Results in Engineering 24 (2024) 103152

Contents lists available at ScienceDirect

Results in Engineering

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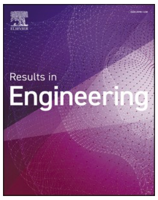

Review article

Casting of particle reinforced metal matrix composite by liquid state fabrication method: A review

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ARTICLE INFO

Keywords:
Metal matrix composite
MMC
stir casting
Reinforcements
wear rate

ABSTRACT

The purpose of this study is to investigate the characterization of Metal Matrix Composite (MMC), using liquid state fabrication technique. The paper also considered the latest trend of MMC. The selection of the matrix and reinforcement is an essential component in the production of outstanding composite materials. These materials are used to improve the ultimate strength, hardness, fatigue behaviours, creep quality, machinability, weldability, fracture toughness, wear resistance capacity, and other properties of the composite material. In recent years, aluminium-based metal matrix composite has emerged as a leading class of material due to the exceptional qualities it has. It has been observed, that the metal matrix composite that is produced is highly influenced by both the controlled and uncontrolled elements that are involved in the stir-casting process.

1. Introduction

Composite materials are highly advanced and versatile engineering materials that have increased specific strength in comparison to typical monolithic alloys. This has led to an expansion of their applications in the sectors of automobile manufacturing, aviation manufacturing, medicine, infrastructure, and the military industry. The selection of matrix alloy and reinforcement particles depends on its application [1–4]. Aluminium Metal Matrix Composites (AMMCs) are gaining attention for their exceptional strength, low density, and enhanced wear resistance, making them suitable for industries like defense, automotive, and aerospace [5–8]. Increasingly, industrial waste materials, such as Cupola Slag (CS), are being utilized as cost-effective reinforcements, offering both sustainability and improved mechanical properties. CS is a high-hardness by-product with significant potential in AMMCs [9–11]. The revolutionary effects of cutting-edge processing techniques, such additive manufacturing (AM), on both design and production make their incorporation a must-have in contemporary material science. In comparison to more conventional manufacturing processes, AM allows for more design freedom, less material waste, and the efficient production of complicated geometries. Using this cutting-edge method in research greatly improves the relevance of material studies, and it has already shown useful in a variety of sectors, including aerospace and medicinal applications. Incorporating additive manufacturing into the introduction allows academics to tackle current issues and come up with fresh answers [12–14]. A complete fishbone diagram of producing better quality of metal matrix composite shown in Fig. 1.

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https://doi.org/10.1016/j.rineng.2024.103152
Received 8 August 2024; Received in revised form 28 September 2024; Accepted 12 October 2024

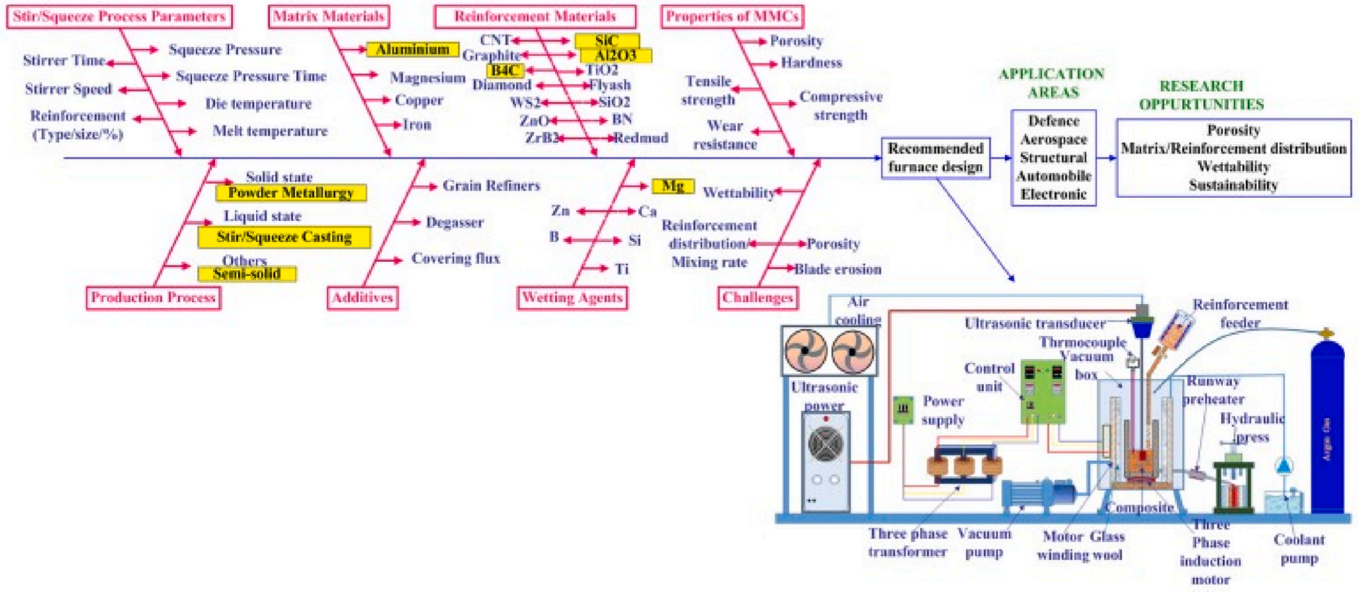

Fig. 1. A complete fishbone diagram of producing better quality of metal matrix composite [15]
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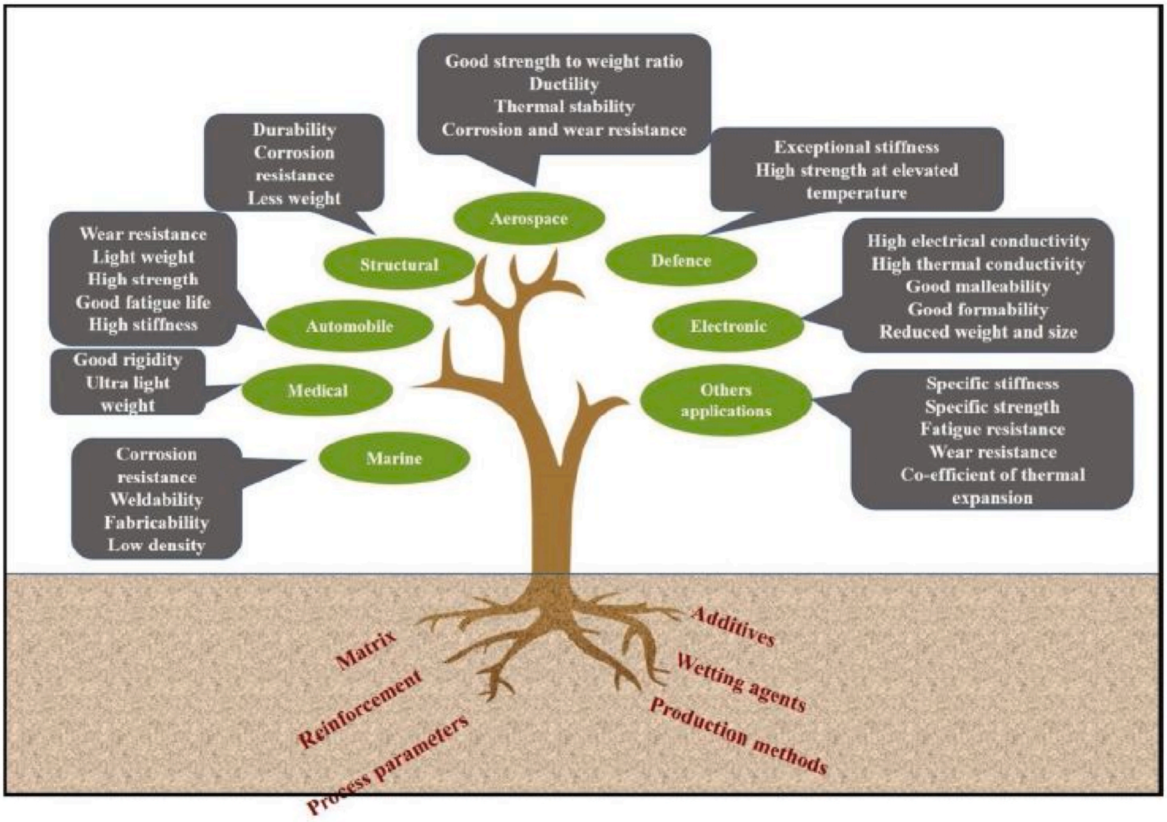

Fig. 2. Different application of aluminium matrix composite [15]
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1.1. Matrix material

The high strength, low density, high stiffness, cheap cost, and superior fatigue behavior of aluminum matrix composites (AMCs) have led to their widespread application in research work [16,17]. This is because AMCs have all of these same characteristics. Magnesium has been used in a wide range of applications, including the aircraft industry, car sectors, and military departments, owing to its lightweight nature (density of about 1.74 g per cubic centimeter) [18]. There is a significant improvement in heat resistance, sufficient strength, high damping capacity, and low wear rate when magnesium matrix composite (MMC) is reinforced with ceramic particles [19]. Copper matrix

Table 1
Application of various particulate reinforcements of composite.

Sl. No.	Reinforcement	Application	References
1.	SiC	Propeller shaft, connecting rod, brake rotors, driveshaft	[22,23]
2.	TiB_2	Defence, automotive, and thermal management area	[24]
3.	B_4C	Automotive applications	[22]
4.	Flyash	Covers, pans, shrouds, casings, pulleys, manifolds, valve covers, brake rotors	[25,26]
5.	Al_2O_3	Brake discs, pistons, cylinder heads	[27]
6.	TiC	Pistons, connecting rods	[23,28]
7.	ZrB_2	Aerospace applications	[29]
8.	Si_3N_4	Automotive parts	[29]

composites are being used in a wide variety of applications, including the construction of radiators, electronic components, jet engine casings, and more. Utilization of ceramic particles in conjunction with alumina and silicon carbide is essential to the improvement of copper matrix composite [20]. This composite material is used in the production of electronic goods because of its high heat conductivity and low wear rate [21]. Carbon fiber reinforced copper matrix composite. Fig. 2 depicts an example of a new kind of use for aluminum matrix composite.

1.2. Types of reinforcement used

Reinforcement particles play a very important role to make the composite. Reinforcement added in matrix material to improve its mechanical, thermal, and tribological properties. Reinforcement is in the form of granular or particulate. Sometimes more than one reinforcement are used to improve mechanical properties. For better mixing of reinforcement into the matrices, sometimes magnesium is used for better wettability. Application of different reinforced composites are mentioned in Table 1.

In order to substantially improve the mechanical characteristics of composite materials, both synthetic and non-synthetic reinforcements are absolutely necessary. Synthetic reinforcements, which include glass fibers, carbon fibers, and ceramic whiskers, are designed to provide higher strength, stiffness, and heat resistance. These reinforcements are manufactured, specifically, for certain uses [30]. Due to the fact that they may be modified to fulfill specific performance requirements, they are well suited for business sectors such as the aerospace, automotive, and construction industries. On the other hand, non-synthetic reinforcements, which include natural fibers such as jute, hemp, and bamboo, are produced from sources that are renewable. An option that is sustainable is provided by these materials, which are not only lightweight but also biodegradable and beneficial to the environment [31]. In spite of the fact that synthetic reinforcements often provide superior performance, non-synthetic alternatives are attracting an increasing amount of attention for environmentally viable applications [32].

The following is a description of the many sorts of reinforcements that are used in metal matrix composites.

1.2.1. Silicon carbide (SiC)

Silicon carbide is widely used as reinforced particulate for making metal matrix composite due to its easy and uniform distribution in MMC. Great advantage of using Al/SiC composite in aircraft factory due to its strength to weight ratio and which is about three times greater than mild steel. Overall porosity of SiC reinforced composite increases with the addition of SiC content [33].

Al/SiC composites may undergo the formation of the intermetallic complex Al_4C_3 at a temperature of 400 °C, as shown by the Al-C-Si phase diagram. The phase diagram provides insights into the interactions and phases that occur in the Al-SiC system across different temperatures and compositions [34]. The possible chemical reaction that happened among Al-C-Si at 700 °C is shown below in Eqs. (1)–(3).

$$3\ SiC + 4\ Al = Al_4C_3 + 3\ Si \tag{1}$$

$$3\ C + 4\ Al = Al_4C_3 \tag{2}$$

$$Al_4C_3 + SiC = Al_4SiC_4 \tag{3}$$

SiC particle reinforced magnesium matrix composite remarkable development in yield strength and hardness. Yield strength increment up to 9.8 % compared to magnesium matrix [35]. SiC_p/WE43 magnesium matrix composite improved wear resistance capacity, prevent crack propagation and generate brittle tribolayer [36]. Silicon carbide has more abrasive, and resist acids and other salts up to 800 °C. Silicon carbide reinforcements are capable to resist all thermal shocks because of their high thermal conductivity and low thermal expansion. Al/SiC composite has a low wear rate and enhanced coefficient of friction [22].

The influence of temperature on the spatial arrangement of SiC reinforcement in Al356/SiC composites [37]. Their research revealed that the temperature during the processing of the composite has a substantial impact on the dispersion of SiC particles. At lower temperatures, the dispersion of SiC particles may be more homogeneous, but at higher temperatures, the particles may aggregate or disperse unevenly. The magnesium powder was injected into the mixture in order to improve its wettability. It was shown that the compocasting process was more effective in improving the distribution of SiC particles throughout the aluminium matrix. It was found that ultimate tensile strength more at higher temperature compocasting method. During the fractography test, deeper and uniform dimple found at 300 °C which indicate more ductility in nature. The density of SiC particulates is greater than the aluminium alloys which makes sure the overall density of the final composite increases compared to its base aluminium matrix. SiC particulates increase the hardness of composite that developed wear resistance capacity of prepared composite. Al356/SiC composite maintains its potentiality at high temperature because of its better UTS and good wear rate.

Y. Sahin [38] conducted research on the mechanical characteristics and tool life behaviour of a SiC reinforced aluminium matrix composite that was manufactured by the stir casting technique. Reinforcement used various types of grain size such as 110 μm, 45 μm and 29 μm for a better outcome. Agglomeration formed when grain size less than 110 μm which seemed from scanning electron microstructure. Hardness and porosity increases with increase in the volume percentage of SiC. Porosity increases specially for low particle size reinforcement because reducing inner particle spacing. It is perceived that tool life reduced with enhance in cutting speed of entirely cutting condition for 45 μm size and 10 % reinforcement of SiC.

The microstructure of semisolid slurries is more consistent on nano-sized Al7075/SiC composite composed by ultrasonic-assisted semisolid stirring for stirring temperatures of 615 °C and 620 °C instead of remaining stirring temperatures because of creating a larger shear force [39]. Significant improvement of mechanical properties was noticed for SiC reinforced composites instead of unreinforced matrix alloy.

The mechanical and wear characteristics of a nano-sized SiC powder reinforced AA2219/SiC composite were reported by Faisal and Kumar [40]. It was observed that the insertion of 2.5 % SiC nano particles, as opposed to the unreinforced matrix, resulted in a hardness improvement of around 66 %. Related results were revealed for the ultimate tensile strength and flexural properties where approximate 20 % development was noticed.

The mechanical and wear behaviour of an Al7075/SiC composite reinforced with SiC powder was elucidated by Thella Babu Rao [41]. SEM analysis revealed that reinforcement particles are distributed uniformly with minimal agglomeration and also make a better interfacial bonding in between matrix material and reinforcement particulates. Mechanical characterization revealed that UTS and hardness significantly developed with enhancing the SiC grain size and its content.

The distribution of various particle sizes in the SiC powder-reinforced A356/10 vol%SiC aluminium matrix composite was examined by Yang et al. [42]. For fabrication, SiC powder mixed into melt detained 600 °C by using a mechanical stirrer and 45° four-bladed impeller turning at 600 rpm for 5 min. Concentrated shearing force formed between stator and rotor along with in the openings on the stator wall split up SiC agglomerates into separate scattered particulates and uniformly distributed in the aluminium matrix.

The microstructure and mechanical characteristics of micro-sized SiC powder reinforced Al-Si-SiC aluminium matrix composites made using the stir casting manufacturing process were examined by Singh et al. [43]. Results revealed that hardness, UTS, and yield strength of the Al-Si-SiC aluminium matrix composite developed by 17 %, 38 %, and 13 % respectively instead of unreinforced aluminium matrix Al-Si (LM30). The SEM micrograph observed that eutectic silicon builds up like a coarse needle shape and is scattered with primary silicon cuboids. SEM micrograph also established the uniform distribution of reinforcement and high bonding strength in between matrix and reinforcement. Fracture analysis noticed that SiC reinforced composite negligible plastic deformation that enhanced load-bearing capacity but unreinforced matrix composite having a significant amount of plastic deformation.

The weight percentages of Al6061/SiC aluminium matrix composites supplemented with SiC powder and produced by stir casting were studied by Maurya et al. [44]. These weight percentages were 0, 1, 2, 3, and 5. The scanning electron microscopy (SEM) study revealed that the reinforced particles were distributed uniformly throughout the aluminium matrix, with just a little amount of porosity being formed. In addition, the hardness and tensile strength of the material improved as the proportion of SiC reinforced particles contributed to the overall weight of the material.

The influence of two SiC particle sizes, 10 and 50 μm, on the mechanical properties of an Al/SiC aluminium matrix composite was explained by Ye et al. [45]. The optimum micrograph clearly demonstrated that the SiC particles were dispersed uniformly over the whole aluminium matrix, with just a little amount of agglomeration occurring. When the grain size of SiC particles was lower, the particles served as reinforcement for loading and fractured. However, when the grain size of SiC particles was greater, the particles were able to differentiate themselves from the aluminium matrix a great deal more effectively. Because of this, smaller grain size SiC particles have a stronger anti-compression, which results in these particles having a higher yield strength.

An experimental study on the microstructure and mechanical behaviour of an Al6082/SiC aluminium matrix composite reinforced with nanoscale SiC particles was carried out by Zhu et al. [46]. The microstructure of the molten matrix indicated that SiC particles are evenly dispersed throughout the matrix, and the EDX analysis demonstrated that SiC particles are present. Instead of using an unreinforced aluminium matrix, the UTS, yield strength, and elongation of the Al6082/SiC composite were all improved by 1.26 %, 8.92 %, and 12.60 % respectively.

1.2.2. Titanium diboride (TiB_2)

Titanium diboride is used as reinforcement in the composite for its better physical and mechanical properties. TiB_2 has excellent mechanical properties like high strength and high melting point which widely uses erosive, abrasive, corrosion, or high-temperature environment. TiB_2 never reacts with molten aluminium alloy, therefore aluminium matrix composite reinforced with TiB_2 distracts to produce small brittle elements, decreases wear rate, and increases the coefficient of friction. In order to produce TiB_2 by an exothermic salt reaction, commercial-grade powder potassium hexaflurotitanite (K_2TiF_6) and potassium tetrafluroborate (KBF_4) salts are used. The equation for these salts may be seen below. The chemical interaction that took place between the salts was used in this method, which resulted in the creation of TiB2 inside the molten aluminium alloy [47]. A result obtained from XRD analysis demonstrated the presence of TiB_2 particles throughout the whole composite.

$$3\ K_2TiF_6 + 6\ KBF_4 + 10Al = 3\ TiB_2 + (9KAlF_4 + K_3AlF_6) \tag{4}$$

The mechanical properties and characterisation of an aluminium matrix composite reinforced with TiB2 powder and AA7075 containing TiB_2 are investigated by Meti et al. [48]. Stir casting fabrication process was used to fabricate the aluminium matrix composite by mixing different weight percentages (5, 7.5 %) of TiB_2 reinforcement. Microstructure revealed that AA7075/TiB_2 has obtained some porosity due to the existence of TiB_2 agglomeration. AA7075/7.5%TiB_2 composite has more agglomeration and more porosity instead of AA7075/5%TiB_2 composite caused by the development of reinforcement content.

The impact of employing the stir casting process on the microstructure and mechanical characteristics of Al6061/TiB_2 composites with varying percentages of TiB_2 powder reinforcement (3 %, 6 %, and 9 %) is described by Pazhouhanfar and Eghbali [49]. Microstructure and X-Ray diffraction pattern of TiB_2 particles. Optical micrographs of stir casted composites established that TiB_2 particles are uniformly distributed throughout the matrix. The findings indicated that the microhardness of the composite increases by 44.7 %, 47.3 %, and 51.3 % as the volume fraction of TiB_2 ceramic particle reinforcement increases. The ultimate tensile strength also increases as the TiB_2 content increases. The profound depression formation of Al6061/3 wt%TiB_2 composites during the fractography test suggests that they are more ductile in character. The number of TiB_2 reinforcement particulates increased, resulting in shallower dimples. Depth of dimples was reduced with enhancing reinforcement content and a few cleavage facets were also noticed on the fracture portion of composites.

The stress-strain behaviour of nano and microparticles of TiB_2 powder (0.5, 1.5, 3, and 5 vol%) in an A356/TiB_2 aluminium matrix alloy that was reinforced was examined by Akbari et al. [50]. The temperature of the casting during stirring, the size and quantity of reinforcement, and other variables were varied for every sample. Porosity was increased when reinforcement size decreases and increases with proportional to reinforcement content. Ultimate tensile strength decreased with increases the casting temperature at the constant particle of reinforcement. A decrease in ultimate tensile strength and the formation of agglomeration were observations that were made when the nano TiB_2 reinforced composite included more than 1.5 vol%. A comparison of the fracture behaviour of nano particle reinforced composite and micro particle reinforced composite revealed that the former had more ductility during fracture.

The microstructure and characterisations of stir-casted Al/TiB_2 aluminium matrix composites reinforced with TiB_2 particles at different weight percentages (1.4, 2.4, 4 and 5.5 %) were examined by Poria et al. [51]. Microstructural analysis observed that TiB_2 particles were uniformly distributed throughout the matrix with proper bonding which leads to the finer grain structure of composite. Micro hardness developed significantly with an increasing weight percentage of TiB_2 content because TiB_2 ceramic particulates have a higher hardness value. Wear rate reduced accordingly with enhancing weight percentage of TiB_2 reinforcement.

The machinability of an aluminium matrix composite consisting of Al7050/6 wt%TiB2 that was produced using the in-situ manufacturing process was studied by Rui-song et al. [52]. An exothermic reaction of salts, as shown in Eq. (5) and Eq. (6), was used in the creation of the composite. Micrographs taken with a scanning electron microscope showed that the TiB_2 reinforcement was distributed evenly over the whole molten matrix. Results revealed that the surface quality of Al/TiB_2 aluminium matrix composite is much better caused by less grain size of TiB_2 reinforcement and enhanced adhesion at interfaces in between molten matrix and reinforcement particulates.

$$2KBF_4 + 3Al = AlB_2 + 2KAlF_4 \tag{5}$$

$$AlB_2 + TiAl_3 = TiB_2 + 4Al \tag{6}$$

The behaviour of different weight percentages (3, 6, 9, and 12) of TiB_2 powder reinforced AA6061/TiB_2 aluminium matrix composites made using an in-situ manufacturing process was examined by Singh et al. [3]. Hardness developed significantly with enhancing the incorporation of reinforcement particles caused by hard and rigid behaviour of TiB_2 particles which resist plastic deformation. XRD revealed that the existence of TiB_2 particles in the matrix. SEM micrograph exhibited the uniform distribution of reinforcement within the matrix.

The microstructure and solidification characteristics of composites containing 6 wt% TiB_2 particles reinforced with Al-$Si_7Mg_{0.3}$/TiB_2 and Al-Cu_5MgTi/TiB_2 examined by Egizabal et al. [53]. The results indicated that the use of TiB_2 as a reinforcement decreased the time it took for solidification by up to 15 % in the case of the Al-$Si_7Mg_{0.3}$ alloy, and by 30 % in the case of the Al-Cu_5MgTi alloy. In addition, the micrograph revealed that the inclusion of TiB_2 reinforcements in Al-Si alloy and Al-Cu alloy resulted in the development of smaller grains, which effectively reduced the occurrence of porosity. The study found that the bonding between TiB_2 particles is more pronounced in Al-Cu alloys compared to Al-Si alloys. Reinforcement contributes to the reduction of flaws, such as porosity and micro shrinkages.

The mechanical properties at high temperatures of aluminium matrix composites reinforced with 5 wt% micro-sized TiB_2 particles, namely Al6061/TiB_2 and Al7015/TiB_2 investigated by J. Oñoro [54]. The results showed that the addition of TiB_2 had a significant effect on the hardness of the Al6061 and Al7015 alloys. The hardness increased from 80 to 130 HV for the Al6061 alloy and from 138 to 154 HV for the Al7015 alloy. It was noted that the ultimate tensile strength decreases progressively as a result of the softening of the matrix. Adding TiB_2 particles reduced the malleability of aluminium alloys.

The microstructure and mechanical properties of an A380/TiB_2 composite that was created by the in-situ casting process were examined by Liu et al. [55]. During the solidification process, it was noted that TiB_2 grains have a reduced nucleation effect on the aluminium alloy. Matrix components, such as magnesium, facilitate the formation of small grains of TiB_2 particles, hence increasing the rate at which nucleation occurs. The stress-strain curve demonstrates that the TiB_2 reinforced composite exhibits greater strength compared to the unreinforced aluminium alloy.

A microstructural analysis of an aluminium matrix composite reinforced with TiB_2 that was produced by the in-situ approach was carried out by Wang et al. [56]. The aluminium matrix was strengthened by including TiB_2 by the aluminothermic reaction of KBF_4 and K_2TiF_6. The microscopy indicated that the TiB_2 particles were evenly distributed. The intermetallic combination Al_3Ti enhances the rate at which the TiB_2 reinforcement segregates inside the grains of aluminium.

In their study, Yi et al. [57] examined the impact of heat treatment on an Al-Si alloy (ZL109) that was strengthened with TiB_2 particles produced using the in-situ casting method. X-ray diffraction analysis confirmed the presence of TiB_2 particles dispersed uniformly inside the matrix. The findings indicate that ZL109/TiB_2 composites have superior strength in comparison to ZL109 alloy at temperatures up to 400 °C. At temperatures beyond 260 °C, the ultimate tensile strength decreases for both the matrix alloy and the ZL109/TiB_2 composite.

1.2.3. Boron carbide (B_4C)

Boron carbide (B_4C) reinforced composites are widely used due to their high strength, high hardness, good chemical stability, and low density compared to SiC and Al_2O_3 [22]. The density of composite reduced and porosity enhanced with increase in the volume fraction of B_4C reinforcement. A bigger grain size (71 μm) of B_4C was generally homogenous mixing in aluminium alloy matrix and smaller grain size (29 μm) led to agglomeration and segregation with porosities [58]. Boron carbide is an excellent material and it is used for producing bulletproof vests, Armor tanks, etc. [59]. B_4C reinforced AZ91D/B_4C magnesium matrix composite developed hardness and wear resistance capacity compared to AZ91D alloy [60].

Table 2
Physical properties of Fly ash (precipitator-spherical particles) [62] (Reproduced with permission from Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 40 (8), 887–893. (2018). Copyright 2018 Taylor and Francis.).

Properties	Significance
Density (g/cm^3)	2.17
Bulk density (g/cm^3)	1.26
Melting point (°C)	>1200 °C
Modulus (Gpa)	143–310
Moisture content, %	2
Particular shape	Regular/irregular
Colour	Gray

1.2.4. Fly ash

Fly ash in large quantity is generated from any coal thermal power plant as a waste product and is easily available to use as reinforcement to produce MMC [61]. The physical properties and chemical composition of fly ash (precipitator-spherical particles) showed in Tables 2 and 3 respectively. Fly ash plays a very important role as reinforcement for making composite which improved strength, stiffness, wear-resistant, etc. Fly ash particulates are basically two types: cenosphere hollow particles (Density <1 gm/cm^3) and precipitator-spherical particles (Density = 2∼2.5 gm/cm^3). Fly ash particles distribute uniformly in the intergranular region of aluminium matrix composite and improve its mechanical and tribological properties [62]. Chemical composition of cenosphere fly ash particle consists of 62.79 % SiO_2, 24.24 % Al_2O_3, 3.86 % Fe_2O_3, 1.28 % MgO and 1.78 % CaO [63]. Range of cenosphere particulate size in between 5 and 500 μm. Shell thickness ranges between 1 and 18um [64]. It is noticed that cenosphere fly ash particulates consist of better spherical shape structure compared with precipitator [65]. Magnesium matrix composite reduced the overall manufacturing cost and land pollution for the addition of fly ash particle reinforcement which prepared by the stir casting fabrication method [19].

1.2.5. Aluminium oxide (Al_2O_3)

Aluminium oxide (Al_2O_3) is used as a reinforcement particle for making composite due to its high hardness, high melting point, and high density compared to the parent matrix material. Aluminium oxide is homogeneously distributed throughout the matrix of Al6061 with low agglomeration. Porosity decreases and strength increases with adding aluminium oxide as reinforcement [66]. Partial agglomeration can be detected in case of a higher weight percentage of Al_2O_3 added as reinforcement. It was observed that wear loss reduced due to some amount of aluminium oxide mixed with matrix [67]. ZX51/Al_2O_3 magnesium matrix composite developed overall strength and hardness of composite prepared by stir casting and also revealed that Al_2O_3 was uniformly reinforced throughout the matrix [18]. The various weight percentage of Al_2O_3 reinforced magnesium matrix composite developed wear resistance capacity up to 28 % compared to magnesium alloys at the high sliding speed [68]. Alumina reinforced copper matrix composite reduced porosity level and increased hardness compared to pure copper matrix [20].

1.2.6. Titanium carbide (TiC)

Titanium carbide (TiC) is added in matrices for making composite as reinforcement particles which modify its mechanical, thermal, and tribological properties. TiC particles were more uniformly distributed in grain boundary. It was found that 4 wt% TiC reinforcement in Al7075/TiC composite has a minimum wear rate at 9.81 N loads, 3 m/s sliding velocity, and 1500 m sliding distance [4]. Titanium carbide makes better bonding with LM25 which develops the strength of the final composite and also reduced its specific wear rate [69]. TiC particles with a weight percentage of 0, 2.5, 5, 7.5, and 10 are homogeneously distributed in Al6061 prepared by stir casting [70]. TiC reinforced (0, 2, 4, 6, and 8 wt%) copper matrix composite developed electrical

Table 3
Chemical composition of Fly ash (precipitator-spherical particles) [62] (Reproduced with permission from Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 40 (8), 887–893. (2018). Copyright 2018 Taylor and Francis.).

Composition	SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	SO_3	Na_2O	K_2O
Wt.%	53.1	26.23	4.59	1.10	3.17	0.62	0.21	0.95

resistance conductivity of composite up to 1.6 %. It also noticed that TiC particulates enhanced UTS and hardness of composite about 19.67 % and 24.77 % respectively [71].

1.2.7. Zirconium di-boride (ZrB_2)

Zirconium di-boride (ZrB_2) holds significant promise for critical applications due to its unique properties. These applications include its use in thermal protection systems for rocket propulsion and hypersonic flight, as well as in molten metal crucibles. ZrB_2 is prized for its high melting point, exceptional thermal conductivity, and impressive resistance to oxidation, making it an ideal material for extreme temperature environments. Its ability to withstand severe thermal and mechanical stresses further cements its role in these advanced aerospace and industrial applications. The AA2024/ZrB_2 aluminum matrix composites (AMCs) are made using the in situ Al–K_2ZrF_6–KBF_4 reaction system. ZrB_2 particles, which are sub-micron and nanosized, improved the tensile properties of the composites by mostly improving the grain structure [72]. Researchers in this study created in-situ ZrB_2/AA6016 aluminum matrix composites using a reaction system, followed by LSHR (large strain hot rolling) and FSP (friction stir processing). Notably better are the composites' tensile strength, stretch, hardness, and grain fineness [73].

1.2.8. Aluminium nitride (AlN)

Aluminium nitride powder, often known as AlN powder, is a high-performance ceramic material that is renowned for its exceptional thermal conductivity, electrical insulating qualities, and high temperature stability. It finds widespread use in the fields of electronics, LED substrates, and heat sinks. This investigation demonstrates that the agglomeration of AlN particles is diminished and the oxidation of aluminium granules is prevented through moist milling with acetone. Wet blending, cold isostatic pressing, and heated extrusion were employed to effectively fabricate AlN/Al composites, which demonstrated enhanced tensile strength and thermal expansion in comparison to pure aluminium [74]. Aluminum matrix composites (AMCs) reinforced with different amounts of AlN particles (0–15 wt%) by stir casting are the subject of this investigation. At 15 wt percent AlN particle reinforcement, the results reveal the best combination of tensile strength, compressive strength, and hardness [75].

1.2.9. Silicon nitride (Si_3N_4)

Silicon nitride (Si_3N_4) is a high-performance ceramic renowned for its remarkable strength, thermal stability, and resistance to abrasion and corrosion. Its uses include cutting tools, bearings, and aircraft components, making it suitable for rigorous technical situations. Aluminium 7075 alloy, reinforced with 4 %, 8 %, and 12 % silicon nitride (Si_3N_4), was produced using stir casting. Subsequent to casting, heat treatments and porosity assessments were performed. The analysis of chemical composition, microstructure, and hardness demonstrated a homogeneous dispersion of Si_3N_4 using scanning electron microscopy [76]. Aluminum matrix composites (AMCs) reinforced with pre-oxidized β-Si_3N_4 whiskers were produced by hot pressing. An amorphous SiO_2 layer enhanced interfacial bonding, hence improving mechanical characteristics. Optimal whisker oxidation (1 h) enhanced final tensile strength by 11 %, however extended oxidation diminished performance [77].

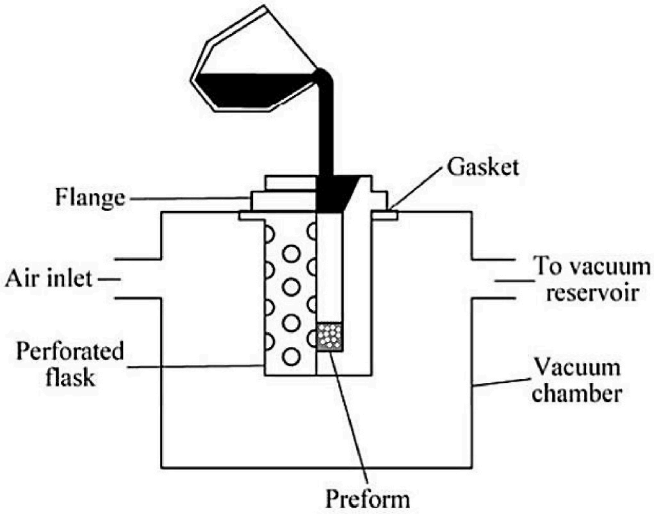

Fig. 3. Schematic diagram of melt infiltration method [79]
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2. Liquid state fabrication process of metal matrix composite

The liquid state fabrication method of metal matrix composite is noticeable to numerous industries due to moderately simple and cost-effective. Liquid state production of metal matrix composites contains the integration of the distributed stage into a melt, monitored through its solidification. To offer enhancing mechanical properties of the composite, better interfacial attachment amid the distributed stage and the molten matrix should be achieved. Types of liquid state fabrication process mentioned in below.

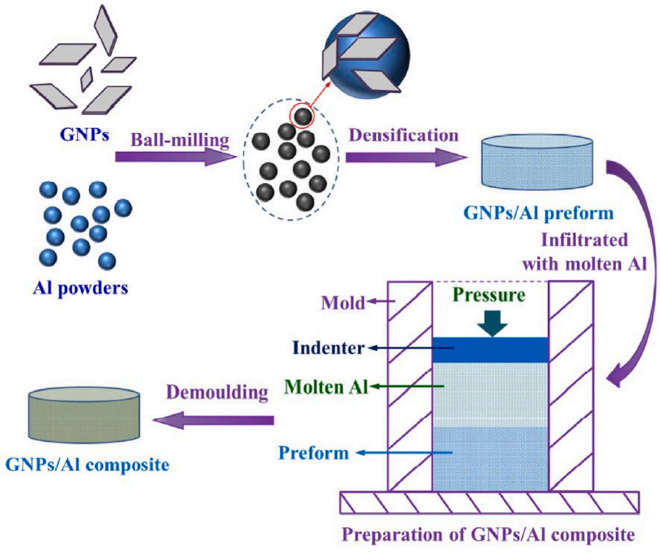

Fig. 4. Fabrication of GNPs/Al composite by pressure infiltration process [81] (Reproduced with permission from Journal of Alloys and Compounds, 732, 748–758. (2018). Copyright 2018 Elsevier.).

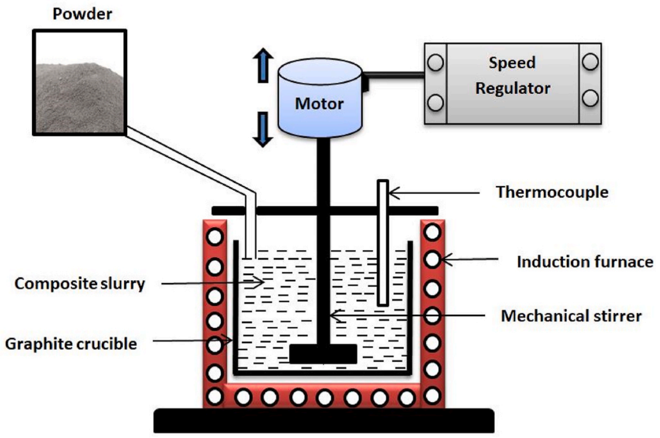

Fig. 5. Schematic diagram of stir casting fabrication setup [86]
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2.1. *Infiltration method*

Infiltration is classified into two categories viz. melt infiltration or pressureless infiltration. During the melt infiltration process, particles are first retained within the die, and therefore the melt is then penetrated thereto and allowed to solidify with no external pressure. Zhou et al. [78] investigated the behaviour of Al6061/Ti_3SiC_2 aluminium matrix composite fabricated by melt infiltration process at low temperature. The chemical reaction of particles throughout the matrix was done at 950 °C. Gecu et al. [79] analysed the tribological performance of 304 stainless steel chips that were incorporated to A356 alloy by melt infiltration process done at 730 °C. A schematic diagram of the melt infiltration method is shown in Fig. 3 Results established that satisfactory preheating temperature developed wear resistance of the composite. During the pressure infiltration method, outside pressure is used directly. Instead of other fabrication methods, the pressure infiltration process offers excellent features [80]. Yang et al. [81] revealed the mechanical characterization of aluminium matrix composite reinforced by graphene nanoplates fabricated by using pressure infiltration process. The schematic diagram of the pressure infiltration process depicts in Fig. 4 Results revealed that the pressure infiltration process developed the mechanical properties of Al/GNPs composites.

The infiltration processes, which include both melt and pressure infiltration, are essential for improving the characteristics of composites. Both melt infiltration and pressure infiltration rely on the retention and solidification of particles without the application of external pressure to enhance mechanical characteristics. The results show that both techniques improve the mechanical performance and wear resistance of different types of composites.

2.2. *Stir casting*

Stir casting is a commonly used technology for fabricating metal matrix composites. It involves the use of mechanical stirring or the conventional approach to thoroughly mix the matrix material and reinforcing particles in a liquid condition. Stir casting is a cost-effective and inexpensive method for producing aluminium matrix composites. This technique is favoured for its simplicity, ease of use, and ability to be used in large-scale manufacturing. Several crucial process factors affect stirring, with the primary ones being stirring speed, stirring temperature, and stirring duration. These parameters have a direct influence on the microstructural changes and mechanical characteristics of the resulting composite. The schematic layout of the stir casting manufacturing setup is shown in Fig. 5. Hamedan and Shahmiri [82] examined the fundamental distinctions resulting from the use of the stir casting technique in the production of A356 composite materials reinforced with SiC nanoparticles. The experiment included determining the optimized settings for stirring temperature (650 °C, 700 °C, 750 °C, and 800 °C), stirring speed (450 rpm, 700 rpm, and 950 rpm), and kind of master powder. Ezatpour et al. [66] fabricated a composite material consisting of Al_2O_3 particles reinforced using a stir casting process. They observed that the volume percentage of porosity creation rises as the weight fraction of alumina increases. Porosity is directly proportional to the duration of stirring during the mixing process. Kalaiselvan et al. [59] fabricated a composite material by incorporating 10 μm-sized B_4C particles into an AA6061/B_4C aluminium matrix using the stir casting method. To enhance the bonding between the matrix and the reinforcement, K_2TiF_6 flux was added to improve wettability. The study revealed that the B_4C particles were uniformly distributed throughout the composite material. Jayabharathy and Mathiazhagan [83] examined the mechanical and tribological properties of a hybrid magnesium matrix composite, AZ91/TiO_2/Gr, which was fabricated using the stir casting method. The results showed a 10 % increase in hardness for the hybrid magnesium matrix composite compared to the basic magnesium alloy. Singh et al. [84] fabricated a copper matrix composite reinforced with TiC and Cr particulates. The composite was created using the stir casting method, with a continuous stirring period of 15 min and a stirrer speed of 500 rpm. The grain size of the TiC and Cr particulates was less than 80–90 μm. The findings demonstrated that the composite exhibited enhanced ultimate strength and hardness in comparison to the copper matrix. Ravikumar et al. [85] examined the mechanical properties of an Al6063/TiC aluminium matrix composite produced by stir casting. They discovered that the hardness and tensile strength improved when reinforcement was added to the matrix. Bhowmik et al. [86] fabricated an aluminium matrix composite reinforced with SiC/TiB_2 using the stir casting process. They demonstrated that the addition of reinforcements improved the mechanical strength of the composite.

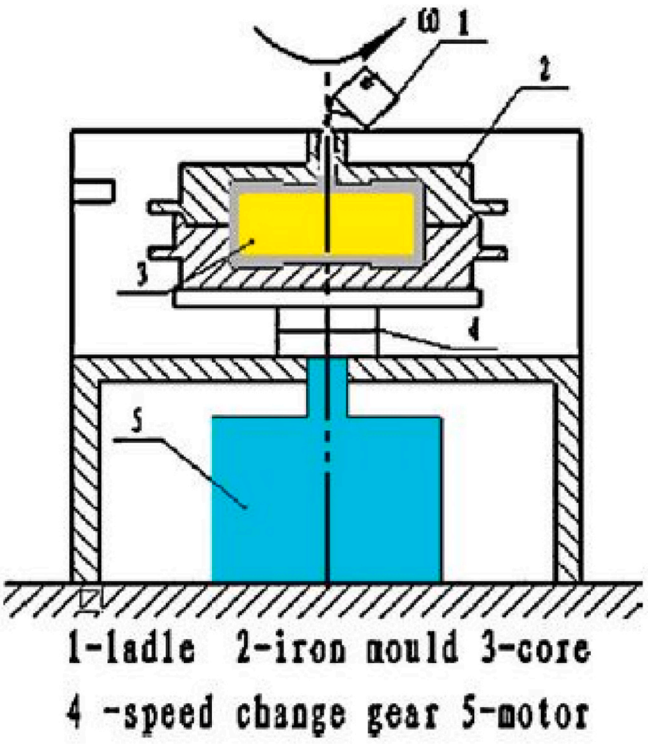

Fig. 6. Schematic diagram of vertical centrifugal casting setup [91]
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Improving the machinability of metal matrix composites (MMCs) is a critical function of stir casting. Stir casting produces a more consistent

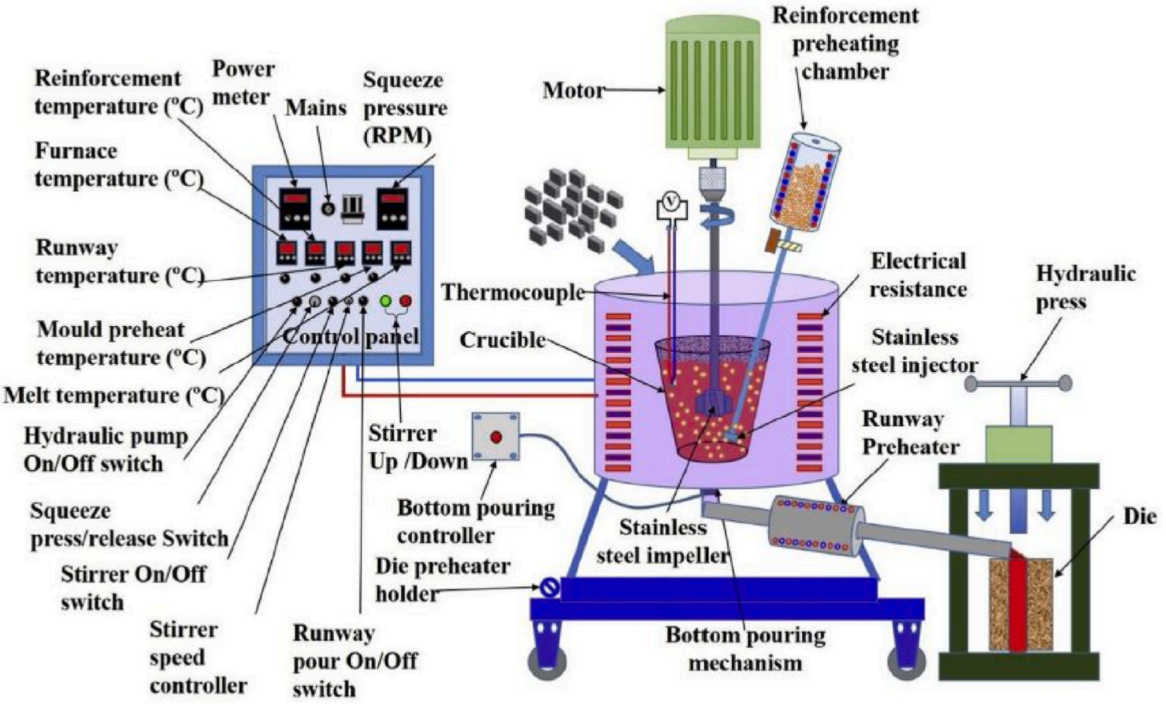

Fig. 7. Schematic diagram of squeeze casting [15]
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composite structure by uniformly spreading reinforcing elements, such as ceramics, throughout the molten metal. Because of this consistency, machining results in less tool wear, fewer flaws, and a better surface polish. The interaction between the matrix and reinforcement may be better controlled in stir casting, which optimizes the hardness and strength. This, in turn, affects cutting forces and tool life. In general, MMCs are more suited for precision and long-term industrial applications because to stir casting's improved machinability [87,88].

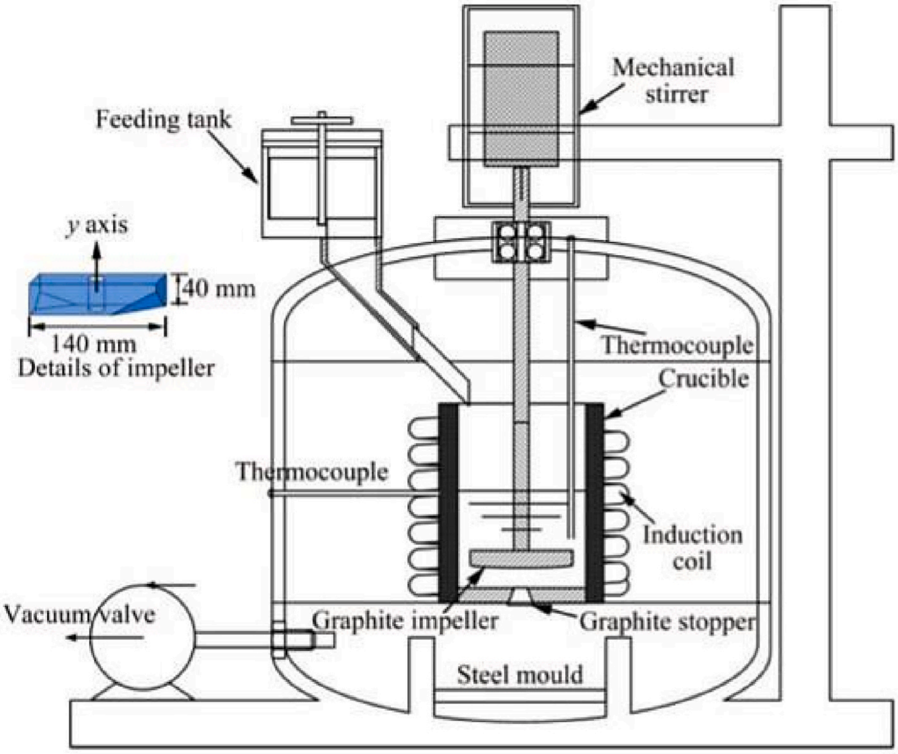

Fig. 8. Schematic diagram of stir vacuum casting setup [93]
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2.3. Centrifugal casting

Centrifugal casting is a technique of manufacturing composite through pouring the melt into a fast rotating shape. It is a comparatively cost-effective route during which the melt is thrown out in the direction of the mould surface by force under considerable pressure. It is mainly classified into horizontal and vertical axis. Fig. 6 showed the vertical centrifugal casting system's schematic design. Process elements of Al–B–Mg composites produced by the centrifugal casting technique were examined by Adelakin and Suarez [89]. Under this technique, an electrical motor drives a heated dipper that revolves around a vertical axle from a centrifugal caster with free arm linking. Establishing a superior cast filler mix with improved micrographs and increased strength, centrifugal casting produced. Wang et al. [90] investigated the transferral behaviour of Al/SiC aluminium matrix composite produced by centrifugal casting. Microstructure revealed that SiC particulates moved to the boundary section of the casts due to the centrifugal stroke, leading to un-uniform particulate dispersion. The piston prepared by centrifugal casting with optimized control factors confirms the superb wear resistivity performance [91].

Centrifugal casting is an efficient and economical method for fabricating composites, providing substantial control over material characteristics via high rotating forces. Research has shown its capacity to enhance microstructure and strength, while issues like as uneven particle dispersion persist. Additional optimization may augment its capabilities for sophisticated applications, including wear-resistant components.

2.4. Squeeze casting

Squeeze casting is a process that combines elements of casting and hydraulic forging. Fig. 7 illustrates the schematic diagram of squeeze casting. Squeeze casting involves the rapid discharge of molten material into a mould, followed by immediate forging using a hydraulic press exerting significant force. The route connects the base pouring and the mould to transport molten material from the furnace to the die. Venkatesan and Xavior [92] examined the microstructure and mechanical properties of a composite material made of AA7075 aluminium matrix supplemented with graphene nanoparticles. The composite was manufactured using a technique called stir and squeeze casting. The AA7075/0.3 % graphene composite exhibited a uniform distribution of reinforcement particles throughout the matrix. The results indicated that the highest ultimate tensile strength (UTS) of 255 MPa (MPa) was seen when the graphene particles were present at a concentration of 0.3 %. Sekar et al. [67] investigated the mechanical and wear properties of an Al/Al_2O_3 aluminium matrix composite manufactured using a stir and squeeze casting technique. The squeeze casting process was conducted at a temperature of 750 °C and a pressure of 600 MPa.

Squeeze casting, combining casting and hydraulic forging, enhances the mechanical properties of composites by promoting uniform particle distribution. Studies on AA7075/graphene and Al/Al2O3 composites demonstrate significant improvements in tensile strength and wear resistance, underscoring the effectiveness of stir and squeeze casting techniques.

2.5. Vacuum die casting

Vacuum casting of the die cavity reduces gas entrapment during metal injection and minimizes porosity in the casting. The outcome is a die casting with an enhanced degree of characteristics. Fig. 8 depicts stir vacuum die casting schematically. The major advantage of this technique is decreased void content within the composite by decrease in the amount of gasses within the molten metal. Mechanical properties and casted density are enhanced in this technique. Li et al. [93] conducted a study on the microstructural evaluation and mechanical characterisation of an AA6061/31%B_4C aluminium matrix composite that was produced using a sophisticated stir vacuum casting procedure. Scanning electron micrograph revealed that B_4C particles are homogeneously distributed in the entire aluminium matrix material. Casted aluminium matrix composite obtained superior tensile strength of 340 MPa instead of AA1100/31%B_4C.

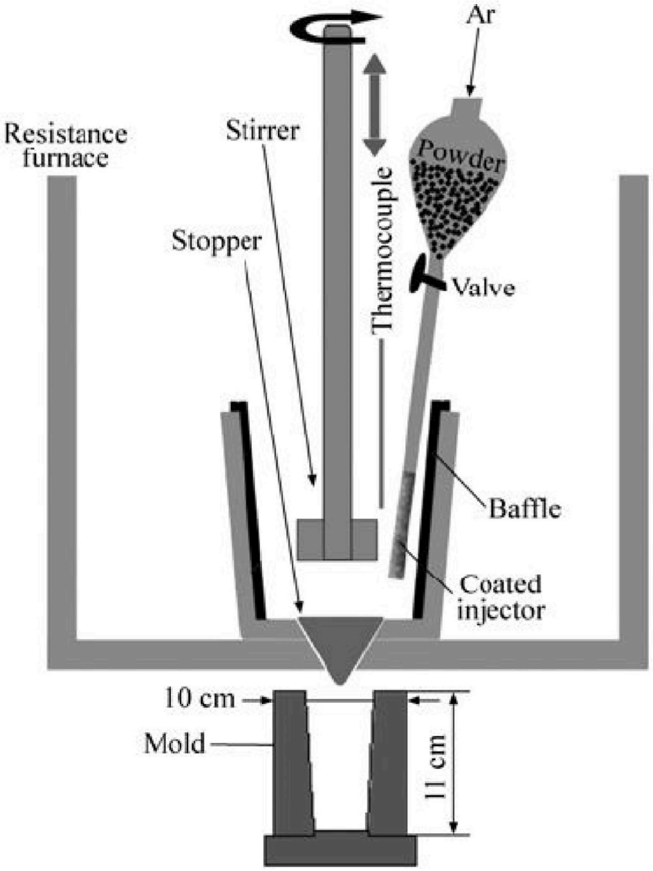

Fig. 9. Schematic diagram of compocasting method [94]
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2.6. Compocasting

During compocasting, the incorporation of preheated reinforcements moved into semi-solid metal at 690 °C temperature by strenuous agitation [94,95]. Fig. 9 depicts a schematic diagram of compocasting method where initial solid particulates are converted to semi-solid slurry and discharged to the die cavity and pressed during the solidification period. The slurry movement is often prepared by powered vibration, motorized stirring, and cooling slant methods to allocate the reinforcements [96]. The major solid particulates turned within the semi-solid slurry decrease clustering and cause well dispersal of the reinforcements, grain modification of the matrix, and very less void content instead of the stir casting method [97]. Major benefits of compocasting dwell extraordinary fabrication cycle period, minor casting temperature that supports to enhance die lifespan considerably [98,99]. When stirring is done in the cold temperature range of the aluminium matrix, the wettability also improves. This system is still in its early stages of use, and only a few brake cylinders and pistons have been made this way [100]. Kumarasamy et al. [101] created and studied an Al7075 matrix composite made of fly ash and graphite particles that was strengthened. It was made using a two-step compocasting process. The goal of this work is to find ways to make gear manufacturing in the aircraft business stronger mechanically. The microstructure showed that

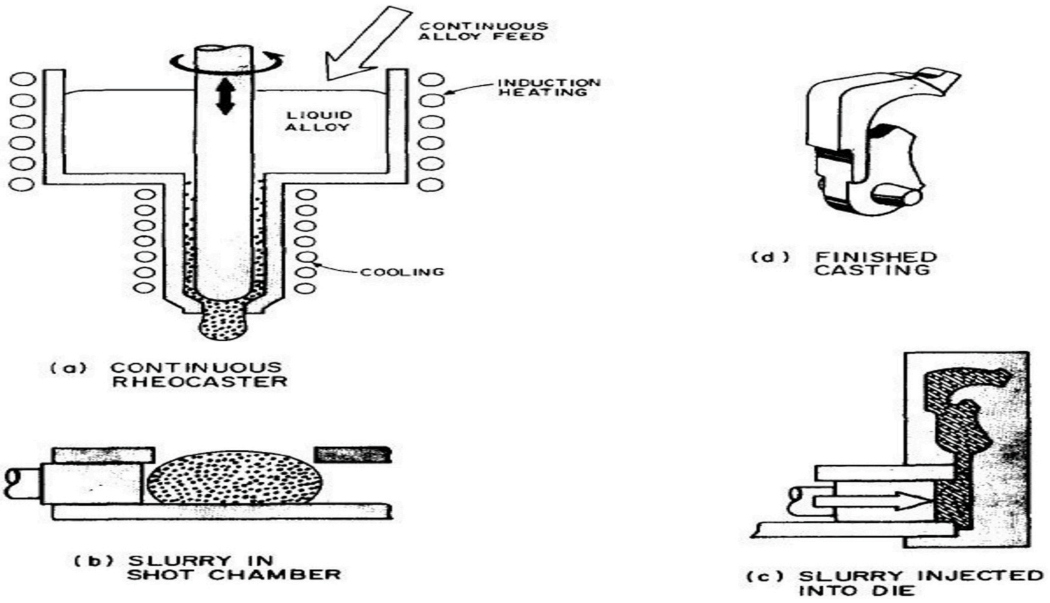

Fig. 10. Schematic diagram of rheocast process [105]
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the reinforcing particles were spread out evenly.

Compocasting offers significant advantages, including improved reinforcement dispersion, grain refinement, and reduced void content compared to stir casting. Its lower casting temperature enhances die lifespan, while improved wettability strengthens the material. Though still in early use, compocasting shows promise for high-performance applications.

2.7. *Rheocasting*

The rheocasting technique involves the preparation of a semi-solid slurry from the melt by applying shearing action and mechanically inserting reinforcement during the solidification process. The prepared mixtures are directly transferred to a mould as a result of the design of the components. This method has therefore newly become the well-liked manufacturing method thanks to its cost-effectiveness and high production [102]. The particulates dispersal of composite is far developed by intensive shearing, and a superb microstructure improvement arises as an impact of the pressure application [103]. The rheocasting process prevents agglomeration because reinforcement incorporates partially solid melt. Reinforcement particles must be steady at a particular working temperature and also non-reactive during the rheocasting process. A schematic diagram of the complete rheocast process is shown in Fig. 10. Excellent casted components of composites like complicated parts, higher mechanical strength, superb metal filling, and better wear performance may be prepared by using this process. The major drawback of the rheocast method is that the assembly services required an advanced technology and workers need related knowledge and preparation. The rheocast method was used by Curle and Ivanchev [104] in order to construct and characterise a SiC powder reinforced Al359/SiC aluminium matrix composite manufactured. It is observed that hardness developed from 73 to 93 HRB with enhances SiC content.

2.8. *In situ*

In situ process is a fabrication technique, during which distributed phase are formed within the matrix as a result of drizzle from the molten metal for the period of its cooling and solidification. Liu et al. [106] developed TiB_2 incorporated A380/TiB_2 aluminium matrix composite fabricated by in situ technique through the elemental reaction of two salts viz. potassium hexaflurotitanite (K_2TiF_6) and potassium tetrafluoroborate (KBF_4). It was discovered via the use of micrographs that the alloying components play a significant part in the formation and growth of the in situ particles. TiB_2 particles were included into the UTS, which resulted in the development of up to 159.7 MPa. Baskaran et al. [4] produced a TiC reinforced aluminium matrix composite that was generated using an in situ reactive process approach. They then investigated the tribological behaviour of the composite by employing Taguchi's L27 Design of Experiment in order to reduce the number of tests that were conducted. The XRD examination revealed that the intensity peak was greater in the composite that had 8 wt percent of TiC reinforcement. In the grain boundary, it has been found that the distribution of TiC particles is more homogeneous among the particles. During the confirmatory test, it was discovered that the projected value of wear rate is very near to the value that was obtained from the experiment.

In summary, the in situ manufacturing method significantly improves the mechanical and tribological characteristics of aluminum matrix composites. The addition of TiB_2 and TiC particles significantly enhances strength and wear resistance, illustrating the efficacy of this approach for advanced material development.

3. Factors influencing the properties of metal matrix composite

This study is very important for making quality metal matrix composite with minimizing casting defects. This study reveals the consequent effect of material properties and microstructural evaluation about prepared composites. Based on the literature survey [1,59,107–109], supreme factors that ultimately influenced the various properties of casted composites are shown below.

3.1. *Distribution of reinforcement particulates*

During the casting process, the metal matrix mixture is greatly affected by how well the support is distributed. A regular spread of matrix and support is very important for getting a higher quality metal matrix hybrid with better features. A maximum percentage of reinforcement content enhances void formation that crucially affects ductility [110]. Density variation between the matrix material and reinforcement particle reveals the main reason for non-uniform

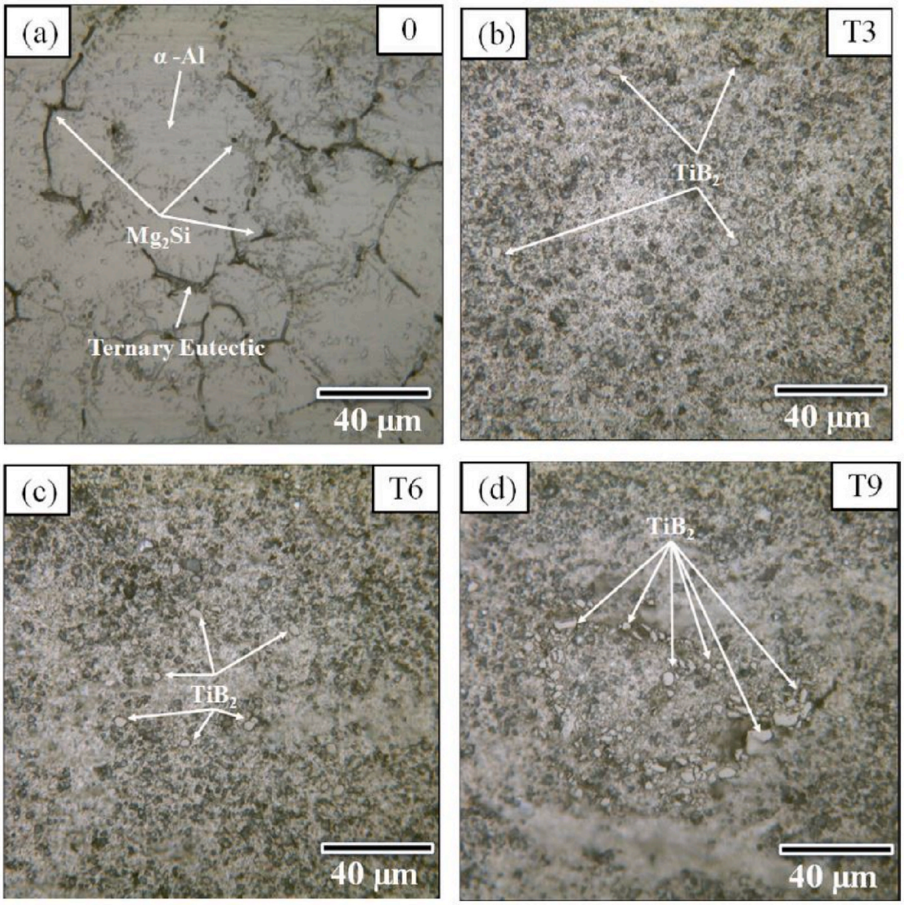

Fig. 11. Uniform distribution of AA6061- TiB_2: (a) AA6061 as casted, (b) 3 % TiB_2, (c) 6 % TiB_2 and (d) 9 TiB_2 [49] (Reproduced with permission from Materials Science and Engineering: A, 710, 172–180. (2018). Copyright 2018 Elsevier.).

distribution due to particulates float either adequate in a mixing [59]. Quantity of reinforcement particle enhanced in microscopic structure due to enhances particle content in the matrix material. The homogeneous distribution of TiB_2 particles throughout the matrix is seen in Fig. 11, which can be found in Ref. [49]. In general, the vortex approach is used for the purpose of ensuring that reinforcement is distributed uniformly across the matrix. The formation of a vortex between inner and outer surfaces mostly depends on stirrer speed after melting molten material [82]. High stirring speed creates a vortex at the melting surface caused by gas entrapment and change in viscosity [108].

In summary, attaining a consistent distribution of reinforcement inside the metal matrix is essential for improving the mechanical characteristics of hybrid composites. The vortex technique efficiently enables this dispersion, hence boosting quality, reducing void formation, and improving ductility in the final product.

3.2. Porosity development in composite

Porosity development is a major defect that directly affects material properties. Porosity appeared during the casting process due to hydrogen gas generation from the surface of molten metal either shrinkage at solidification state or both of two. The size of reinforcement agents also affects porosity formation. Reduce porosity percentage with incorporation of less grain size of reinforcements [1,111]. The maximum volume percentage of reinforcement particles leads to enhanced porosity formation and clustering. Elsewhere, minimum volume percentages of reinforcement agents have comparatively better fluidity than the possibility of cluster formation with particulate movement [33]. Corrosion appears in composite due to maximum porous content at a particular location that affects properties of the casted composite. It can be partially avoided by maintaining a few parameters like degassing matrix material during casting, compo-casting, rolling after composite preparation, forging after heating, and so on [50,112]. Fig. 12 shows that porosity formation on aluminium matrix composite caused by the addition of SiC particles.

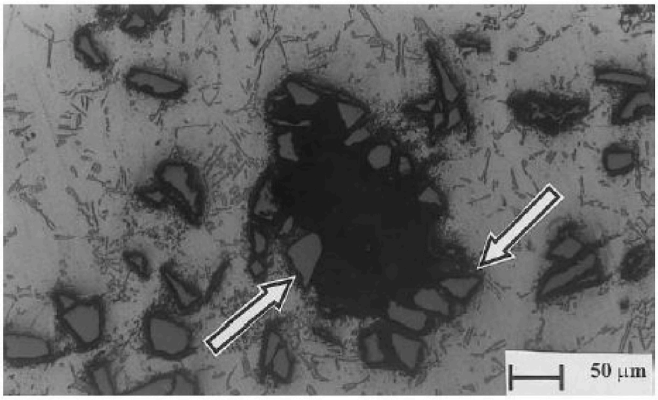

Fig. 12. Porosity formations on A356/3%SiC composite [33] (Reproduced with permission from Materials Science and Engineering: A, 315 (1–2), 217–226. (2001). Copyright 2001 Elsevier.).

In conclusion, porosity profoundly affects the characteristics of cast composites, determined by the dimensions and volume of the reinforcement. Strategies such as degassing and post-processing procedures

Table 4
Process parameters affecting MMC.

Parameters		Affect	Source
Percentages of reinforcement content		Improved properties Density developed	[2,52,58]
Grain size of reinforcement particulates		Homogeneous distribution Reduce agglomeration	[1,38]
Processing parameters	Stirring temperature	Viscosity developed Reduce clustering	[39,116]
	Stirring time	Uniform distribution Better mixing	[39,50]
	Stirring speed	Vortex formation Reduce porosity	[82,117]

may reduce porosity, hence improving the performance of aluminum matrix composites containing SiC particles.

3.3. *Interconnection between matrix and reinforcement*

Interaction between matrix and reinforcement particles highly influences the material properties and stiffness of the composite. The microscopic structure of the casted composite shows a clear idea about the interconnection between matrix and reinforcement agents throughout the composite and also show various defects formation during casting like clustering, agglomeration, porosity. Agglomeration increases with enhances weight percentage of reinforcement content [113]. The solidification technique plays a vital role that identifying the interaction between matrix and reinforcement. Wettability of material leads to liquid-state process which is avoided by enhancing the temperature of molten material during melting. On the other hand, higher melting temperature associates chemical interfacial reaction between matrix and reinforcements that affect strength in the interface section [109]. Interfacial bonding impacts stress assortment around the particulates and micro-crack formation into the matrix that raised excessive plastic energy dissipation [114]. Various techniques are observed for enhancing wettability such as magnesium and lithium addition in matrix material, reinforcement coating, pre-work on reinforcement particulates, reinforcement cleaning by ultrasonic methods, and different etching procedure [115]. Metal coating on reinforcement particulates enhances surface energy and develops wettability by increasing contact surfaces. The coating is applied for different reasons such as protecting filler materials, enhancing wettability [108].

The interplay between matrix and reinforcing particles substantially influences the composite's material characteristics and rigidity. Efficient solidification procedures and enhanced wettability via diverse approaches are essential for reducing flaws and improving interfacial bonding, hence boosting composite performance.

4. Parameters affecting metal matrix composite prepared by stir casting

The process parameters are crucial in producing high-quality metal matrix composites using the stir casting fabrication method. The enhancement of various mechanical and tribological characteristics of the final composite material is influenced by process factors. The impact of process factors on the physical characteristics of metal matrix composites is shown in Table 4. The significant influence of major process factors on the final composite, as demonstrated in prior studies using stir casting, is detailed below.

4.1. *Percentages of reinforcement content*

Weight percentage reinforcement selection is mostly an affecting factor for manufacturing metal matrix composite in different sectors to simplify our needs compared to other parent matrix materials. The ratio of reinforcement particle weight to total reinforcement weight has a significant impact on mechanical and tribological characteristics. For composites to be suitable for use in aircraft, the reinforcing density must be lower than the matrix material density. This will result in a lighter end product. Literature survey of previous research work based on weight percentage of reinforcement added shown in Table 5.

Table 5
Literature survey of previous research work based on weight percentage of reinforcement added.

Source	MMC	Wt.% of reinforcement	Findings
Kumar and Murugan [118]	Al6061/ AlN_p	0, 5, 10, 15 and 20 %	UTS increases
Arab et al. [2]	Al/SiC	5 and 10 %	UTS increases
Kalaiselvan et al. [59]	Al6061/ B_4C	4, 6, 8, 10 and 12 %	Hardness and UTS increases
Y. Sahin [38]	Al2024/ SiC	10 and 20 %	Hardness increases
Meti et al. [48]	Al7075/ TiB_2	5 and 7.5 %	Hardness and UTS increases
Canakci & Arslan [58]	Al2024/ B_4C	3,5,7 and 10 %	Hardness increases and density decreases
Poria et al. [51]	LM4/TiB_2	1, 2.5, 4 and 5.5 %	Hardness and wear depth increases
Girish et al. [119]	Cu/TiC	0, 2, 4, 6 and 8 %	UTS, hardness and electrical conductivity increases
Alaneme and Odoni [20]	Cu/Al_2O_3	10 %	UTS and wear resistance increases
Poddar et al. [35]	AZ91D/ SiC	15 %	Yield strength and hardness increases
Gorji et al. [18]	ZX51/ Al_2O_3	0, 2.25, 4.50, and 6.75 %	Overall strength and hardness increases

4.2. *Grain size of reinforcement particles*

When MMC is manufactured using the stir casting process, the grain size of the reinforced particles has an effect on the properly homogenous dispersion of the material. As the size of the reinforcement grows, the porosity of the material rises [50]. Increases in ultimate tensile strength may be achieved by including reinforcement particles of a smaller grain size while maintaining the same quantity of reinforcement particles. The formation of agglomeration occurs when those particles with a smaller grain size are strengthened. As the volume fraction rises, both the hardness and porosity of the material increase as well [38]. An increase in the volume % of smaller grain size reinforcement is associated with an improvement in the hardness of an aluminium metal matrix composite that is reinforced with boron carbide of varying micro particle sizes [58]. Reinforced composites with larger particle sizes have a higher density in comparison to those with smaller particle sizes [1].

Ultimately, the consistency and qualities of metal matrix composites are greatly affected by the size of the reinforcing particles' grains. The tensile strength, hardness, and porosity of a material are all improved with smaller particles, while the density and overall performance are negatively impacted by bigger ones.

4.3. *Processing parameters*

Processing parameter for stir casting fabrication method plays a most vital role to prepare better composite with high strength, improved hardness, reduce clustering, and minimize porosity formation. Various types of casting processing parameters are shown below.

4.3.1. *Stirring temperature*

Stirring temperature plays an important role in stir casting method which helps to reduce the clustering effect in the final composite and also control the viscosity of molten metal for making porous-free composite material. Generally, particle clustering is formed due to low

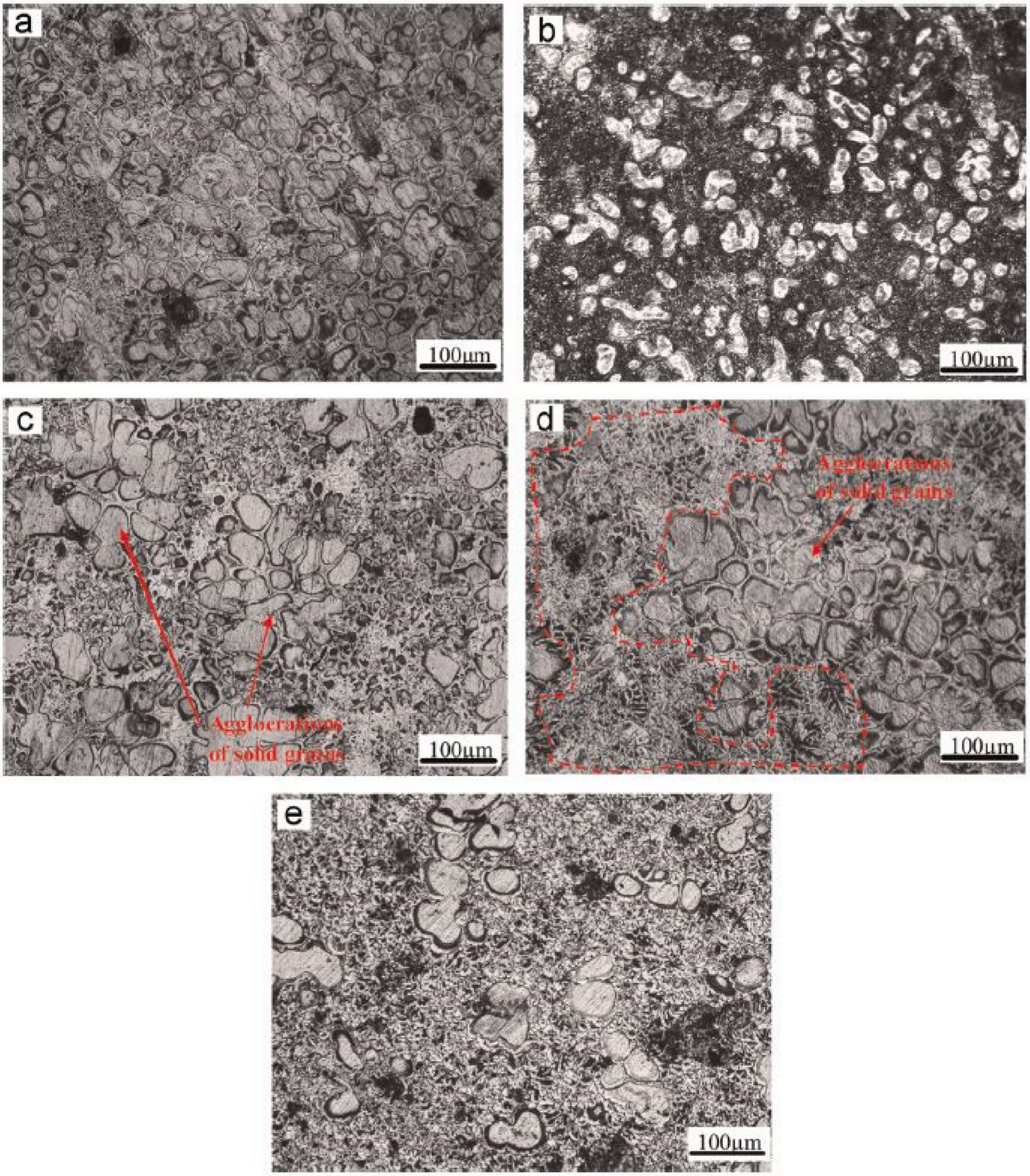

Fig. 13. Microstructure formation of Nano sized silicon carbide reinforced Al7075/SiC aluminium matrix composite at different stirring temperature at constant stirring time 20 min. (a) 615 °C, (b) 620 °C, (c) 625 °C, (d) 628 °C and (e) 630 °C [39]
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viscosity in molten metal [116]. Stirring at low temperature, a huge amount of shear force is needed to overcome viscosity. Solid grains adjacent to liquid phase due to deformation of the lateral surface region. Semisolid spheroidal grains were observed when stirring temperature in between 615 °C and 620 °C. Agglomeration is found in microscopic structures when stirring temperature greater than 625 °C. A huge part of the liquid zone takes place in a microscopic structure when stirring temperature greater than 628 °C. Quantity of grains reduces exceptionally with stirring temperature greater than 630 °C shown in Fig. 13 [39].

Finally, reducing particle clustering and regulating the viscosity of the molten metal are both achieved by adjusting the stirring temperature in the stir casting process. Ideal spheroidal grain structures are achieved by keeping temperatures between 615 °C and 620 °C; on the other hand, agglomeration and decreased grain amount are the results of temperatures that are too high.

4.3.2. *Stirring time*

Stirring time is noticed as a very important process parameter for making sound metal matrix composite. In order to achieve a good bonding between the matrix material and the reinforcement particles, the stirring duration has an effect on the uniform distribution of reinforcement particles. When the amount of time spent stirring is increased, it has been discovered that the porosity of the substance increases [120]. With an increase in the amount of time spent stirring, the spheroidal grains that are present in semisolid slurries of composite material are

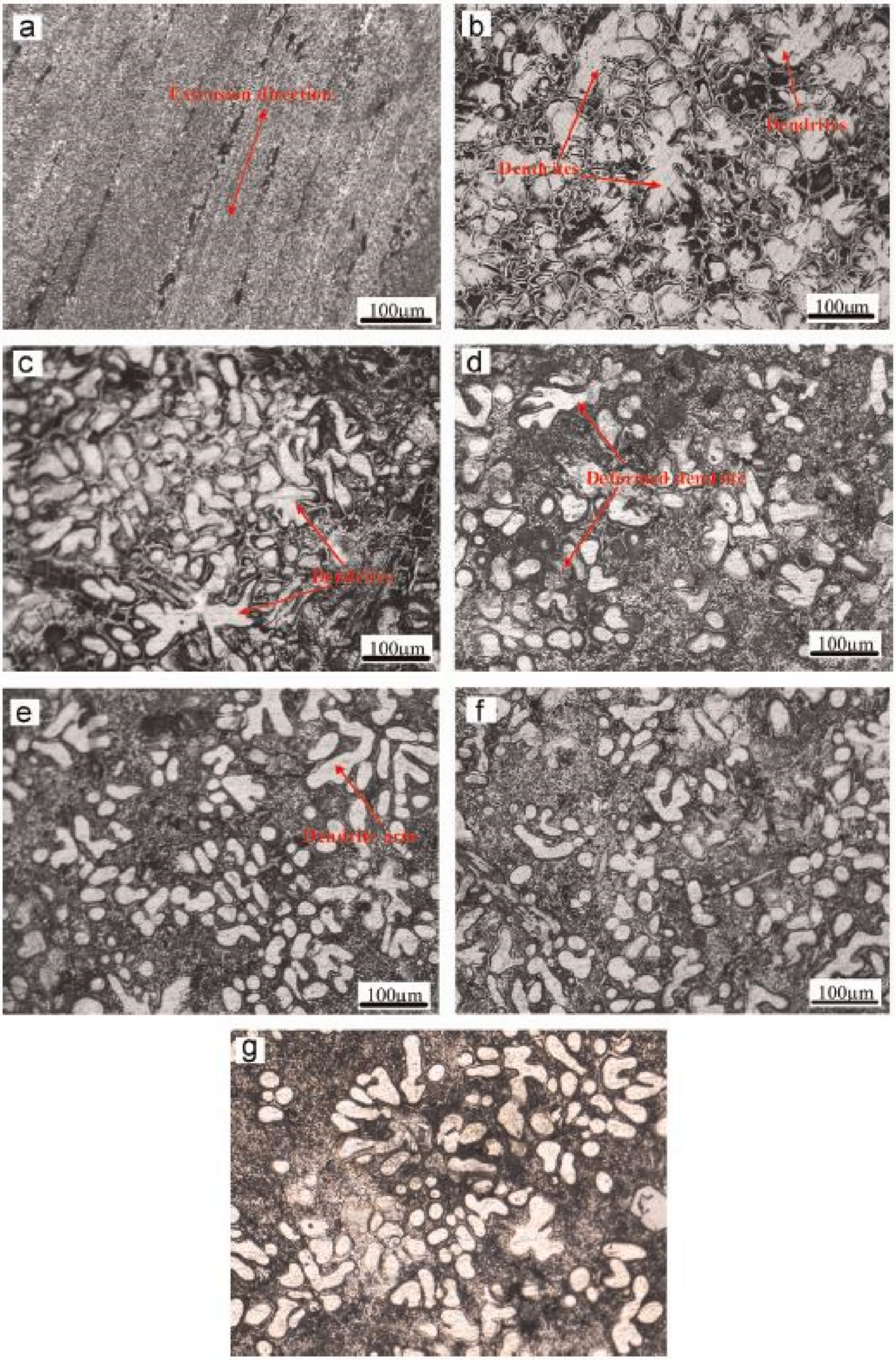

Fig. 14. Microstructure of Nano sized silicon carbide reinforced Al7075/SiC aluminium matrix composite for different stirring times at constant stirring temperature 620 °C. (a) As extruded Al 7075, (b) final composite with 5 min stirring, (c) final composite with 10 min stirring, (d) final composite with 15 min stirring, (e) final composite with 20 min stirring, (f) final composite with 30 min stirring [39]
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dramatically affected. The basic stage of stirring was characterised by the presence of coarse-type dendrites in the microscopic structures. When the stirring speed is increased by more than 10 min, coarse dendritic of the microstructure is prepared to be removed. Coarse dendrite vanishes but few impair dendrites retain in microstructure even up to 15 min stirring time. Few distorted dendrites are observed in the grain boundary and are also partially broken at the time of stirring. These sub-boundaries develop large-boundary with increasing stirring time of more than 15 min. Microstructure formation changes and a maximum number of spheroidal grain forms with the increase in stirring time above 20 min. The results of this experiment demonstrate that a shorter stirring time results in fewer spheroidal grains, whereas a longer stirring time results in an excessive amount of energy consumption, as seen in Fig. 14.

Finally, the amount of time that is needed to agitate the metal matrix composite is critical for getting the best possible bonding. While longer stirring times improve reinforcement particle dispersion, they also increase energy consumption and porosity. The key to successful composite manufacturing is striking a balance.

4.3.3. Stirring speed

Stirring speed has a direct influence on vortex formation and reduces porosity formation which directly effects on microstructure and mechanical properties of the final composite material. Formation of vortex depending upon the stirring speed helps to move particles between inner and outer surfaces. Degassing is the only way to reduce the percentage of porosity in the final composite during melting. The highest compressive yield strength is found at medium stirring speed (700 rpm) and the shear rate increases with the increase in stirring speed. It is observed that maximum stirring speed increases porosity due to turbulence formation [83]. Increasing stirring rate interrupt the oxide formation and reduce the formation of voids in the composite [117].

Finally, improving the mechanical qualities and microstructure of composites relies heavily on stirring speed optimization. For optimal compressive yield strength, stir at a medium speed of 700 rpm; higher rates might cause turbulence, which increases porosity.

5. Conclusions

Recently industries are upgraded its material for developing its performance such as lightweight, low cost, better fatigue strength, better tensile strength, wear resistance capacity to enhance its application in aerospace and aircraft application, designing automotive parts, etc. It is found that aluminium matrix composites highly impact on the ultimate composite product which fulfilling its criteria depending upon its appropriate application. Various reinforcements added with a matrix material to improve its particular strength prepared by stir casting fabrication method. During the mixing process, a number of significant process factors, including the weight % of reinforcement material, the grain size of reinforcement particles, and processing parameters such as stirring duration, stirring speed, and stirring temperature, have direct influence on the metal matrix composite.

The incorporation of advanced reinforcement materials like graphene, TiB_2, and Al_2O_3 into metal matrices has demonstrated considerable promise in improving the mechanical properties of composites, rendering them viable for a broad spectrum of applications across sectors such as automotive, aerospace, and thermal management. The paper further explores the efficiency of different casting methodologies, with an emphasis on stir casting and squeeze casting. These techniques have been shown to facilitate uniform dispersion of reinforcement particles within the matrix, resulting in enhanced tensile strength and wear resistance. The reviewed studies highlight that composites like AA7075/graphene and Al/Al_2O_3 achieve substantial mechanical property enhancements when produced via these casting methods. Additionally, the integration of hydraulic forging within squeeze casting not only optimizes particle distribution but also reinforces the overall structural integrity and performance of the final composite material. During stir casting, the proper stirring speed, stirring duration, and stirring temperature have a significant influence on the uniform mixing, uniform distribution, vortex creation, porosity elimination, rise in viscosity, and reduction in clustering. A suitable uniform distribution, better strength, reduced weight, and the elimination of agglomeration and segregation are all outcomes that may be achieved by the use of a lower grain size in conjunction with the right weight % of reinforcement.

In summary, the casting of particle-reinforced metal matrix composites (MMCs) via liquid state fabrication techniques marks a notable progression in materials science. The findings from this review enhance the comprehension of the core principles influencing MMC behavior and provide a foundation for future advancements in composite manufacturing technologies.

CRediT authorship contribution statement

Abhijit Bhowmik: Writing – original draft, Project administration, Methodology, Conceptualization. **Raman Kumar:** Visualization, Resources, Investigation, Data curation. **N. Beemkumar:** Visualization, Software, Investigation, Formal analysis. **Ambati Vijay Kumar:** Writing – review & editing, Resources, Investigation, Conceptualization. **Gurbhej Singh:** Visualization, Supervision, Project administration, Investigation. **Ankur Kulshreshta:** Writing – original draft, Resources, Methodology, Funding acquisition. **Vikasdeep Singh Mann:** Writing – review & editing, Visualization, Project administration, Formal analysis. **A. Johnson Santhosh:** Writing – review & editing, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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