MATERIALS PHYSICS AND MECHANICS REVIEW

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Investigation of aluminum metal matrix composite fabrication processes: a comparative review

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ABSTRACT

Aluminum alloys are widely used in industry because of their superior mechanical qualities and high specific strength-to-weight ratio. Al-matrix composites (AMC) may identify the newly synthesized material because it has the mechanical properties of pure aluminum alloys with reinforcement from a variety of ceramics. Matrix materials have included aluminum alloys, with ceramic reinforcements including aluminum oxide (Al_2O_3), magnesium oxide (MnO), graphene nanoplatelets (GNPs), boron carbide (B_4C), silicon carbide (SiC), graphite (Gr), fly ash (FA), etc. The best, most practical, and most cost-effective way to create the composites is by the stir casting process. The review focuses on the two-step stir-casting process for AMCs production. Reinforcement pre-heating temperature, injection rate, porosity, wettability, stirrer structure, stirring time and speed, purge, pouring temperature, solidification rate, and mold temperature are examined to optimize the casting process. Optimal conditions include preheating particles at 200–500°C for 30–60 min, maintaining a feeding rate of 8–10 mg/min, stirring speeds of 700–800 rpm for 10–40 min, and using a 30-degree to 60-degree impeller-blade angle. Emerging trends suggest enhancements such as microwave heating, ultrasonic probe usage, inert environment incorporation, and electromagnetic stir casting for improved wettability and uniformity.

KEYWORDS

aluminum alloys • composites • reinforcements • ceramics • stir-casting

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Introduction

Partially reinforcing a matrix of aluminum creates a strong structural material with widespread use in aerospace and automotive applications [1]. Al-matrix composites (AMCs) are a class of materials with desirable qualities achieved by reinforcing ductile metallic alloys with hard particles [2]. These materials have superior mechanical properties, including a higher significant modulus of elasticity, higher specific strength with reduced weight densities, greater operational temperature, and better durability against wear [3]. Most tasks associated with the automotive, electrical, and aerospace sectors found an AMC material to be a superior substitute to current conventional aluminum alloys [4]. Particulate AMCs are notable because of their enhanced damping capacity, machinability, resistance to friction and seizure, and low thermal expansion coefficient, among other characteristics [5]. AMCs are manufactured in a way that allows for a wide range of reinforcing element and base matrix changes during the melt-stirring process. Maximizing Young's modulus, yield strength, and tensile strength while keeping toughness to a minimum should be the fabrication targets for ultralight material composites [6]. Instead of employing monolithic alloys, researchers have investigated the prospect of increasing resistance to fracture and heat shock at elevated levels by modifying production parameters like melt stirring and solidification rate [7]. Composites deteriorate in their ability to withstand heat, corrosion, and wear as time passes. In order to better understand and enhance the performance of AMCs, numerous researchers have conducted tensile strength [8], compressive strength [9], impact resistance [10], dry sliding wear [11], and fracture tests [12], as well as metallurgical tests such as scanning electron microscope (SEM), transmission electron microscope (TEM), optical microscope (OM), X-ray spectroscopy (XRS), and X-ray diffraction (XRD), etc. [13]. It has been decided to concentrate on the stir-casting approach for the fabrication of AMCs due to it being a very inexpensive melt-stirring technology currently available [14]. The main benefit of this manufacturing process is that, in comparison to other methods, it is easy to implement, has few limitations, and can be used to make a wide variety of shaped components in huge quantities [15]. Figure 1 shows the historic development of the AMCs.

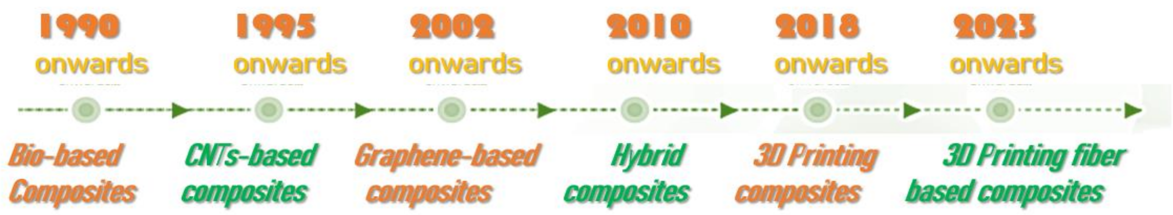

Fig. 1. Historic development of the AMCs

The objective of this paper involves understanding and optimizing the methods used to create these composites. Stir casting stands out as an innovative and practical method for making aluminum metal matrix composites (AMCs) in the ever-changing world of materials engineering. This innovative method uses mechanical agitation to evenly distribute reinforcing elements in an aluminum matrix, improving mechanical qualities and performance. This research explores the stir casting technique and shows its promise as a flexible and cost-effective way to make sophisticated composite materials for varied industrial applications. This study seeks to open new materials science and engineering frontiers by nuancedly exploring its principles, methods, and problems.

Matrix and reinforcement particles

Matrix

The choice of matrix alloy for stir casting aluminum matrix composites (AMCs) depends on several factors including desired mechanical properties, corrosion resistance, thermal stability, and cost considerations. Some common aluminum alloys used as matrix materials (Fig. 2) in stir casting include:

1. Al-SiC alloy (e.g., 6061, 4032): these alloys offer good castability, mechanical properties, and corrosion resistance. They are commonly used in automotive and aerospace applications.
2. Al-Cu alloys (e.g., 2024, 7075): these alloys offer high strength and excellent fatigue resistance. They are widely used in aerospace, automotive, and structural applications.
3. Al-Mg alloys (e.g., 5083, 5052): these alloys offer good weldability, corrosion resistance, and moderate strength. They are commonly used in marine and structural applications.
4. Al-Zn alloys (e.g., 7075, 7050): these alloys offer high strength-to-weight ratios and good fatigue resistance. They are often used in aerospace and sporting goods applications.
5. Al-Ni alloys (e.g., 2124): these alloys offer high strength and excellent fracture toughness. They are used in aerospace applications where high strength and toughness are required.
6. Al-Li alloys: these alloys offer significant weight savings compared to traditional aluminum alloys due to the low density of lithium. They are used in aerospace applications where weight reduction is critical.

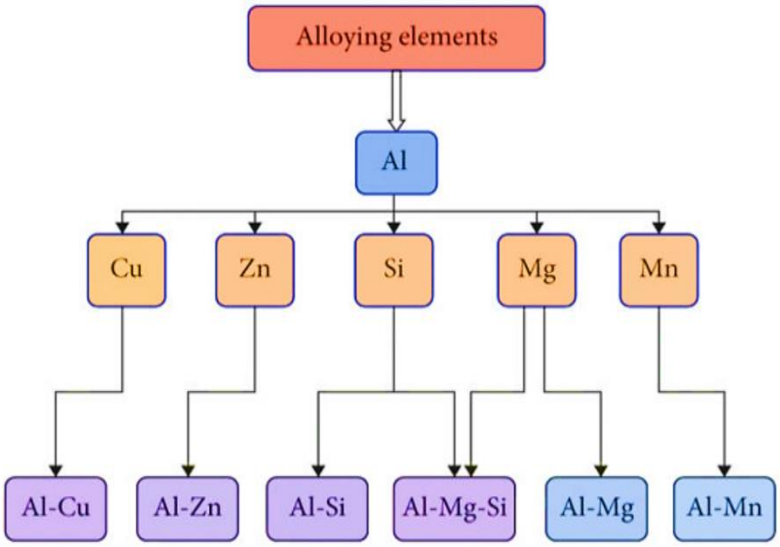

Fig. 2. Aluminum metal matrix composites

When selecting a matrix alloy for stir casting AMCs, it's essential to consider the compatibility between the matrix alloy and the reinforcement material, as well as the processing conditions required for stir casting.

Reinforcement

The manufacturing process is very sensitive to the choices made in the processing variables. Many scientists have synthesized composites using many organic (coconut shell ash (CSA) [16], fly ash (FA) [17], etc.) and non-organic reinforcements, such as Mg [18], SiC [19], TiC [20], Al_2O_3 [21], WC [22], B_4C [23], TiO_2 [20], and many more as shown in Fig. 3. The reinforcement size, shape, and behaviour are critical processing parameters in the fabrication of aluminium-based advanced composite materials. AMCs with lower particle sizes display improved mechanical characterizations, although reinforcement size is the most influential component overall. Candiani et al. [24] developed a stir-casting technique for the synthesis of AA 6061-Al_2O_3 composites. Al_2O_3 particles were inserted at a depth of 5−20% in AA-6061 to create composites with somewhat uniform dispersion. The micro-hardness and tensile strength of the specimens showed an increase with increasing weight content in this investigation. Through the use of a stir casting technique, binary ceramic reinforced composites based on AA6061/SiC/Fly-ash were manufactured. 10 wt. % of SiC and FA-based particles were utilized for reinforcement, whereas the percentages of fly ash in the matrix ranged from 0 to 2.5 to 5 to 7.5 to 10 wt. %. Both particles were evenly distributed throughout the composite matrix alloys throughout the synthesis process for AA6061/10%SiC/7.5. The tensile strength and microhardness of composites made with fly ash have increased, while the percentage of fly ash used in their construction has decreased [25]. Stir casting was used to fabricate AA-2014-based composite reinforcing molybdenum disulfide (MoS_2), boron nitride (BN), and graphite (Gr). Reinforced ceramics composed of 4 wt. % BN, 4−8 wt. % MoS_2, and 6 wt. % Gr has found use. The hardest possible Vickers microhardness value was achieved by composite material, with a 28 % increase in hardness above the basic matrix (AA 2014) [26]. Many scientists have found that using mono-, binary-, multiple-, or tri-reinforcement in the ceramic's manufacturing through the melt stirring approach improves the material's AMC performance [27−29]. There is a clear difference in performance between binary or single-reinforced AMCs and multi-reinforced composites [20].

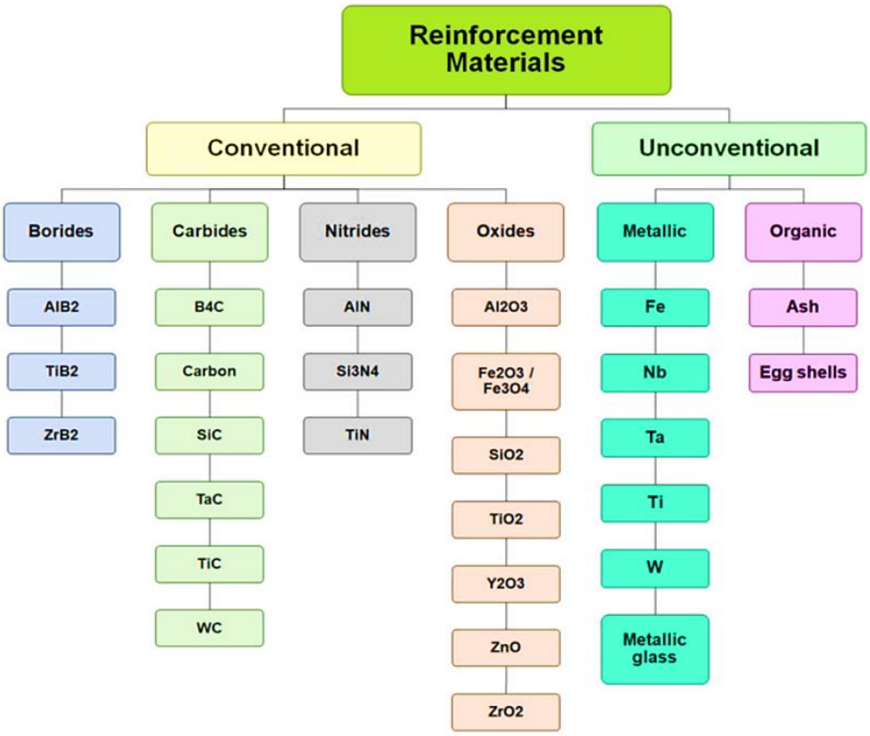

Fig. 3. Various organic and inorganic materials used as reinforcement

Experimental setup

AMC Fabrication Processes

Fabrication processes for aluminium metal matrix composites (AMCs) as shown in Fig. 4, encompass various methods such as stir casting, powder metallurgy, squeeze casting, infiltration, spray deposition, mechanical alloying, direct metal deposition, extrusion, hot pressing, each offering unique advantages and challenges tailored to specific application requirements [30–32].

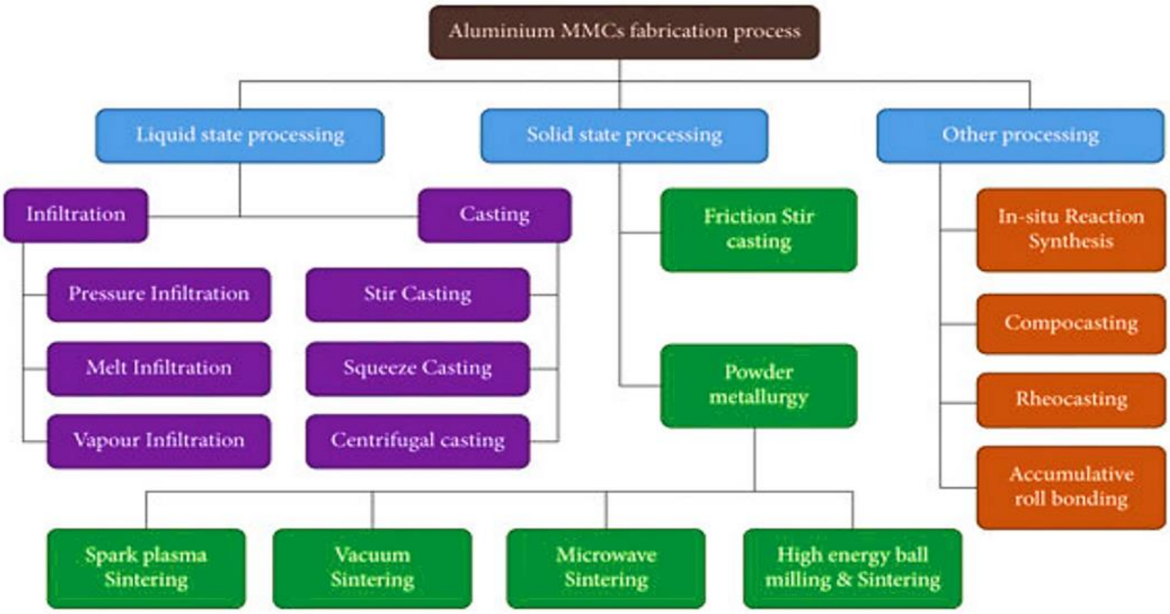

Fig. 4. AMCs fabrication process

Stir casting

Stir casting is a popular and cost-effective way to make aluminium metal matrix composites. Melting aluminium in a furnace crucible at 700–800 °C starts the process. After melting aluminium, a mechanical stirrer forms a vortex in which warmed reinforcing particles like SiC or Al_2O_3 are slowly added. Preheating the particles prevents molten aluminium from cooling too quickly and improves wetting and bonding. To ensure particle dispersion, stirring is done for a defined time. After mixing, a degassing agent may release trapped gases, lowering porosity. After mixing, the composite is put into a prepared mold and cooled to harden. Machining or heat treatment may obtain the desired dimensions and qualities [33–36].

Powder Metallurgy

Fabrication of aluminium metal matrix composites using powder metallurgy is accurate and adaptable. The procedure starts with aluminium powder and SiC or Al_2O_3 reinforcing particles. These components are combined, commonly in a ball mill, to distribute reinforcement evenly throughout the aluminium matrix. A die is used to compress the blended powder mixture under high pressure to generate a "green" compact that maintains the intended component shape. A temperature below aluminium's melting point is used to sinter this compact. A dense composite material is formed when particles connect during sintering [37–42].

Squeeze casting

Liquid metal forging, or squeeze casting, is an innovative production technique for aluminium metal matrix momposites (AMCs). Aluminium being melted in a furnace. After melting, aluminium is placed into a prepared mold with reinforcing material like ceramic particles or fibers. After pouring, a hydraulic press forces the molten metal to fill mold holes and thoroughly permeate reinforcing material. High-pressure application continues until the metal hardens, creating a thick composite with low porosity and good matrix-reinforcement bonding. High pressure removes gasses and refines the microstructure, improving composite mechanical characteristics. After solidification, the mold is opened and the cast item is expelled for machining or heat treatment [43–46].

Infiltration

Infiltration is a complex technique for making aluminium metal matrix composites (AMCs) by infusing molten aluminium into a porous reinforcing material like ceramic particles or fibers. After preparing and moulding the preform, it is warmed to reduce moisture and improve wettability. The mold is subsequently filled with molten aluminium, frequently with external pressure or a vacuum, to guarantee thorough penetration into the preform's pores. Pressure or vacuum overcomes molten aluminium's surface tension, enabling deep penetration and minimizing voids. After the metal completely penetrates the preform, the composite cools and solidifies [47–50].

Friction stir process

A new solid-state joining and processing method called friction stir processing (FSP) improves the microstructure and mechanical characteristics of aluminium metal matrix Composites (AMCs). FSP generates frictional heat by plunging a specialized spinning tool with a pin and shoulder into the material. The tool may move over the surface because localized heat softens the material without melting it. The tool stirs the material, breaking down and dispersing reinforcing particles in the aluminium matrix. Intense plastic deformation and mixing refine microstructures, distribute reinforcements homogeneously, and increase mechanical qualities including strength and fatigue resistance [51–54].

Stir casting process

In recent years, stir casting has emerged as a prominent method for fabricating aluminium metal matrix composites (AMCs), owing to its simplicity, cost-effectiveness, and versatility. This paper aims to provide a comprehensive overview of the stir-casting process, elucidating its principles, methodologies, advantages, and challenges.

According to the usual approach, liquid, solid, and semi-solidroutes are the categories that have been used to classify AMC production techniques [55]. The production of AMCs has been accomplished by using methods (Fig. 4) such as powdered metal metallurgy, liquid manufacturing, squeeze-casting, and spraying deposition, amongst others, which have been used by a number of researchers [56]. Stir-casting routes are preferred over other methods of production because of their simplicity and effectiveness in making AMCs [57]. Melt stirring motion is used in the stir-casting process to distribute reinforcing components throughout the matrix. S. Ray's early research on stir-casting of composites mostly included the fabrication of composite material using aluminium alloy as a matrix material reinforcing alumina particles. AMCs have been manufactured using a stir-casting amalgamation process [58]. Melting and stirring of molten material casting is the most efficient and cost-effective of the well-established methods of producing AMCs [59]. Base alloys are melted into a graphite crucible furnace and then stirred beyond their melting point as part of the stir-casting technique [60]. Casting the AMCs entails adding warmed particles to a molten slurry, stirring it continually for a certain amount of time, and then pouring the material into moulds of choice [61]. The melting of pure aluminium alloy requires heating higher than its liquidus point [62]. Additionally, it undergoes cooling to an intermediate concentrated slurry and is stored in a semi-solid state [63].

This is the stage when the preheated particles are combined with the molten liquid. Once again, the slurry is brought to a condition of perfect liquidity by heating, and then it is well mixed [64]. To get the right distribution of particles in the castingmould, AMCs are prepared in a certain way that prevents the solidification of the melt while yet allowing the suspended ceramic particles to remain in place [65]. The ultimate distribution of particulates within the solid casting is influenced by various factors related to material properties and method limitations [66]. These factors include the temperature at which the material is pre-heated, the rate at which reinforcing material is introduced, the extent to which the particulates are wetted by the molten material, the presence of porosity, the speed and duration of stirring, stirrer design, the use of chemical agents for degassing, and the rate at which solidification occurs along with the preheating temperature of the mould [67].

Results and Discussions

The purpose of this research is to describe the causes and limitations that impact stir casting throughout the two-step stirring process [68]. When making AMCs composites, reinforcement contents of up to 30 % by volume may be made via stir casting [69]. One primary concern in the stir casting process is the settling of particles during the process of heating and the process of solidification of the substances in metallic moulds [70]. This issue has to be resolved with the use of a stir-casting route as shown in Fig. 5.

Reinforcement thermal stabilization temperature and particle injection rate

The particles are subjected to preheating at an optimal temperature in order to minimize the presence of undesirable gases originating from reinforcements in addition to the aluminium alloy [71]. Additionally, this preheating process serves to improve the bonding between the particles, hence enhancing the wetting behaviour of reinforcement particulates with base materials. Casting composites may be difficult due to the nonuniform dispersion of the particles and the resulting poor mechanical characteristics. Typically, particles are heated between 200 and 500 °C for 30–60 min [72]. The gaseous moisture in the reinforcement is removed. The optimal reinforcement injection rate plays a critical role in achieving optimal casting performance for advanced metal castings (AMCs) since increasing the feeding rate leads to the production of agglomerates of solid particles. Research conducted by scientists has shown that maintaining a consistent feeding rate within the range of 8–10 mg/min throughout the length of stirring yields excellent results [73].

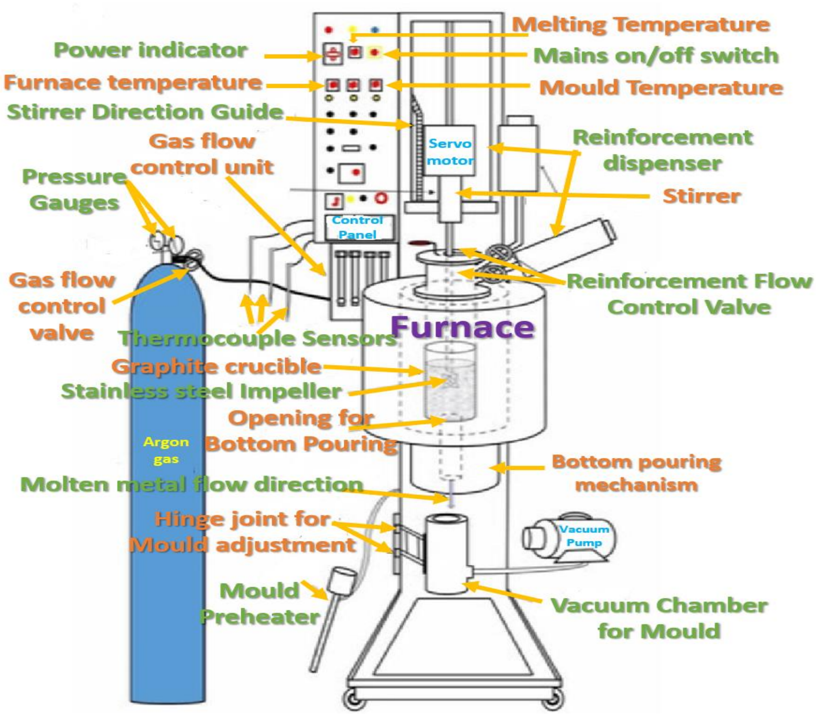

Fig. 5. Stir casting machine and its components

Void fraction and wetting behavior

Wettability describes the ability of a molten metal to spread and adhere to the surface of reinforcement particles, promoting uniform distribution and strong interfacial bonding. A high degree of wettability facilitates the wetting of reinforcement particles by the molten metal, leading to improved mechanical properties and enhanced homogeneity. Throughout the stirring process, the contact angle and interfacial surface tension have a substantial impact on the surface's wettability [74]. A lower contact angle suggests that the components are more wettable to one another. It is essential to take these aspects into account in order to produce the best possible wettability between the components [75]. A drop in mechanical properties might result from a lower wettability. When making composites using the melt stirring technique, porosity becomes a major concern [76]. Composites' mechanical performance degrades as their porosity increases.

Structure of a stirrer

A mechanical stirrer with blades may be used to create a vortex in a molten liquid, which allows particles to be added and distributed evenly [77]. For effective mixing, it is essential to optimize the design of the stirrer blades. To create an efficient vortex and encourage material homogeneity, mechanical stirrers might have two, three, or even more blades [78]. It is well-known, however, that composites made via mechanical stirring processes are best handled by single-step impellers. The formation of a vortex occurred as a consequence of the stirring process, which facilitated the transfer of particulate matter into the molten alloys [79]. This led to the creation of a homogenous dispersion of aluminium matrix composites (AMCs). Consequently, the careful determination of an appropriate impeller-blade angle is a crucial factor in achieving favourable axial flow and the angle of 30° has been identified as the most effective in promoting the uniform dispersion of particles while minimizing undesired agglomerations [80]. In some instances, blade angles of 45° and 60° have been seen to provide a consistent distribution in the manufactured samples [81].

Time and speed of stirring

As a matter of wettability, the speed at which the mixture is stirred is a crucial limiting factor. Most researchers have found that stirring speeds in the range of 700–800 rpm, at a cost of about 10 min, yield the most appropriate results [82]. The rotational speeds play a determining role in the formation of the vortex, leading to the distribution of particulates inside the reinforcement and matrix material liquid mixture. Enhanced mechanical characterizations of synthesized materials may be attained by comprehensive agitation over a suitable duration [83]. Particles' suitable mixing rate is another difficulty that is strongly affected by aided factors such as stirrer blade design, stirring speed, and duration, and so becomes a problem to be optimized [84].

Purge

To remove air bubbles and other inclusions from molten materials, purging or degassing is performed, and chemicals like tetra-chloro-ethane and sodium hexa-chloro-aluminate are added to improve wettability [85]. Nevertheless, more investigation is required to determine the effectiveness of the decontamination action.

Casting temperature

The temperature at which the molten metal is poured has a significant role in the solidification process. It is crucial to sufficiently increase the pouring temperature to guarantee that the metal flows smoothly and to prevent the formation of structures with coarse grains [86]. There is a significant level of responsibility associated with the excellence of casting. In order to prevent the entrapment of gases, it is essential that the pouring rate of molten materials remains consistent and homogeneous [87]. The measurement of the distance between the mould and the crucible is a critical factor that significantly impacts the quality of the casting process.

Solidification rate

The process of directional solidification in the context of melting materials of AMCs serves to decrease the likelihood of wear and tear [88]. The pace at which solidification occurs is primarily influenced by the degree to which the form and size of the mould are compatible. Similarly important to casting quality is the mould's proximity to the crucible [89].

Temperature of mould

Preheating the permanent mould is a great way to avoid porosity, the most detrimental flaw in AMC casting [90]. Metal moulds provide significant improvements over sand moulds, and they may be customized to meet the needs of the manufacturer in terms of thickness (at least 25 mm) as well as overall size and weight [91]. In addition, the use of metallic moulds would enhance the mechanical characterizations of the cast aluminium matrix composites (AMCs) [92]. Furthermore, many types of coating materials are used to enhance the die life of AMCs. Coatings such as silicate and graphite in water may be applied using spraying them within the moulds [93–96].

Emerging trends

1. Improving the mechanical performance of synthesized AMCs requires overcoming certain difficulties that arise during the melt stirring process and producing improved castings.
2. During the stir casting process, ensuring that the reinforcing particles are evenly dispersed is an important issue that arises. The dispersion of particulates inside composites is influenced by many factors, including the density of the materials (both matrix and reinforcement), the size (macro, micro, and nano) of the particulates, the degree of viscosity of the heated substance, and the right use of the stirring rate and stirring duration. These factors all contribute to achieving a uniform and homogenous dispersion.
3. The two-step stir casting technique was shown to provide the most favourable outcomes when ideal factors such as stirring speed, stirring duration, and federate were carefully controlled. Additionally, it was advised to use a three pitched-blade stirring impeller for this procedure.
4. The typical stir casting technique is often used in the industry. However, there are opportunities for improvement in the design of this process. One such enhancement is the use of an ultrasonic probe during the stir casting process. This modification may result in improved wettability and more uniform mixing of particle phases in the molten mixture.
5. The use of an inert environment in bottom-poured stir-casting has been extensively investigated by several researchers. This approach uses a setup that incorporates an inert atmosphere and bottom-pouring additives to prevent the occurrence of unwanted chemical reactions induced by gases. Additionally, it reduces porosity and improves the uniformity of particle matter.

6. Electromagnetic stir casting employs an electromagnetic stirrer as a viable alternative to conventional liquid stirring in order to mitigate surface flaws often seen in AMCs. In the context of electromagnetic stir-squeeze casting, the use of an ultrasonic transducer and bottom pouring connectors enhances the processing capabilities of the composites.
7. Numerous studies have used a range of optimization approaches (analysis of variance (ANOVA) [97], swarm optimizer (SO), fuzzy logic (FL), finite element method (FEM) [98], etc.), and others, to effectively manage and optimize the stir-casting process factors. The objective is to produce optimal outcomes within the given set of variables. The suggested factors have been offered to improve the mechanical characteristics of AMCs. Further research is required to investigate this subject in greater depth in the future.
8. Microwave heating has garnered increasing attention as a promising method for the fabrication of composite materials due to its ability to provide rapid and volumetric heating, precise temperature control, and energy efficiency. Microwave-assisted composite castings may also be studied in aerospace, automotive, and manufacturing. Microwave-assisted processing for industrial AMC and composite material manufacture may be studied for scalability, cost-effectiveness, and environmental sustainability [99–101].

Sustainability of stir-casting process

When evaluating the sustainability of the stir-casting process for aluminium metal matrix composites (AMMCs), several key sustainability issues are to be considered [102,103]:

1. Energy consumption. Stir casting typically requires significant energy input for melting aluminium and maintaining process temperatures. The energy intensity of the process, especially if traditional fossil fuel-based energy sources are used, can contribute to greenhouse gas emissions and environmental impact. Implementing energy-efficient practices and utilizing renewable energy sources can help mitigate these sustainability concerns.

2. Raw material usage. The sustainability of stir casting is influenced by the choice of raw materials, particularly aluminium and reinforcement particles. Aluminium extraction and processing have environmental implications, including energy consumption, resource depletion, and emissions of greenhouse gases and other pollutants. Sustainable sourcing practices, recycling of aluminium scrap, and utilization of eco-friendly reinforcement materials can help reduce the environmental footprint of AMMC production.

3. Waste generation: Stir casting can generate waste in the form of scrap metal, slag, and other by-products. Proper waste management practices, such as recycling of aluminium scrap and utilization of waste materials for other applications, can minimize waste generation and promote circular economy principles. Additionally, efforts to optimize process parameters and minimize defects can help reduce material losses and waste.

4. Emissions and pollution. The stir casting process may release emissions and pollutants into the environment, including particulate matter, volatile organic compounds (VOCs), and greenhouse gases. Controlling and mitigating these emissions through the use of pollution control technologies, such as exhaust systems and filtration devices, can help reduce environmental impact and protect air quality.

5. Occupational health and safety: Worker health and safety considerations are integral to the sustainability of any manufacturing process, including stir casting. Exposure to molten metal, fumes, and hazardous chemicals poses risks to workers' health and well-being. Implementing appropriate safety measures, providing training and personal protective equipment (PPE), and ensuring compliance with occupational health and safety regulations are essential for safeguarding worker health and promoting sustainable practices.

6. Lifecycle assessment: Conducting a comprehensive lifecycle assessment (LCA) of the stir casting process can provide insights into its overall environmental impact, from raw material extraction and processing to end-of-life disposal or recycling. By quantifying environmental indicators such as energy consumption, greenhouse gas emissions, water usage, and waste generation, LCAs can inform decision-making and identify opportunities for sustainability improvements.

Conclusions

The fabrication of particulate-based AMCs may be done quickly and cheaply by the stir-casting approach. Researchers have shown that a homogenous distribution of the particulate, together with superior wettability and little porosity in the cast AMCs, is achieved by carefully controlling the parameters that play a vital role in the synthesis process, which involves adding particles to molten materials. The optimization of stir casting parameters is essential for achieving high-quality advanced metal matrix Composites (AMCs). Through careful control of variables such as pre-heating temperature, injection rate, stirring speed, and impeller-blade angle, significant improvements in mechanical characteristics can be attained. Key findings include:

1. reheating particles between 200 and 500 °C for 30–60 min enhances wettability and minimizes undesirable gases;
2. maintaining a consistent injection rate of 8–10 mg/min yields optimal casting performance;
3. stirring at speeds of 700–800 rpm for approximately 10–40 min facilitates the formation of a vortex and homogenous dispersion of particles;
4. an impeller-blade angle of 30–60° proves most effective in promoting uniform particle dispersion;
5. mold thickness should be at least 20-25 mm to avoid porosity;
6. emerging trends such as the use of ultrasonic probes and electromagnetic stir casting offer promising avenues for further improvement;
7. the sustainability of the stir casting process for AMCs hinges on optimizing energy usage, minimizing waste generation, and mitigating emissions while ensuring worker health and safety.

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