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Review

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

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Abstract

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

Introduction

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

Among the available matrix materials (Al, Mg, Cu, Fe, Ti) for MMCs, Al and Mg are the common ones. Magnesium-based composites have fascinated significant attention due to its attractive mechanical properties over monolithic alloy. However, some disadvantages have restricted the progress of magnesium usage in automobiles. The primary reason is the low ductility and low resistance to fracture. Mg is very reactive at elevated temperature. However, it can be controlled with surface coatings or its naturally occurring oxide [5]. During the production of Mg-based MMCs, an inert atmosphere should be maintained to avoid oxidation with the environment. A significant disadvantage of using iron as the matrix is its brittleness and less impact strength compared with composites. Therefore, steel-based metal matrix composites show great potential only for wear-resistant applications. It is not suitable for marine environment application [6]. Copper-based MMCs are mainly used for the application where the thermal and electrical conductivity property plays a significant role. For many applications, pure Cu cannot be used as a matrix because of its low strength [7]. Among the several available matrix materials, aluminium and its alloys are widely used to produce MMCs. Some of the attractive properties of aluminium are less weight,

economically feasible, easy to process with different techniques and possess the high strength to weight ratio and excellent resistance to corrosion [2].

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

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

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

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

Similarly, Casati and Vedani [22] focussed on nanoparticles reinforced MMCs. Kala et al. have given mechanical and tribological properties of Al-based MMCs produced by stir casting attention [11]. Therefore, it is quite evident from this review that so far none of the reviews have focused on the primary production process such as stir casting process. There are very few review papers on MMCs that focus on the stir casting process. Kumar and Menghani [23] reviewed stir casting process and its issues, however, the developments in stir casting design and recommendations are not covered. Although the processing issues in the production of AMMCs by stir casting is discussed by Suthar and Patel [24], machining and applications of AMMCs are also discussed, and so it is entirely different from this review. Kumar et al. [25] briefly reviewed the fabrication and characteristics of MMCs produced by stir casting. Shabani and Mazahery [26] introduced a new method called semisolid agitation process in the stir casting process, as a result, improved the mechanical properties of the composites.

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

- First, it describes the various production processes for MMCs by using schematic illustrations.
- Following this, several stir casting furnace designs are discussed again with the help of schematic illustrations. Stir casting is evaluated because of it being an established and economical process to produce AMMCs. The recommended furnace design is also provided in the later section so that the researchers can make an informed decision in choosing a furnace for producing AMMCs that will exhibit the desired properties.

- The next section focuses on AMMCs by discussing and comparing the properties of matrix and reinforcement materials especially Al_2O_3 and SiC. The process parameters that can influence these properties, as well as additives that can enhance these properties, are also discussed.
- Finally, challenges in the production of AMMCs using stir casting and recommendations to overcome the challenges are discussed and concluded by highlighting some of the advanced application for AMMCs and possible research opportunities.

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

Section snippets

Production processes for MMCs

Fig. 3 shows the evolution of the production processes used by researchers worldwide for the production of MMCs. The data is presented chronologically based on a Scopus database search (Search terms: Aluminium Metal Matrix Composites; Production

Method Names) conducted on 4th April 2018. The evolution of the stir casting process is highlighted in yellow colour, and the final text box refers to the recommended stir casting furnace design discussed later in Section 6.1.

The production processes …

Stir casting furnace design used for the production of AMMCs

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

1. Achieving a uniform distribution of particles in the …

…

Properties of AMMCs produced through various stir casting processes

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

Challenges in the production of AMMCs using stir casting process

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

1. Uniform distribution of reinforcement particles is a significant issue even with micron-sized particles that severally influences especially the mechanical properties of the MMCs. Factors such as the …

…

Recommendations

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

Research opportunities in the production of MMCS

Production of MMCs as discussed earlier involves many challenges. There are large deviations in the properties of MMCs produced using various casting methods. Hence, it is challenging to select an appropriate method for a specific application. The process parameters and conditions should be optimized for the production of several compositions of MMCs. Published literature are not sufficient to finalize process parameters for many of the existing and new matrix as well as reinforcement materials …

Conclusions

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

1. Among the production methods, stir/squeeze casting, powder …

…

Declaration of interest

None. …

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