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Improvement in Manufacturing of Aluminium-Based Functionally Graded Materials through Centrifugal Casting—A Review †

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Abstract: The global demand for functionally graded materials (FGMs) has grown rapidly. This research reviews FGMs and the production technologies that affect their physical, structural, and manufacturing properties. We discuss the aluminium alloys and ceramics used in the fabrication process based on their engineering uses in many industries. Centrifugal casting is the versatile and commercial viable method to manufacture FGMs. These FGMs possess a variety of applications in automobile and aerospace industries owing to their enhanced mechanical strength and thermal and corrosion resistance.

Keywords: functionally graded materials; centrifugal casting; aluminium alloys; mechanical properties; industrial applications

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1. Introduction

Materials are crucial for the development of civilization and culture. Advanced materials have been developed due to the limitations of conventional materials due to the increased demand and the optimization of industrial uses. FGMs have significantly reduced these constraints through the property of location-specific performance within a single component [1–3]. FGMs exhibit improved composite performance and durability over homogeneously reinforced composites. Therefore, FGMs have gained popularity due to their ability to create bespoke products for high-tech industries like aerospace, automobile, biotechnology, and nuclear industries. Compared to regular composites, the mono-reinforced FGMs have one constituent irregularly distributed within their matrix, whereas hybrid FGMs have multiple constituents. The continuously variable constituent distribution density over the matrix yields a continuous gradient in both circumstances. Moreover, FGMs are fabricated with several ingredient combinations, with ceramic/metal being the most frequent one. Ceramic/metal FGMs with metal alloys (matrix) and secondary phases (ceramics) are compositionally graded from a ceramic phase to a metal phase. Because of their improved hardness, strength, machinability, toughness, heat, wear, and corrosion resistance, these FGMs have become popular. In addition to the graded volume, FGMs reduce thermal stresses and promote phase attachment, enhancing fracture resistance and toughness [4,5]. Aluminium and its numerous alloys play an essential role in industries owing to their enhanced properties, including light weight, financial viability, comfort of production, excellent strength-to-weight ratio, and corrosion opposition [6]. Therefore, researchers choose aluminium alloys as common matrix materials due to their ability to withstand ceramics. The metal–ceramic combination allowed mechanical, electrical, thermal, and tribological capabilities to be integrated at normal and high temperatures. Many methods are employed to make FGMs from aluminium and its alloys [7]. The goals and uses of the composite determine the reinforcement materials utilized in the FGM production process. FGMs improve the matrix alloy in several ways, including its tensile strength, thermal stability, chemical resistance, wear resistance, and friction coefficient. The common ceramic reinforcements include oxides, carbides, borides, and nitrides. Also, the general non-ceramic reinforcements are fly ash, marble dust, and graphite. They possess improved mechanical, thermal, and tribological properties. Hybrid FGCs are gaining popularity in different industries for their improved composite qualities, achieved by appropriately mixing reinforcement particles for an application [8]. Multiple researchers have examined metal matrix composite (MMC) production procedures through stir casting [9,10]. The stir casting technique's processing and technical issues, mechanical characterization, and applications have been examined [11]. Centrifugal casting is one of the economical methods followed by the stir casting process to manufacture aluminium/ceramic FGMs. Development, production methods, and material composition of FGMs for diverse purposes have been the focus of several global studies over the past decade.

Reviews briefly describe the problems of these procedures, but they are limited and unconsolidated. Therefore, this assessment briefly explains the available fabrication routes for FGMs in the centrifugal casting methodology. We examine the composition of the matrix material, the reinforcing material, the functionality of the transition, the geometry of the final constituent, and the spectrum of applications to determine the acceptability and viability of liquid production procedures. The next section discusses the properties of matrix and strengthening resources used to manufacture FGMs, focusing on aluminium and its alloys for industrial applications.

2. FGM Fabrication through Centrifugal Casting

The FGM manufacturing technology of casting has progressed significantly to fulfil the growing demands of many industries. Centrifugal casting is the best cylindrical FGM casting method due of its versatility and commercial viability. This casting method is divided into horizontal centrifugal casting (HCC) and vertical centrifugal casting (VCC) based on the revolving axis. Centrifugal casting produces tubular pipes, washers, sleeve bushes, cylindrical inner liners, shell casts, etc. In the creation of FGMs, stir casting route is employed to mixes for their ceramic reinforcement in the molten metal matrix to make MMCs. Then, mechanical stirrers are used to enhance the proper mixing of ceramic grains in the melt [12]. Later, the molten metal fusion is poured into the centrifugal casting die (Figure 1), and the centrifugal forces create a hollow cylindrical component, which is suitable for automobile applications such as engine piston, cylinder, and brake disc. The formation of gradient property is the challenging task in the FGM manufacturing process due to the influence of various material and production variables [13]. Choosing the right reinforcing size and density is the one of the ways to achieve the gradient property through the centrifugal casting methodology [14]. This helps to accomplish the desirable gradation and regulated solidification in mono and hybrid FGM composite casting during the production with centrifugal forces. Usually, matrix particle density variance, wall thickness, solidification period, reinforcement magnitude, texture, and volume affecting centrifugal casting are the variables that influence production and should be considered while fabricating the FGMs [15]. Table 1 summarizes some of the literature showing the different reinforcement effects on the aluminium composite.

The optimization of production constraints improves FGM composites' tribological and mechanical performances, regardless of the matrix and elemental compositions [20]. Centrifugally cast aluminium-reinforced magnesium FGM composite exhibited superior hardness compared to the one with in situ Mg_2Si and primary silicon production. A higher magnesium content increases porosity, affecting the casting quality [21]. Phosphorous in the melt refined the grains and reduced the shrinkage porosity. Centrifugally cast SiC strengthened A356 functionally graded composites (FGCs), and the composites with 0, 10, and 20 wt.% reinforcement had a greater wear resistance than stir-cast homogeneous aluminium composites. A higher ceramic concentration in the FGC's outer layer increased hardness and fracture resistance. Centrifugally cast aluminium alloy FGC reinforced with Al_2O_3 elements exhibited a better anti-abrasion wear compared to the unreinforced alloy [19]. Centrifugal force increased the reinforcing particle segregation and enhanced microhardness and tensile strength in the outer layer [22]. Similarly, the mechanical characteristics and wear response studies of Al6061/SiC FGC showed an increased hardness, an increased wear resistance, and a decreased elongation with the growing SiC particle volume fraction. Dislocation motion, ductility, and fracture area were reduced with SiC particle gradient dispersion [23]. Cast aluminium Al-Si alloys are chosen for FGC fabrication owing to their corrosion and wear opposition, enhanced strength, and low thermal expansion coefficient [24]. The coarse eutectic silicon construction of Al-Si alloy has been refined, leading to improved hardness, ductility, and tensile strength. Incorporating grain modifiers like salt or strontium into a rapid cooling process following heat treatment has been shown to increase the mechanical performance [25]. Magnesium and copper, two common alloying elements, boost yield strength and heat treatability, producing the composite useful in aerospace and automotive settings [26]. The gradient distribution of reinforcement elements was recognized based on size, shape, and concentration [27]. Centrifugal force, cooling rate, mould temperature, melt transfer temperature, and mould–melt temperature difference all controlled the ceramic distribution well [28]. These parameters determined Al–Si FGC mechanical and tribological reactions [29,30]. The centrifugal mixed-powder method eliminated the disadvantages of centrifugal castings for nano-particle-reinforced FGM composites [31]. This combines powder metallurgy and centrifugal casting by pre-setting the combined powder in a revolving mould before pouring the molten metal.

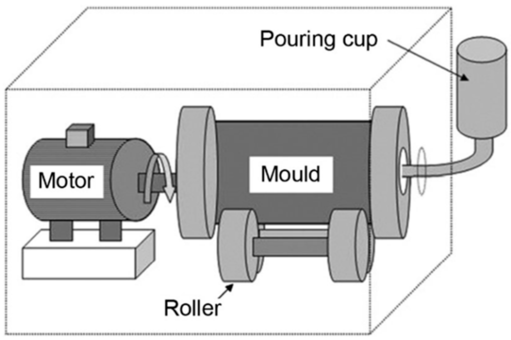

Figure 1. Layout of the horizontal centrifugal casting process for FGMs.

Table 1. Reinforcement effect on the aluminium metal matrix composite.

FGMMC Combination	Casting Route	Outer Hardness	Inner Hardness	Inference	Ref.
Pure Al/20 wt.% Al_2O_3	HCC	47 BHN	43 BHN	The produced FG tubes have the largest concentration of reinforcing particles in their outer zone, confirmed through their microstructure.	[16]
Al/10 wt.% Si_3N_4	HCC	88 HRB	71 HRB	The concentration of reinforcement grows from the interior to the periphery of the cast ring. The radial stresses from centrifugal casting push the second distinct phase to the exterior zone of the matrix of composite materials.	[17]

Table 1. *Cont.*

FGMMC Combination	Casting Route	Outer Hardness	Inner Hardness	Inference	Ref.
Al–7Si-0.3 Mg/ 10 wt.% SiC	HCC	199 HV	140 HV	Heat-treated composites showed variable wear rate and friction coefficient variations, with varying sliding distance.	[18]
A356/20 wt.% SiC	VCC	135 BHN	110 BHN	Microstructural study confirmed the SiC particle segregation from outer to inner area.	[19]

3. Conclusions

Few advanced composites are universally accepted as metal-based FGCs. This study reviews the creation and advancement of FGCs, including production procedures and material compositions for various applications. Centrifugal casting is the most cost-effective and recognized technology for manufacturing FGCs, meeting the industrial invention demands for mono- and hybrid-graded FGMs. Aluminium and its alloys were chosen as the common matrix materials for their ability to withstand ceramics. Secondary phase reinforcement with carbide-based ceramics showed a superior mechanical performance compared to that of other ceramic families. Overcoming the matrix–particle interface wettability issues was a major hurdle in the FGM material selection. Due to its good wetting, titanium-based ceramics are developed as graded material constituents. Using modern analytical tools for numerical simulation and modelling enhances FGM development's predictive performance and helps designers identify bottlenecks before structural breakdowns occur.

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