI	Sn-15 wt% Pb/SiC, TiC and Al_2O_3		Higher production rate, larger part size compared to gas pressure Variety of part geometry, part size compared to squeeze casting	Requires ultra powerful drive system Additional processing time requires	Conrod for the control surface	[81]
Squeeze casting infiltration	AlSi12/Al_2O_3	Hardness 492 HV_{10}	Improves wettability Homogeneity Less shrinkage porosity Reduced casting defects	Limited flexibility in part geometry Less productivity High pressure and tooling cost	Engine block, brake disc, piston, fuel pipe, rack housing, suspension arm, brake calliper, pump case, flange, connecting rod	[82]
Stir/gravity casting	A356 (Al-Si7Mg)/10% fly ash	Tensile 45–62 MPa	Simplest process Suitable for mass production Suitable for fully mechanized casting	Additional heat treatment required to get good mechanical properties Relatively slow process	Manifolds, cylinder heads, water pump housings	[88,117]

(*continued on next page*)

Table 1 (*continued*)

Process	MMCs	Properties	Advantages	Disadvantages	Application	References
Centrifugal casting	Al–B–Mg	Hardness 80 –90	Better mould filling Dense grain structure Virtually free from porosity Hollow interiors without cores High mechanical strength Wall thickness can be controlled High wear resistance	Poor casting at inner surfaces	Automotive piston [91] Sewerage pipes Brake rotors Paper mill rolls Textile mill rolls Nozzles Liners for IC engines	[89]
Squeeze casting	AA7050 (AlZn6CuMgZr)/ 0.3% graphene	UTS 255 MPa	Uniform distribution of reinforcement particle at 0.3% graphene	Additional setup and so increases the cost of production	Aerospace and automotive industries as well as for thermal management	[93]
Vacuum casting	AA6061 (AlMg1SiCu)-31% B_4C	UTS 340 MPa	B_4C particles are uniformly distributed and well dispersed within the matrix material	Additional attachment and higher cost of vacuum pump and connections	Automotive, aerospace, the military and nuclear industry	[94]
Compocasting	Al7075 (Al-Zn6MgCu)-fly ash cenosphere, Gr	Hardness 62 HRB, tensile strength 213 MPa	Homogenous distribution of reinforcement particles is achieved Improved wettability between reinforcement particles and matrix alloy	Semi-solid route suffers from porosity and processing difficulties due to high viscosity and precise control of the process parameters [118]	Worm gear production in the aerospace industry	[96]
Rheocasting	Al356 (Al-Si7Mg)-SiC	Hardness 73–93 HRB	Complex parts, porosity-free, reduced shrinkage, excellent mechanical performance, heat treatable and good surface finish	Complex and expensive technology	Wear-resistant components	[109]
In situ	A380 (Al-Si8Cu3Fe)-TiB_2	UTS 159.7 MPa	Good bonding between the particle and the matrix, which will enhance the high-temperature properties	Ductility reduces with the increase in reinforcement fraction	Automobile and aerospace industries	[111]
Spray atomization and deposition processing	LM13 (Al-Si12Cu)/Zircon	Hardness 80 HV	Flexibility Good interfacial bonding	Costly capital equipment, porosity	Automotive industry	[119]
Screw extruder/Metal injection moulding	AA6016 (AlMg1SiCu)/ (0–20 wt%) graphite	Hardness 46.6 HV, compression strength 248 MPa	Good dispersion High hardness value Superior wear resistance Mass production of small and intricate parts Precise	Only small parts can be manufactured using small	Electronic industry, electronic packaging, heat sinks, heat spreaders, base plates, coolers, discs and rings	[120]
Accumulative roll bonding	AA1050/NanoTiC	UTS 58 MPa	High corrosion resistance High strength	Requires large load capabilities Expensive dies Low production rate	Structural, automotive applications	[121]

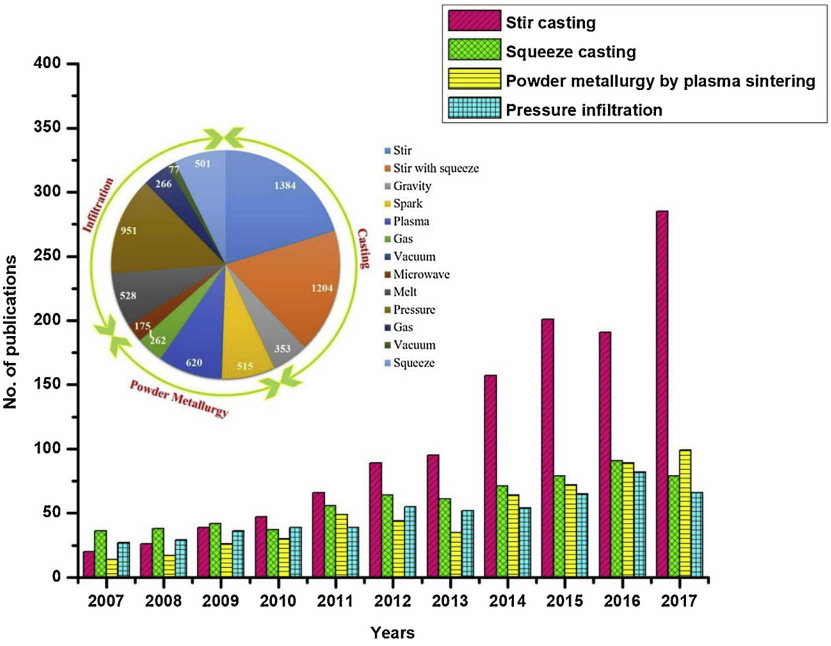


Fig. 26. Number of publications on aluminium metal matrix composites during 2007–2017 (Source: www.scopus.com).

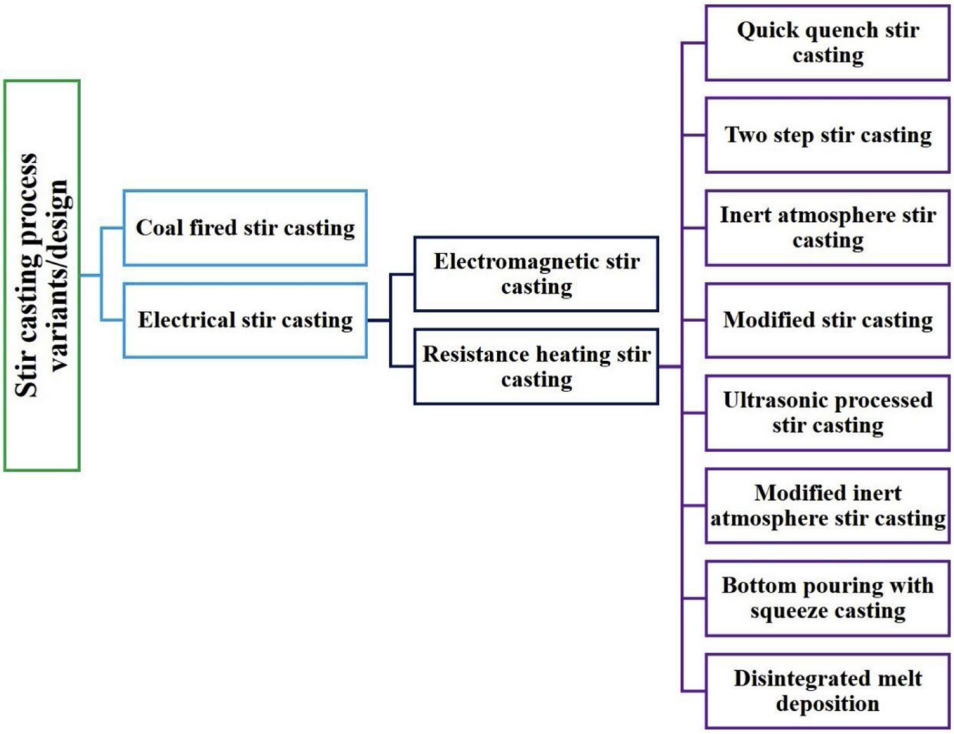


Fig. 27. Stir casting process variants.

opened using automatic control, the molten mixture is conveyed to the die through a runway preheater which maintains the temperature of the melt. This process is shown in Fig. 18. The maximum squeeze pressure of 101 MPa was applied. They reported that the end effect of using stir-squeeze casting process improved the hardness to 81.1%, ductility to 31.6%, impact strength to 106.3% and the ultimate tensile strength to 92.3% than that of the base alloy.

3.2.9. Disintegrated Melt Deposition (DMD)

Gupta et al. [136] investigated a novel technique termed as “Disintegrated Melt Deposition (DMD)” to overcome the issues with conventional casting namely uniform distribution of the reinforcement and interfacial integrity between the reinforcement and the matrix that strongly influences the mechanical properties. The DMD technique is a modification of the spray atomization and deposition technique developed by them earlier. In this process, the composite melt prepared though mechanical stir casting is poured through a centrally drilled hole in the graphite crucible and the stream of the melt is disintegrated using two linear argon gas jets at an angle normal to melt stream. The composite melt slurry is subsequently deposited on a metallic substrate located at a certain distance from the gas integration point. This process is shown in Fig. 36. Using DMD process, Gupta et al. [136] produced

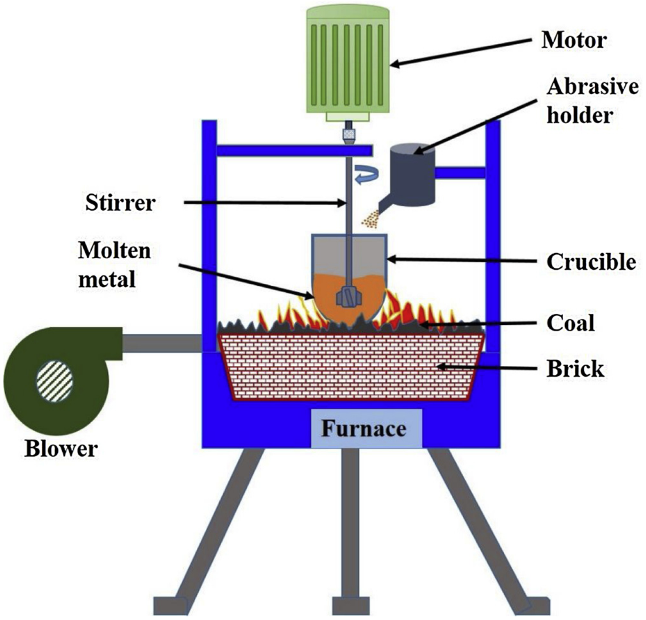


Fig. 28. Coal-fired stir casting [Redrawn from [122]].

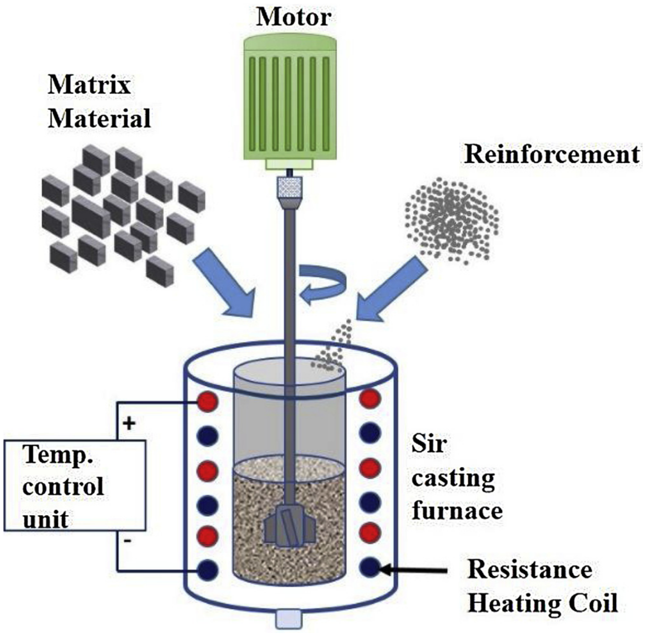


Fig. 29. Conventional resistance stir casting [Redrawn from [10]].

successfully an aluminium-based MMCs containing up to 14.5 wt% of SiC particulates. They observed an increase in the UTS value and attributed it to the DMD technique which enabled to achieve uniform distribution of the SiC particles as well as superior interfacial integrity with the Al-Cu matrix.

3.3. Electromagnetic stir casting

Prakash et al. [138] produced A356/5%SiC composite using electromagnetic stir casting as shown in Fig. 37. The SiC particles mix into the molten metal above the liquidus temperature. An electromagnetic field produced through three-phase induction motor stirs the molten material for a particular period at a particular stirring speed leading to uniform distribution of particles resulting in lower casting defects and improvement in fatigue strength. The MMC formed by this technique

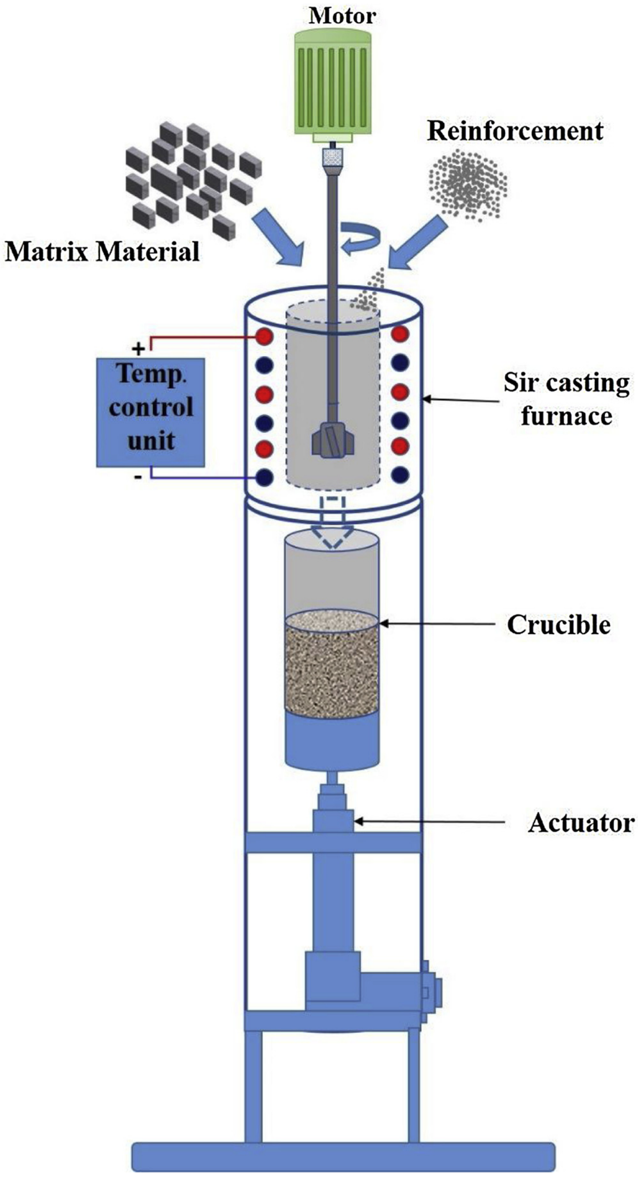


Fig. 30. Quick quench stir casting [Redrawn from [126]].

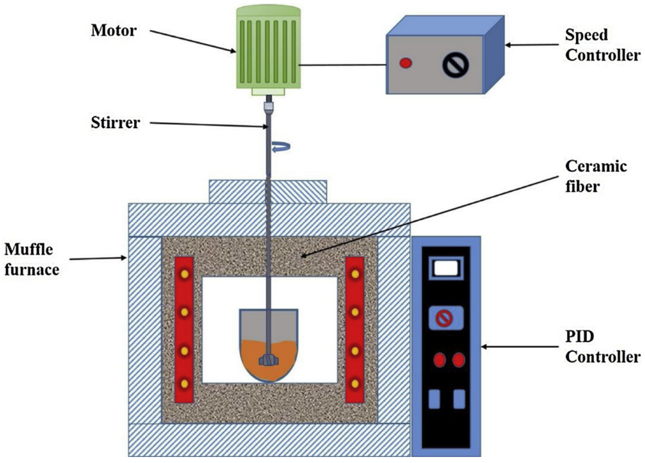


Fig. 31. Two-step stir casting [Redrawn from [127]].

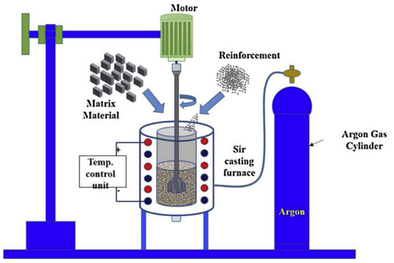


Fig. 32. Stir casting process under inert atmosphere [Redrawn from [132]].

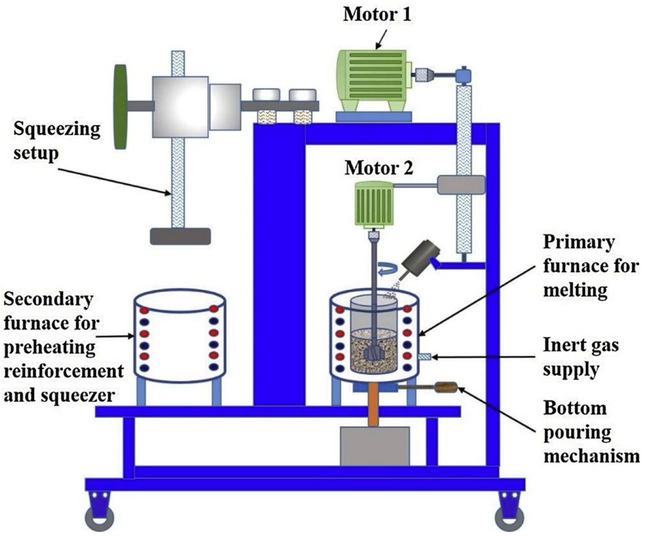


Fig. 33. Modified stir casting setup [Redrawn from [133]].

have slightly better mechanical properties than those formed with the help of conventional stir casting process. Kumar et al. [139] produced A359-2, 4, 6, 8% Al_2O_3 composite using an electromagnetic stir casting at a melt temperature of 750 °C with a stirring speed of 300 rpm. The result proved that the addition of reinforcement in the matrix material improved hardness and the ultimate tensile strength at 8% reinforcement addition to the matrix. In the mechanical stir casting process, the stirrer mixes particles into the melt, but when stirring stops, the particles floats or settles depending on its density. However, in the electromagnetic stir casting process, the material rotates continuously by the electromagnetic field until solidification and this results in a homogeneous distribution of the reinforcement particles.

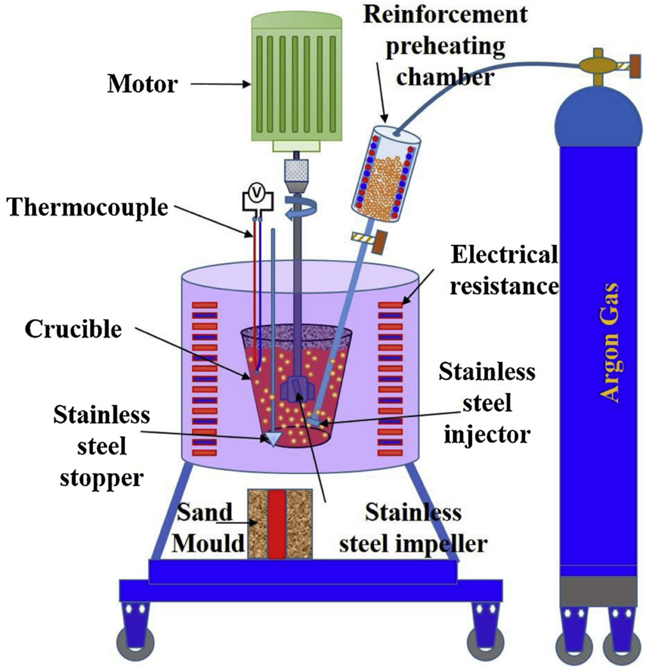


Fig. 35. Stir casting process under modified inert atmosphere [Redrawn from [47]].

3.4. Assessment of various stir casting furnace designs

Table 2 summarizes the various stir casting furnaces discussed in this section that have been either developed by researchers or commercially available ones used for the production of MMCs. This table would be of immense help in understanding the furnace design appropriate for a given application or desired properties.

4. Properties of AMMCs produced through various stir casting processes

The properties of AMMCs can be tailored made to suit an application by proper selection of matrix and reinforcement, stir casting process parameters and additives to enhance the quality of the MMCs. This section discusses the various matrix and reinforcement materials available. Following this, the mechanical properties of AMMCs produced using the three prominent reinforcement materials namely Al_2O_3, SiC and B_4C are listed and compared. The next subsection

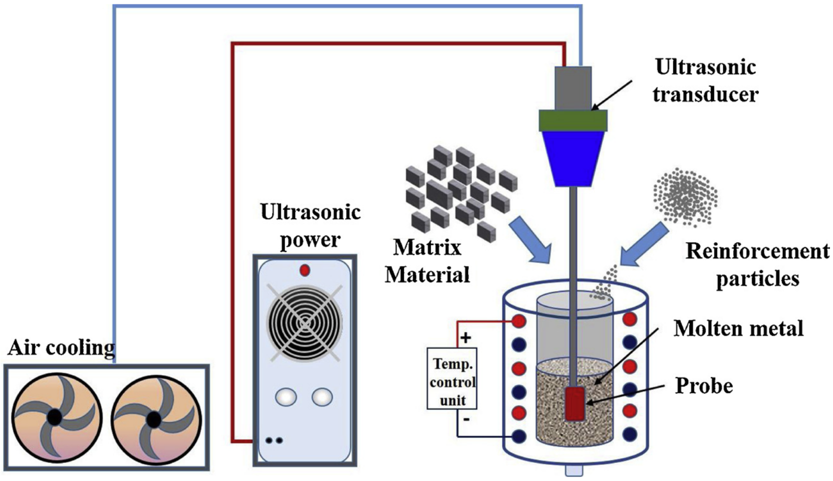


Fig. 34. Ultrasonic processing of composites [Redrawn from [134]].

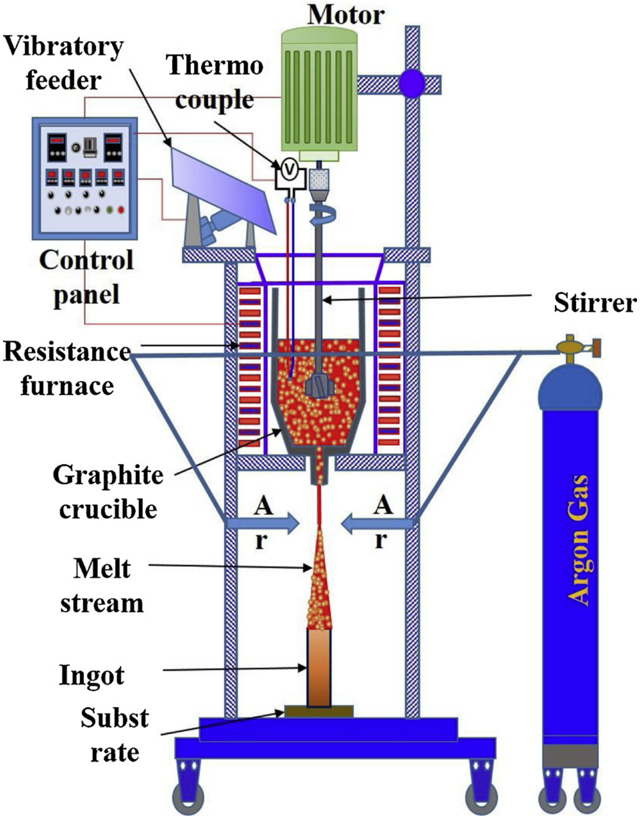


Fig. 36. Disintegrated melt deposition [Redrawn from [137]].

discusses the process parameters used in the stir casting process and concludes with additives that can be used to enhance the properties of the produced MMCs.

4.1. Properties of various matrix materials

Aluminium (ore) is one of the most abundant metal that is available in the earth [141] and is also easily recyclable. There are several grades of aluminium alloys frequently used as the matrix material for the production of AMMCs and the most commonly used matrix material used by researchers are discussed with its properties and applications in the following Table 3. The ISO designation for the matrix material is included so that it is easier for the readers to relate to the material composition since different researchers use different grade designations.

Pure aluminium is not commercially used in any applications because of its low strength. The alloying elements such as silicon, zinc, magnesium, copper, and manganese, etc. are added to increase the mechanical properties using special processing techniques. Al 2024 has copper as an alloying element resulting in poor weldability and relatively low corrosion resistance. It can be used in automobile applications to reduce the weight of the vehicle. Al 6061 is the alloy of aluminium, silicon, and magnesium and it is the most versatile alloy in aluminium series. However, it has medium strength when compared to other Al alloys such as Al 2024 and Al 7075. Zinc and magnesium are the alloying elements in Al 7075 alloy. Al 7075 alloy can be used in many applications where high strength and corrosion resistance is required. Primarily, it can be used in coastal regions. LM25 and LM6 alloys can be recycled without any purification process and so can be reused to prepare the MMCs. Thus depending upon the required property in the AMMC, the matrix material can be selected using Table 3.

4.2. Properties of various particulate reinforcement materials

The primary function of reinforcement particle is to reinforce the matrix phase. The volume fraction of reinforcement typically is in the range of 5–30% of the matrix material [147]. In most cases, 5–10% would be sufficient for micron size particles and in the case of nanomaterials even less than 5% can result in significant improvement in the mechanical properties. The reinforced MMCs can produce a range of property enhancement over monolithic alloys. The materials used and the salient properties achieved by researchers are shown in Table 4.

The organic reinforcements such as fly ash and red mud improve the strength of the composite reasonably, and the cost is meagre, but comparatively, it has more porosity than other reinforcements. The inorganic reinforcements such as Aluminium oxide and Silicon carbide are extensively used to produce MMCs among the wide varieties of reinforcements. Because the interfacial bonding between the matrix and reinforcement are very high and hence produce high strength MMCs. Boron carbide is a hard particle, and it can improve the strength of the composite. It is more suitable for wear resistant automobile applications. Graphene and tungsten disulfide have the self-lubrication property, and as such it is reinforced with the Al matrix for the sliding wear applications especially for automobile moving parts such as a piston, cylinder, brakes, etc. Diamond has high thermal conductivity but is relatively very expensive. Researchers have produced MMCs using the reinforcements mentioned in Table 4, and the selection of

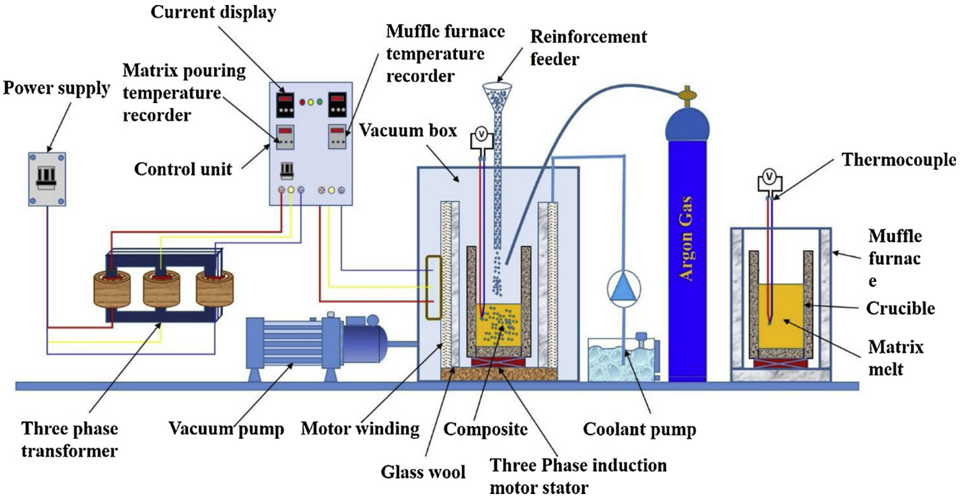


Fig. 37. Electromagnetic stir casting [Redrawn from [140]].

Table 2
Various stir casting furnace design comparison including advantages and disadvantages.

S. no.	Furnace design	Advantages	Disadvantages	Remarks	References
1	Coal-fired stir casting	Less electricity consumption	Solid waste by-product		[122]
2	Conventional stir casting	Simple process	Cluster formation	Good mechanical properties and cost of production is competitively low	[88]
3	Quick quench stir casting	Homogeneous composite Simplicity Flexibility	Low production rate	Flexibility and applicability to large-scale production	[126]
4	Two-step stir casting	Uniform particle distribution		Finer particles can be added resulting in superior mechanical properties	[128,127]
5	Stir casting process under an inert atmosphere	Avoids the formation of undesired phases	Increased porosity percentage	Improved specific strength Improved wear resistance	[130,131]
6	Modified stir casting setup	Uniform distribution of particles	–	Nearnet-shape or net-shape of MMC parts can be produced	[133]
7	Ultrasonic processing of composites	Exceptional distribution of reinforcement	Particle agglomeration	Additional cost for ultrasonic	[134]
8	Stir casting process under a modified inert atmosphere	Homogeneous distribution of particles and improved wettability		Injection of composite powder enhances the wettability and improves uniform distribution of particles	[47]
9	Bottom pouring stir casting set up with squeeze casting attachment	Significant reduction in porosity	Relatively slow process and higher cost of the setup	Improved overall mechanical properties	[135]
10	Disintegrated melt deposition (DMD)	Superior interfacial integrity between matrix and reinforcement particles	The process is comparatively expensive and time-consuming	Improved overall mechanical properties	[136]
11	Electromagnetic stir casting	Uniform particle distribution Low porosity	Moderately higher setup cost, excess EMS frequency causes large axial porosity	Produces cast MMC with smaller grain size and better particulate matrix interface bonding, improved tensile and hardness of the composite parts	[139]

Table 3
Frequently used Al matrix materials for the production of AMMCs.

S. no.	Matrix material	Salient properties	Applications	References
1	Al Pure/AA1100 (Al99)	Recyclability, ductility, workability and corrosion resistance	Metal spinning, decorated foil pouches for food and drink, food packaging trays.	[142]
2	AA2024 (AlCu4Mg1)	High strength to weight ratio, machining to a high surface finish, high fatigue strength, high specific strength	Thin sheets, truck wheels, aircraft structures, screw machine products, scientific instruments, veterinary and orthopaedic braces, and rivets	[142,143]
3	AA6061 (AlMg1SiCu)	Excellent for heat treatment, easy to work, weld and machine the product with reasonable strength	For all kind of structural applications especially a truck, marine frames, railroad cars, and pipelines	[144]
4	AA7075 (Al-Zn6MgCu)	High fatigue strength, high corrosion resistance, reasonable machinability, high strength-to-density ratio	Rock climbing equipment, bicycle components, in line skating-frames and hang glider airframes	[145]
5	A413/LM6 (AlMg6)	Excellent fluidity property, high strength, good workability, and high resistance to corrosion	Military and aerospace application due to its excellent joining characteristics	[146]
6	A356/LM25 (Al-Si7Mg)	Excellent castability, machinability, wear resistance and lightweight	Refractory in the thermal protection system, engine piston, moving parts in automobiles	[132]

Table 4
Salient properties of various particulate reinforcements used in the production of MMCs.

S. no.	Reinforcement material	Salient properties	Applications	References
1	Alumina	High strength to weight ratio High hardness	Brake discs, pistons, cylinder heads, connecting rods	[148]
2	SiC	High hardness, stiffness, specific strength, and thermal properties. Resistant to acids, alkalis and molten salts up to 800 °C	Pistons, brake rotors, callipers, liners, propeller shaft, connecting rod, brake rotors, driveshaft, engine cradle, brake disc on ICE bogies	[149,150]
3	B_4C	High strength, low density, high hardness, excellent chemical stability, and neutron absorption capability	Automotive applications	[149]
4	TiO_2	Strong bonding, high tensile strength, hardness and impact strength	Automobile applications	[151]
5	SiO_2	Superior mechanical and tribological properties	Wear-resistant applications	[152]
6	ZrO_2	High hardness and wear resistance	Pistons, cylinder liners, and connecting rods	[153]
7	ZnO	Semi-conductivity, wear resistance, vibration insulation, and microwave absorption and antibacterial effects	–	[154]
8	TiN	High strength and wear resistance	Cutting tools, solar-control films, and other microelectronic applications. Excellent diffusion barrier against most of the metals	[154,155]
9	BN	High strength, low density, high hardness	–	[155]
10	Si_3N_4	High hardness and tensile strength	Automotive parts	[155]
11	TiC	High wear resistance	Pistons, connecting rods	[150,156]
12	Fly ash	Lower cost, high tensile strength, compressive strength, impact strength, and hardness	Covers, pans, shrouds, casings, pulleys, manifolds, valve covers, brake rotors, and engine blocks in automobiles	[157,158]
13	CNT	High strength-to-weight ratio, low density, increase in yield strength, tensile strength, ductility, and hardness	Brake shoes, cylinder liners and aircraft landing gears	[153]
14	Graphite	High thermal conductivity, the coefficient of thermal expansion and low density	Cylinders, pistons, current collectors, base plates and coolers, heat sinks, heat spreaders, discs, and rings	[150,153]
15	Red mud	Low cost, tensile strength, compression strength, and hardness increased with the increase in the weight fraction	Aircraft industry, marine components, bicycle industry, drive shafts, electrical parts and equipment's, brakes, fittings	[159]
16	TiB_2	High strength and wear resistance	High-tech structural and functional applications including aerospace, defense, automotive, and thermal management areas, as well as in sports and recreation.	[160]
17	ZrB_2	High exothermic formation, thermodynamic stability, better bonding strength, high hardness, and wear resistance	Aerospace applications	[155]
18	WS2	Self-lubrication, improved friction and wear properties.	Moving parts of engines	[155]
19	Diamond	High thermal conductivity	Diamond/Al spreader for GaN microwave transistors, water-cooled cold block, fins	[153]

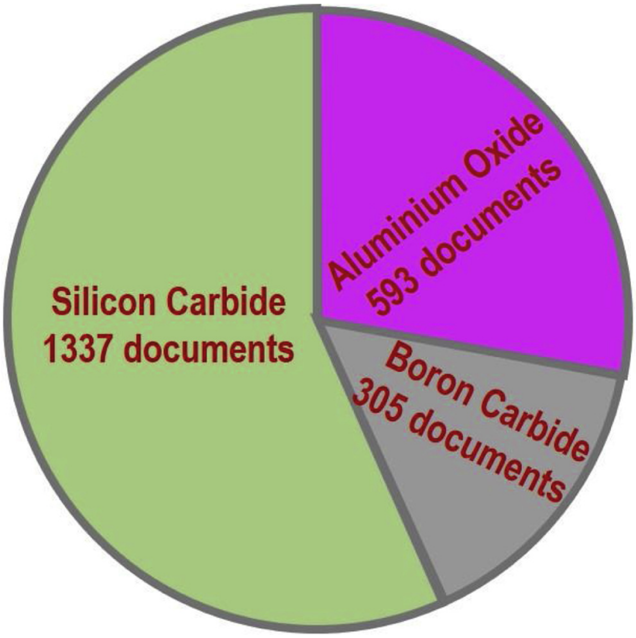


Fig. 38. No. of publications based on reinforcement type published in Scopus.

reinforcement mainly depends on the applications of the MMCs. To further increase the strength of the composite, reinforcement materials are mixed together and then added with a matrix to produce hybrid composites. In the last decade with the advent of nano materials, most of the reinforcements listed in Table 4 have also been used in their nm size. Hybrid MMCs could also include a combination of the same reinforcement but both in micron and nm size or a mixture of different reinforcement particles in micron and nm sizes. AMMCs produced using nm size reinforcement particles are also discussed in the following section. They have their own issues, e.g. CNT is used as reinforcement to increase the strength of the composite, but the problem is agglomeration. The CNT particles are agglomerated easily by the factors such as melt temperature, stirring time and stirring speed and others.

4.3. Mechanical properties of AMMCs

Among the discussed reinforcement materials, Al_2O_3, SiC, and B_4C are the most extensively used for improving the mechanical properties of AMMCs, and so they are only discussed in this section. The high interfacial bonding strength between the matrix and reinforcement of Al_2O_3, SiC and B_4C tend to increase the strength of the composite. The total numbers of papers published in the SCOPUS database in the year between 2008 and 2018 are shown in Fig. 38.

4.3.1. Al_2O_3

Among the several reinforcement particles, Al_2O_3 is most commonly used next only to SiC because of its good interfacial compatibility and non-degrading surface with liquid aluminium [161]. Table 5 summarizes the mechanical properties of various AMMCs produced by researchers worldwide in the last ten years using Al_2O_3 as reinforcement.

4.3.2. SiC

SiC is the most common reinforcement phase added to AMMCs. Table 6 summarizes the mechanical properties of AMMCs produced using SiC as reinforcement.

4.3.3. B_4C

B_4C is the also a standard material added to AMMC as reinforcement next to SiC and Al_2O_3. When compared to other popular reinforcements, B_4C is expensive. Thus the research on B_4C is not extensive. However, it produces good bonding and excellent mechanical properties. Table 7 summarizes the mechanical properties of AMMCs produced using B_4C as reinforcement.

From Tables 5–7, it is observed that the particle size plays a significant role in improving the strength of the composite. In general, the hardness and strength are higher for the composite produced with nano particles. Also, the percentage of porosity is less for composite produced with nano particles as reinforcement. Tables 5–7 could serve as a quick reference in choosing an AMMC for desired mechanical properties/applications.

4.4. Stir and squeeze casting process parameters influencing the mechanical properties of AMMCs

4.4.1. Important process parameters

- **Squeeze pressure:** It is the most influencing factor to improve the quality of the MMCs. It improves the wettability and interfacial bonding between the matrix and reinforcement. The squeeze pressure reduces the percentage of porosity by minimizing the nucleation of gas bubbles [197]. Also, it increases the cooling rate with the

Table 5
Properties of AMMCs produced using Al_2O_3 as reinforcement.

S. no.	Composites	Wt./vol. fraction (%)	Casting method	Particle size	Porosity (%)	Hardness	Ultimate strength (MPa)	References
1	AA2024 (AlCu4Mg1)/Al_2O_3	10, 20 and 30	Stir	16, 32 and 66 (μm)	5	135 BHN	112 (T)	[4]
2	A356 (Al-Si7Mg)/Al_2O_3	1, 3, 5 and 7.5	Stir	20 μm	5.6	75 BHN	450 (C)	[148]
3	A356 (Al-Si7Mg)/Al_2O_3	1, 2, 3 and 4	Stir	50 nm	2.4	72 BHN	630 (C)	
4	Al–4.5 wt% Cu/Al_2O_3	1.5	Stir	50 nm	2.1	92 HV	240 (C)	[162]
5	A356 (Al-Si7Mg)/Al_2O_3	1.5	Stir	20 nm	3.4	120 BHN	265 (T)	[163]
6	AA2024 (AlCu4Mg1)/Al_2O_3	5	Stir	50 μm	8.4	82 HV	224 (T)	[164]
7	A356 (Al-Si7Mg)/Al_2O_3	2.5	Stir	50 nm	–	96 HR	182 (T)	[165]
8	AA2024 (AlCu4Mg1)/Al_2O_3	1	Stir	65 nm	Low	–	215 (T)	[166]
9	AA6061 (AlMg1SiCu)/Al_2O_3	20	Stir	36 μm	–	38 BHN	–	[167]
10	A356 (Al-Si7Mg)/Al_2O_3	1	Stir + squeeze	30	–	70 HRB	220 (C)	[168]
11	A356 (Al-Si7Mg)/Al_2O_3	1.5	Stir	20 nm	2.7	–	190 (C) Yield	[169]
12	AA7075 (Al-Zn6MgCu)/Al_2O_3	6	Stir	20 μm	–	120 HV	290 (T)	[170]
13	A206 (Al-Cu5MnFe)/Al_2O_3	5	Stir	10 μm	8	–	220 (T)	[171]
14	A206 (Al-Cu5MnFe)/Al_2O_3	5	Stir	100 nm	12.2	–	270 (T)	[171]
15	AA7075 (Al-Zn6MgCu)/Al_2O_3	1.2	Stir	50 nm	4.3	160 HV	400 (T) 760 (C)	[172]
16	AA6061 (AlMg1SiCu)/Al_2O_3	2	Stir + squeeze	–	Less	74 HB	193 (T) 361 (C)	[173]

* (T) & (C) are the ultimate tensile and compressive strength values respectively.

Table 6
Properties of composites produced using SiC as reinforcement.

S. no.	Composites	Weight/volume fraction (%)	Casting method	Particle size	Porosity (%)	Hardness	Ultimate strength (MPa)	References
1	AA2024 (AlCu4Mg1)/SiC	5	Stir	18 µm	11.5	74 HV	192 (T)[a]	[164]
2	AA7075/SiC	20	Stir	36 µm	–	50 HB	–	[167]
3	AA6061 (AlMg1SiCu)/SiC	6	Stir	20 µm	–	90 HV	160 (T)	[174]
4	A356 (Al-Si7Mg)/SiC	10	Stir + squeeze	10 µm	4	66 HB	195 (T)	[175]
5	A356 (Al-Si7Mg)/SiC	10	Stir + squeeze	40 µm	–	89 HB	245 (T)	[9]
6	A356 (Al-Si7Mg)/SiC	20	Stir + squeeze	12.6 µm	–	–	178 (T)	[176]
7	AlSi7Mg2/SiC	15	Stir + squeeze	23 µm	10.5	98 HB	165 (T)	[177]
8	Al-Si/SiC	3.5	Stir	50 nm	1.6	78 HB	280 (T)	[178]
9	A356 (Al-Si7Mg)/SiC	15	Stir	–	Low	95 HV	206 (T)	[179]
10	AA6061 (AlMg1SiCu)/SiC	30	Stir + squeeze	16 µm	Low	84 HB	200 (T)	[180]
11	AA6061(AlMg1SiCu)/SiC	6	Stir	20 µm	–	98 HV	270 (T)	[170]
12	AA7075 (Al-Zn6MgCu)/SiC	6	Stir	150 µm	Low	118 HB	269 (T)	[181]
13	AlMg4.5Mn/SiC	5	Stir	–	Low	63.6 HB	–	[182]
14	A356 (Al-Si7Mg)/SiC	10	Stir	7 µm 33 µm	–	141 HB 134 HB	430 (T) 380 (T)	[183]
15	AlMg4.5Mn/SiC	10	Stir	35 µm	2	77 HB	348 (C)	[184]
16	Al/SiC	10	Stir	40 µm	High	67 HB	205 (T)	[185]
17	AA6061 (AlMg1SiCu)/SiC	15	Stir	35 µm	–	82 HV	265 (T)	[186]
18	A356 (Al-Si7Mg)/SiC	3.5	Stir	50 nm	–	–	280 (T) 292 (C)	[187]

[a] (T) & (C) are the ultimate tensile and compressive strength values respectively.

Table 7
Properties of composites produced using B_4C as reinforcement.

S. no.	Composites	Weight/volume fraction (%)	Casting method	Particle size	Porosity (%)	Hardness	Ultimate strength (MPa)	References
1	Al/B_4C	8	Stir	70 µm	–	50 HV	140 (T)	[188]
2	Al/B_4C	8	Stir	80 nm	–	54 HV	155 (T)	[188]
3	A356(Al-Si7Mg)/B_4C	10	Stir	20 µm	–	74 BHN	265 (T)	[189]
4	A356(Al-Si7Mg)/B_4C	10	Squeeze	20 µm	2	68 BHN	270 (T)	[189]
5	A356(Al-Si7Mg)/B_4C	10	Stir	1 µm	1.8	77 BHN	142 (Y)	[189]
6	AA6061(AlMg1SiCu)/B_4C	15	Stir	60 µm	–	80 VHN	260 (T)	[190]
7	AA2024 (AlCu4Mg1)/B_4C	30	Squeeze	33 µm	3	120 BHN	115 (T)	[191]
8	AA7075 (Al-Zn6MgCu)/B_4C	20	Stir	20 µm	–	210 BHN	305 (T) 340 (C)	[191]
9	Al/B_4C	10	Squeeze	30 µm	–	51 HV	132 (T)	[191]
10	Al/B_4C	15	Stir		1.8	77 BHN	210 (T)	[192]
11	AA6061(AlMg1SiCu)/B_4C	15	Stir	30 µm	–	97 VHN	270 (T)	[193]
12	A356(Al-Si7Mg)/B_4C	15	Squeeze	10–21 µm	2.6	69 BHN	135 (Y)	[194,195]
13	A356(Al-Si7Mg)/B_4C	12.5	Squeeze	20 µm	–	75 BHN	–	[196]

(Y), (T) & (C) is the yield, ultimate tensile and compressive strength values respectively

loss of heat through dies.

- **Reinforcement size:** Particle size affects the strength of the material in the stir casting process. The smaller the size, the superior are the mechanical properties.
- **Stirring speed:** The distribution of reinforcement particles in the matrix is controlled by the viscosity of the aluminium melt, which plays a balancing role to ensure it is not too high to offer considerable resistance for particle movement during stirring, and it should not be too low so that it cannot suspend and hold the particles. The inter-particle distance is increased by increasing the speed. The stirring speed depends on the profile of the stirrer blade, and so it is hard to specify a numerical value.
- **Stirring time:** A homogeneous distribution of the particles is desirable to maximize the mechanical properties. Higher stirring time gives uniform distribution and good space between the reinforcement particles. However, the blade profile (shape) also plays a role in deciding the stirring time and so it may not be appropriate to specify precisely.
- **Melt temperature:** The high melt temperature may be desirable as it improves the wetting ability of the melt, but it reduces the viscosity of the melt. The particle agglomeration takes place when the melt temperature is low. So it is required to maintain the melt at an optimum temperature.
- **Stirrer blade design:** The stainless steel stirrer blade are used usually and coated with zirconia to avoid the reaction between stainless steel and Al alloys at higher temperatures. The design of the impeller/blade is essential for creating the vortex and to achieve the proper mixing of the melt.
- **Die preheating temperature:** This is also an influencing process parameter that can influence the property of MMCs. In the case of AlSi9Mg produced through the semisolid squeeze casting process, the size and the shape factor of primary α-Al particles increases with the increase in the die temperature. This resulted in an increase in the mechanical properties, but however, above 300 °C, the shape factor decreases suddenly resulting in lower mechanical properties [198]. Cold shut defect issues raise when the temperature of the die is too low which produce an adverse effect on the mechanical properties. Excessive die temperature leads to a reduction in the life of dies and affects the working conditions.

4.4.2. Methods for process parameters optimization

Several optimization methods are used to optimize the process parameters of the stir casting process. The most prominent ones are Taguchi techniques, grey relational analysis, regression analysis, multi-objective Taguchi method, genetic algorithm, analysis of variance (ANOVA), fuzzy logic [199], swarm optimizer [200] and finite element method. Vijian and Arunachalam [201] generated a mathematical model using multi variable linear regression analysis. Based on the regression analysis, the objective functions are chosen for the genetic algorithm using the weighted sum approach. A genetic algorithm is used as a tool to obtain better mechanical properties of the composites. Senthil and Amirthagadeswaran [202] conducted experiments based on the Taguchi technique for parameter optimization in the squeeze casting process. The confirmation test showed improved mechanical properties in the produced composites. Goyal et al. [203] developed a mathematical model and predicted the optimum process parameters using regression analysis technique. The optimum levels of parameters produced improved mechanical properties, which was validated using ANOVA. Su et al. [204] analyzed the flow behaviour of particles during mixing process in the crucible using finite element method and investigated the parameters such as blade angle, rotating speed, the diameter of the impeller, and the stirrer geometry. Also, the author suggested the parameters level to get the uniform distribution in the stir casting process.

4.5. *Additives to enhance the quality of the MMCs*

Several additives for enhancing the quality of the MMCs are available. Among this Foseco [205] has a range of commercial additives such as grain refiners, degasser, covering flux and wetting agents which are discussed briefly in the following sub-sections.

4.5.1. *Grain refiners*

NUCLEANT 70 is a sodium free grain-refining tablet suitable for the production of AMMCs. This refiner is a self-sinking version that requires no plunging. Dipotassium hexafluorotitanate is used for the production of aluminium alloys except for eutectic and hyper-eutectic alloys. It produces fine dispersed highly efficient nuclei in the melt. **ELDUCTAL 90 S** is a titanium-free grain refining tablet and is particularly recommended for high-conductivity aluminium and has a deleterious effect on electrical conductivity. **PHOSPHORAL L 12** is a grain-refining tablet for eutectic and hypereutectic materials. **COVERAL MTS 1582** is a sodium free grain refining flux specially developed to be used with the Foseco Melt Treatment Station [205,206]

4.5.2. *Degasser*

The degasser is one of the additives used in the production of AMMCs to minimize the hydrogen bubbles, nitrogen, carbon di oxide, and gas bubbles. Degassing can be achieved in three different ways,

a. Addition of chemical agent in tablet forms such as tetrachloroethane, sodium hexachloroaluminate, and hexachloroethane to minimize the presence of hydrogen gas in the melt and also to prevent the melt from getting oxidized. These chemicals are useful to remove the nitrogen and carbon di oxide from the aluminium melt. However, the amount to be added is not specified [164,207–211].
b. Supplying dry nitrogen gas to the melt during the heating process to absorb the gas bubbles and unwanted chemicals using an external setup. The porosity of the produced composite decreased significantly [184].
c. The degassing can also be achieved without adding any chemical additives by dipping the ultrasonic probe into the melt and sonicating for 5 min [166]. It was reported that the addition of degasser to the aluminium melt should be avoided to prevent any unwanted chemical reactions. So, this method can be adopted [212].

4.5.3. *Covering flux*

To remove slag and prevent the oxidation of the melt potassium aluminium fluoride can be used. Koli et al. [213] reported that impurities were removed and the produced component was defective free by incorporating this flux. Potassium hexafluorotitanate (K_2TiF_6) flux added to the melt equal to the amount of reinforcement formed a reaction layer, containing TiC and TiB_2 at the Al-B_4C interface. The strong interfacial bond between the matrix and reinforcement due to the formation of the Ti layer around the particles occurred due to the addition of flux [214].

4.6. *Wetting agent*

Addition of a wetting agent is required to achieve a strong bonding between the matrix alloy and the reinforcement particles by decreasing the surface energy (wetting angle) between them. It enhances the fluidity of the molten metal. Segregation of wetting agent at the interface may change the nature of chemical bond locally at the interface and promote wetting. A chemical reaction at the interface may result in a product covering the entire surface of the dispersoids. The porosity is reduced by adding the wetting agent into the molten metal. The addition of less than 2 wt.% of pure magnesium into the melt improved the quality of the MMC [164]. Pure magnesium of 1 and 1.5% was added in earlier works by Das et al. [215] and Kongshaug et al. [165] respectively and reported that the porosity was decreased. Because of low porosity, the mechanical properties of the produced AMMCs are enhanced. Mohammadpour et al. [216] tried with a different kind of commercially available wetting agent such as Mg, Ca, Si, Ti, Zn, Zr added into the aluminium melt and reported that 1% Mg was more potent among other wetting agents in ceramic metal matric composites [212].

5. Challenges in the production of AMMCs using stir casting process

Stir casting is quite a widely used process for MMCs, but they suffer from certain disadvantages which pose as challenges in production. The following points summarize the challenges faced during the production of AMMCs based on the assessment of literature and experience with producing AMMCs:

1. Uniform distribution of reinforcement particles is a significant issue even with micron-sized particles that severally influences especially the mechanical properties of the MMCs. Factors such as the viscosity of the melt, stirrer speed, stir time and particle size need to be adjusted to achieve a homogeneous distribution of the reinforcement particles. The difference in density between the matrix and the reinforcement can also lead to non-uniform distribution since the particles may either float or settle down. In the case of nano-sized reinforcements, they are not only expensive, but agglomeration and safe handling issues to be tackled appropriately. Reinforcement particle distribution is one of the primary reasons why MMCs have not yet been exploited commercially to the extent it was desired by researchers.
2. Wettability between the solid reinforcement particles and the liquid Al matrix is an important issue that influences the bonding between these two and thus affects the mechanical properties of the MMCs.
3. Porosity is another major issue in the production of MMCs, which seriously influences the strength. There are many possible ways to reduce the porosity in the casted product as discussed in the earlier section and recommended in the later section.
4. Erosion on the stainless steel stirrer blade occurred very often during the production of AMMCs reinforced with Al_2O_3 or SiC or any hard micro particles. A high-temperature grease was applied manually at 300 °C to prevent the stirrer from metal erosion as well as prevent the molten Al from sticking to the stirrer. Replacing blades frequently would be a significant challenge especially for mass production since it will hinder the production rate as well as increases the consumables cost. Moreover, the eroded stirrer blade material can also become part of the MMC and can influence the properties.
5. Reinforcement mixing rate is another challenge since most designs do not allow a constant rate and this is one area that needs to be addressed in the future by the furnace designers.

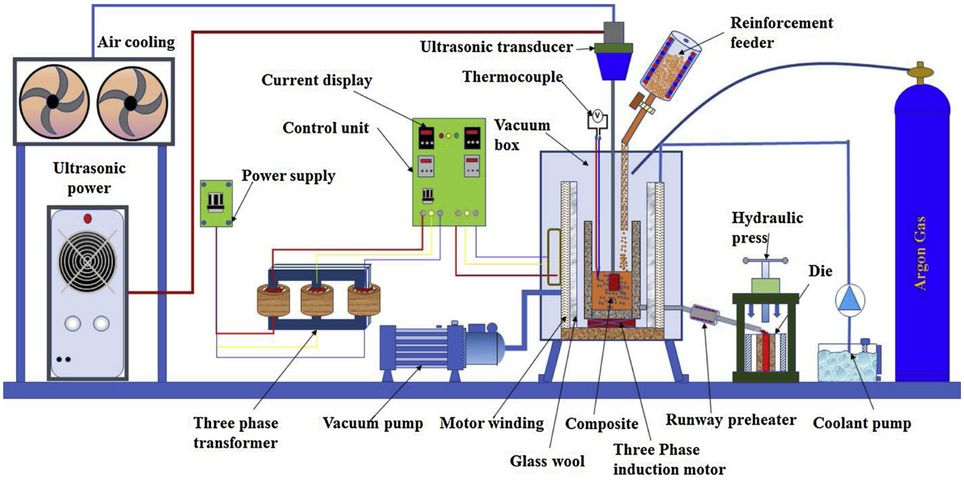


Fig. 39. Recommended stir casting furnace design.

6. Reinforcement may react with the matrix material and can form undesirable phases could also be an issue.

6. Recommendations

The novelty of this review is in the assessment of several stir casting furnace design. Based on the assessment, the best design is recommended. Based on the challenges discussed previously the following recommendations are made.

6.1. Furnace design for the production of MMCs by stir casting

As discussed earlier, there are several furnace designs that could be used in the production of MMCs. Based on the extensive application, excellent mechanical properties, homogeneous distribution of particles and reduced porosity, a bottom pouring stir casting set up using electromagnetic stirring and with an option of ultrasonic stirring especially for nanomaterials along with squeeze casting attachment is recommended for the production of MMC as illustrated schematically in Fig. 39. These recommendations are based on the discussion of results obtained by researchers using those techniques such as ultrasonic stirring, squeeze casting and electromagnetic stirring as discussed in Sections 3.2.6, 3.2.8 and 3.3 respectively. Based on the interaction with commercial furnace suppliers, these features may soon be available in a single setup.

The recommended furnace design mainly consists of ultrasonic powered agitator, electromagnetic stirrer, hydraulic squeeze setup, inert gas supply system and a vacuum box. This proposed system is capable of distributing the nano reinforcement particles uniformly throughout the matrix material with the aid of ultrasonic agitator. The ultrasonic agitator also removes the gas bubbles in the molten metal during the production process. The electromagnetic stirrer is a good substitute for the mechanical stirring to avoid alloy contamination and erosion of stirrer [217]. The squeeze casting attachment provides appropriate squeeze pressure once the molten metal fills the die cavity. This reduces the porosity and improves the mechanical properties. The inert gas supply system helps in feeding and mixing the reinforcement. The vacuum box helps in avoiding the gas penetration during the entire process, and so the casting defects such as porosity and blow holes are reduced. The process parameters such as reinforcement preheater temperature, die temperature, squeeze pressure, squeeze time, runway temperature, ultrasonic agitator, argon gas supply could be controlled with the help of control panel provided with the machine.

6.2. Recommended matrix and reinforcement materials

It is entirely subjective to recommend but based on the application of the AMMCs; it is possible to recommend in general. For high strength applications, Al 7075 (ISO designation: AlZn$_{5.5}$MgCu) is the ideal one since the UTS can range from 280 to 570 MPa based on the heat treated condition. Addition of reinforcement results in further improving the strength of the MMC. LM6 (Al-Si$_{12}$Al-Si$_{12}$Fe) and LM25 (Al-Si$_7$Mg) both exhibit good fluidity thus making it easier to cast into complex shapes as well as exhibits excellent corrosion resistance.

Unlike Al alloys, in the case of reinforcements, the available variety is very high, but general recommendations could be made based on the application of the MMC. Most reinforcements are inorganic ceramic phases as discussed earlier in the Introduction section. Among these, the oxide and carbide based especially Al_2O_3 and SiC respectively in micron size are the most frequently used because of their higher hardness (wear resistance applications) as well as specific strength (high strength to weight ratio for applications in aerospace and automotive industries). For self-lubricating applications, graphite and WS_2 are recommended. MMC production using scrap Al as matrix and appropriate waste by-products of industries (including agro waste) as a reinforcement material, is still an open-ended area in which much independent research could be carried out.

6.3. Recommended stir-squeeze process parameters for the production of AMMCs

The recommended process parameters range for stir with squeeze casting is provided in Fig. 40. These recommendations are based on the results obtained by researchers as discussed in this section. Among all the parameters, squeeze pressure is the most influencing parameter. Most of the earlier researchers reported that 100 MPa squeeze pressure is suitable for grain refinement and fewer porosities. Beyond 100 MPa squeeze pressure, no significant effects were observed [218]. Squeeze pressure holding time was identified as a most influencing factor to improve the product properties. Therefore, it was recommended to use the holding time between 30–45 s, after this there no influence on heat dissipation rate [202]. For the squeeze casting process, the recommended melt temperature is 700 °C for aluminium alloys when the temperature of the melt was brought down from 780 to 680 °C, the macrostructures gradually became finer, and the grains became smaller [219]. To get proper infiltration of reinforcement, the temperature of melt should be above 600 °C [220]. It was reported that the tensile strength and elongation of aluminium alloy (AlSi9Mg) produced through semi-solid squeeze casting is amplified when the pre heating temperature of the die is increased from 200 °C to 250 °C, but no

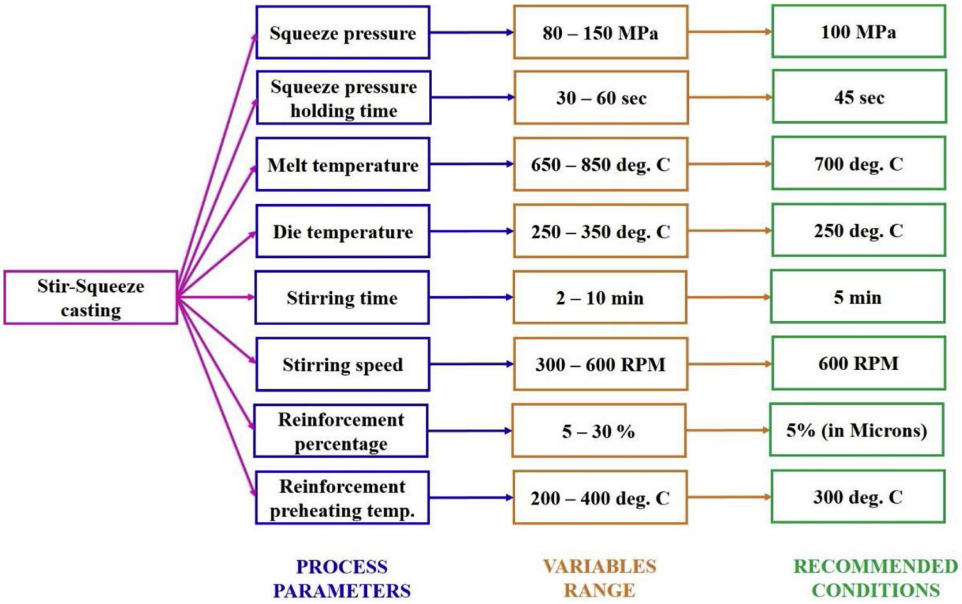


Fig. 40. Recommended process parameters for stir-squeeze casing process [198,202,218–223].

Fig. 41. A typical two blade stirrer.

significant change was observed with the temperature between 250 and 300 °C. At 350 °C, the tensile strength and elongation decreased suddenly and also there were many rosette particles in the microstructure [198]. The stirring time duration should be greater than 5 and less than 10 min to get a homogenous mixture. Above 10 min, leads to the agglomeration of particles, resulting in the reduction of the mechanical properties of the composites [221]. The formation of porosity, oxide skins, and gas formation was observed at higher stirring speeds (700 rpm), and at a lower speed the mixing of reinforcement with the matrix was not proper, reinforcement segregated at the vortex [222]. Stirring speed of 600 rpm produces a homogenous mixture and fewer porosities in the MMCs resulting in improvement of the mechanical properties of the produced composites. However, as discussed earlier this is subjective since the profile of the stirrer influences the vortex intensity. For a typical two blade stirrer profile like the one shown in Fig. 41, the optimum speed is 600 rpm. Ideally, electromagnetic stirring would be good as it avoids physical contact with the melt and the associated issue of stirrer blade erosion. If the electromagnetic stirrer cannot be installed, the stirrer blades could be subjected to hard coatings that could prevent erosion and frequent change of the stirrer. The reinforcement percentage purely depend upon the desired properties of the AMMCs; for micron size particles of SiC and Al_2O_3, it is found to be 10% and 5% weight percentage respectively based on the Tables 5 and 6 given in Section 4.3. Preheating the reinforcement before adding into the melt cleans the surface from impurities especially adsorbed gases and improves the wetting [223]. It also eliminates moisture. Preheating temperature of 250–300 °C is recommended for most reinforcement particles.

6.4. Recommended additives and wetting agent

The recommendations are based on the discussion in Section 4.5. Among the additives, grain refiners are ideal since it can significantly increase the strength of the MMCs without much effort or energy spent. For degassing, tablet form is the easiest way to add to the melt when compared to other ways of degassing the melt. Flux could be added to the melt to help in removing slag (impurities) but not necessary. Once the molten metal melts and before adding the reinforcement, the slag which usually floats at the top could be removed using a scoop while wearing proper personal protective equipment.

To minimize the porosity BORAX in powder form can be mixed with reinforcement in the ratio of 1:2. Tensile and yield strength of the aluminium composite was increased [224].

Several ways are available for improving wetting including the addition of alloying elements, a coating of the reinforcement particles, heat treatment and ultrasonic cleaning of the particles as well as ultrasonic vibration [225]. Heat treatment of the reinforcement particles and alloying is the easiest way. Magnesium is a powerful surfactant, and it has been successfully applied to promote wetting [225]. 1 to 2% is recommended to improve the interfacial bonding between the matrix and reinforcement. More than 2% Mg leads to the formation of low melting constituents resulting in a reduction in the mechanical properties of the MMCs [225]. Proper precautions should be taken while adding Mg to the melt. If the stir casting furnace is equipped with an ultrasonic stirrer, then ultrasonic vibration can also be used to improve wetting. Although the coating of the reinforcement particle with a wettable metal can enhance the wetting, it increases the processing time and cost especially if the coating process is complex and expensive.

6.5. Current applications of AMMCs

The current applications of various AMMCs are listed in Table 8. From this table, it is quite apparent that AMMCs are having commercial significance and so should be pursued by researchers to advance the applications of AMMCs further.

Hybrid AMMCs, as well as those using nano-sized reinforcements, are under research and many investigations are currently being published by researcher worldwide. Hence, the next generation AMMCs will be hybrid composites exhibiting excellent properties. Fig. 42 shows the potential applications of AMMCs in various industries using a tree diagram. The roots indicate the important factors that influence those applications.

Table 8
Current applications of AMMCs.

S. no.	Composite	Applications	Company	References
1	Al/SiC	Disc brakes for high-speed trains	Temponik	[226]
2	Al/SiC	Pistons	Ztotecki	[227]
3	AA2009/SiC 15%	Fan exit guide vanes, F-16 ventral fins and fuel access covers	DWA	[228]
4	6091/SiC 40% 6092/SiC 44%	Electronic packing		
5	Al75/SiC 25% Al70/SiC30 Al60/SiC40	Heat sinks, display equipment, semiconductor inspection parts	Ferro Tec	[229]
6	Al 30%/Al_2O_3 70%	Display equipment parts		
7	Al/Nextel610/45f	Pushrods	3M	[227]
8	Al 60%/Al_2O_3 40%	Cylinder sleeves in engines, piston-recess walls, brake pad backing plates, bearings, brake discs	Ceram Tec	[230]
9	AA2024 (AlCu4Mg1)/SiC 25% AA6061 (AlMg1SiCu)/SiC 20% AA6061 (AlMg1SiCu)/SiC 40%	Outlet guide vanes Hydraulic blocks Wheels Fixed wing structure/skins Helicopter components Pistons Piston pins Cylinder liners Brake callipers Connecting rods Push rods Valve train Chassis components Optical systems Sensors Satellite structures	Materion	[231]
10	AA2024 (AlCu4Mg1)/Al_2O_3	Turbo impeller Heat sink Stator vane Piston head Timing wheel	Elementum 3D	[232]
11	Al/SiC Al/B_4C Al/Al_2O_3	Precision equipment components, thermal management base plates, mirrors, optical housings, armour, brake rotors, connecting rods, and pistons	M Cubed Technologies	[233]
12	Al/Al_2O_3 (nano)	Piston Connecting rods Aerospace Armour	Gamma alloys	[234]

7. Research opportunities in the production of MMCS

Production of MMCs as discussed earlier involves many challenges. There are large deviations in the properties of MMCs produced using various casting methods. Hence, it is challenging to select an appropriate method for a specific application. The process parameters and conditions should be optimized for the production of several compositions of MMCs. Published literature are not sufficient to finalize process parameters for many of the existing and new matrix as well as reinforcement materials especially nanomaterials introduced recently. Some amount of porosity is unavoidable in any casting process, and so techniques for reduction of porosity deserves sufficient attention. Uniform distribution of reinforcement particles is another issue that critically influences the mechanical properties. Similarly, the mechanical properties are also strongly influenced by the bonding between the matrix and reinforcement which in turn is influenced by the wettability [235]. Hardly there is any research on the wettability except by Hashim et al. [225] and Razzaq et al. [235]. With stronger interest in developing environment-friendly techniques, recycling of materials is of utmost importance, and this is again not attracted attention although researchers have recommended it [27]. Using scrap/waste/spent materials for both matrix and reinforcement in the production of MMCs is still an open-ended area in which much exclusive research can be carried out. Fig. 43 depicts the grey areas and the potential research opportunities in the production of MMCs and the possible outcomes.

8. Conclusions

This review has systematically discussed the production of AMMCs with the focus on the stir casting process for the first time. Among the various processes, stir casting is the primary, established and economical process for the production of MMCs. The number of research publications in the area of stir casting included in Scopus database reiterates the importance of stir casting process. Some of the key findings are listed below.

1. Among the production methods, stir/squeeze casting, powder metallurgy and semi-solid are the most promising ones for the production of MMCs. In stir/squeeze casting process, the squeeze pressure is the most influencing parameter that influences the mechanical properties.
2. Al is a more popular matrix material because of its ease in handling during the production process. Among the reinforcement particles, SiC, Al_2O_3, and B_4C are the most commonly used because of their ability to provide better mechanical properties such as strength and hardness.
3. Mg is the most common wetting agent, and about 1–2% is recommended to improve the wetting of the reinforcement particles with the matrix material.
4. AA7075 alloy with 50 nm Al_2O_3 exhibited the highest value for mechanical properties (Hardness – 160 HV, Ultimate Tensile Strength – 400 MPa and Ultimate Compressive Strength – 760 MPa). These properties were further increased by extruding the composites through a conical die.
5. In the case of SiC reinforced composites, A356 matrix with 10% of 7 μm size SiC particles yielded the highest hardness of 141 HB and ultimate strength of 430 MPa.
6. Similarly, in the case of B_4C reinforced composites, AA7075 alloy with 20% of 20 μm B_4C resulted in the highest value for mechanical properties (Hardness – 210 BHN, Ultimate Tensile Strength – 305 MPa and Ultimate Compressive Strength – 340 MPa).
7. The significant challenges in the stir casting process are a uniform distribution of the reinforcement particles, wettability, porosity, erosion of the stirrer blades and reinforcement mixing rate. These challenges in themselves are the future potential research opportunities in addition to the sustainable development of MMCs using recycled matrix and waste reinforcement particles generated in industrial processes.
8. A bottom tapping stir casting furnace with preferably electromagnetic and ultrasonic stirring combined with squeeze attachment would be ideal for the production of AMMCs reinforced with any reinforcement material.
9. By proper selection of the production process and its parameters as well as the matrix, reinforcement material, additives, and wetting agent, good quality MMCs exhibiting enhanced mechanical properties can be produced.

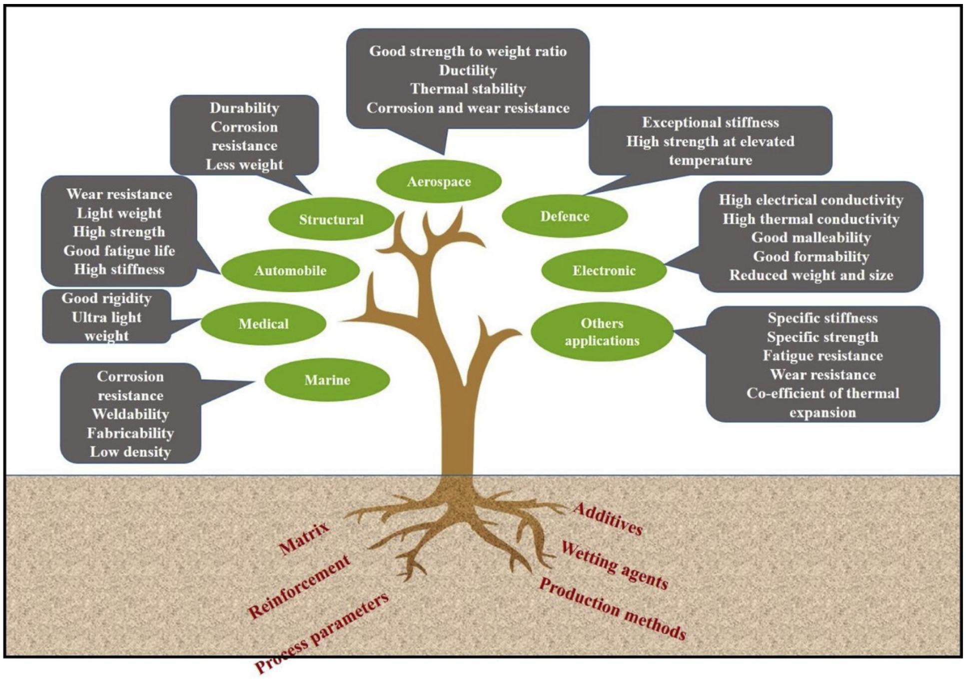
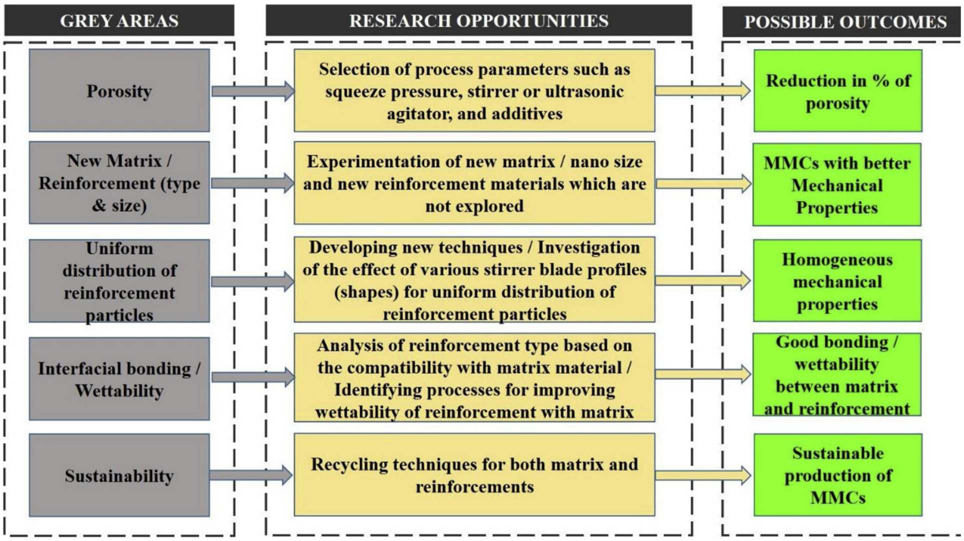


Fig. 42. Applications of AMMCs in various fields.



GREY AREAS	RESEARCH OPPORTUNITIES	POSSIBLE OUTCOMES
Porosity	Selection of process parameters such as squeeze pressure, stirrer or ultrasonic agitator, and additives	Reduction in % of porosity
New Matrix / Reinforcement (type & size)	Experimentation of new matrix / nano size and new reinforcement materials which are not explored	MMCs with better Mechanical Properties
Uniform distribution of reinforcement particles	Developing new techniques / Investigation of the effect of various stirrer blade profiles (shapes) for uniform distribution of reinforcement particles	Homogeneous mechanical properties
Interfacial bonding / Wettability	Analysis of reinforcement type based on the compatibility with matrix material / Identifying processes for improving wettability of reinforcement with matrix	Good bonding / wettability between matrix and reinforcement
Sustainability	Recycling techniques for both matrix and reinforcements	Sustainable production of MMCs

Fig. 43. Grey areas in the production of MMCs.

Declaration of interest

None.

Acknowledgements

The first author extends sincere thanks to Sultan Qaboos University, Oman; Grant No.: CL/SQU-UAEU/17/04, Sultanate of Oman for encouraging research and development. The second author extends sincere thanks to the management of National University of Science and Technology, Sultanate of Oman for supporting his Ph.D. research work. The third author extends his sincere thanks to Vels Institute of Science, Technology & Advanced Studies, India for supporting his postdoc assignment.

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