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Recent Trends in Casting Technology of Functionally Graded Metallic Alloys

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Abstract

Functionally graded materials (FGMs) are a new type of heterogeneous composites defined by a continuous change of properties along at least one direction. Their properties lead to achievement requirements of applications due to the development of industries such as aerospace, automotive, machinery, and biomaterials. Metal matrix composites (MMCs) with a continuous change in reinforcement volume in one matrix alloy direction are functionally graded metallic alloys (FGMAs). Recent developments in FGMAs casting technology, including processing processes, potential applications, and mechanical characteristics, are discussed. Several casting processes, including centrifugal casting, squeeze casting combined with stir casting, sequential casting method (liquid-liquid casting), cast-decant-cast, and compound casting (liquid-solid casting) can be used to make various engineering components for FGMAs, such as pipes, shafts, gears, bushings, hammers, and rolls. Future trends and recommendations for future FGMAs manufacturing with improved characteristics, cost-effectiveness, and mass production are offered based on the scope of this review.

Keywords: Functionally graded metallic alloys, Casting processes, Applications of FGMs, Future trends

1. Introduction

Because of current industrial advancements, there is a desire to build structures that can withstand high gradients of stress, pressure, and temperature in a single direction while retaining structural integrity. This goal has resulted in novel materials, known as functionally graded materials (FGMs), for use in specific industrial applications [1, 2]. FGMs are a novel type of heterogeneous composite materials defined by a continuous change of characteristics in at least one direction to achieve the demands of industrial applications [1, 3-5]. Variations in chemical composition, size, morphology, and structure as a function of location influence their functional and structural alterations [6-9]. They can either be a smooth gradient for homogeneous mixes or a sharp gradient for heterogeneous mixtures [10]. As a result, FGMs have different mechanical, thermal, and tribological properties in different regions. These graded materials suit various applications, including automotive, marine, aerospace, military, and biological [11-18]. Metal/metal, metal/ceramic, ceramic/ceramic, ceramic/ceramic, and ceramic/polymer are several types of artificial FGMs [13]. Metal matrix composites (MMCs) with a continuous change in reinforcement volume in each direction are functionally graded metallic alloys (FGMAs). FGMAs have a progressive or continuous transition in engineering characteristics at the macroscopic scale, allowing a combination of features without a mechanically weak interface. FGMAs with customized characteristics can be adapted to specific applications requiring excellent wear resistance and bulk toughness [19, 20].

FGMs may now be made utilizing various methods, including casting, powder metallurgy, physical and chemical vapor deposition, plasma spray forming, and additive manufacturing [12, 20-30]. Casting processes such as centrifugal casting, squeeze casting paired with stir casting, and stir casting combined with centrifugal casting are the most common, easy, and cost-effective ways to obtain FGMAs [12]. As a result, this review discusses current developments in casting technology for FGMAs and processing procedures, applications, and some mechanical characteristics of FGMAs.

2. Functionally Graded Materials

2.1 Functionally graded materials as new promising materials

FGMs are considered a new type of composite materials which exhibit a continuous change of properties along at least one direction due to the gradient distribution of their phases to achieve the needs of applications originating from industrial growth [1, 3-5]. Variations in chemical composition, size, morphology, and structure as a function of location influence the modification of functional and structural qualities [6-9]. As a result, FGMs outperformed and were more attractive than traditional composite materials. It replaces the mechanical characteristics of FGMs that have abrupt changes at the composite borders with a smooth, continuous, and gradient transition [31, 32].

These graded materials were initially created in 1983 for the Japanese space shuttle project to decrease stresses due to the thermal effect because of increasing temperature due to contact of metal and ceramic [13, 33]. Due to the industry's expansion, interest in FGMs has grown dramatically in recent decades due to its wide ability to produce bespoke products for distinct variations of high-tech applications, such as airplanes, automotive, and biotechnology [13, 31, 34].

2.2 Classification of functionally graded materials

Because these components have gradation in hardness and flexibility, functionally graded structures may be observed in nature, such as human bones and teeth, animal tissues, and bamboo plants [2, 18, 35, 36]. FGMs are categorized into four groups. For starters, it comprises components like ceramic and metal as the matrix and reinforcement of ceramics, metals, or polymers. Functionally graded metallic alloys (FGMAs) based on metal as the matrix are the largest widely utilized combination of materials [19, 20, 31]. The composition of FGMAs, which comprise metal alloys as a matrix and ceramics or metals as reinforcement, has a gradient in composition from reinforcement to metal matrix. Because their capacity enhances mechanical characteristics such as hardness, tensile strength and toughness and improves heat resistance, wear, and corrosion, these FGMAs have garnered broad attention [31, 37].

Secondly, FGM can be a continuous or stepwise graded structure, depending on the type or structure of the gradation, as shown in Fig. 1. The chemical composition or microstructure changes progressively in stepwise graded FGM. The interface is generally observable and visible, as shown in Fig. 1a. Each layer of FG material has the same characteristics. On the other hand, in continuous graded construction, the composition of the first material starts at 0%. It grows throughout the length of the structure until it reaches 100%. However, the other material behaves similarly in the counter direction over its length. As a result, the chemical composition or microstructure varies with position, making it nearly difficult to discern a definite interface boundary across the graded structure, as shown in Fig. 1b [38, 39].

Thirdly, by changing the chemical composition, microstructure, and porosity, three types of FGM may be produced, depending on the gradation type. Chemical composition is changed throughout the material leading to the form of a gradient in phases would be helpful for the desired properties upon the applications [40, 41].

The porosity gradient FGM is defined as a change in bulk material porosity in a specific direction. Pores are created and changed in size and form based on needed characteristics. These are ideal for biomedical applications, and the graduated porosity aids in integrating the implant with the surrounding tissues. Blood circulation to the integrated tissues is aided by porous features, ensuring that the implant heals quickly. The porous structure also decreases weight and increases the implant's elastic modulus to match human tissue [42, 43].

Microstructural gradient FGM is another method for producing various microstructures in the same material by varying the microstructure. Microstructure gradation is achieved through solidification or the control of the heat-treatment process. The production process can be controlled during the quenching of the outer surface while slow cooling of the inner core, resulting in varying microstructures along the radius. The resultant properties feature a high toughness core and high hardness of the exterior surface to resist wear, for example, casehardening of steel gear and bearings or shafts [44, 45].

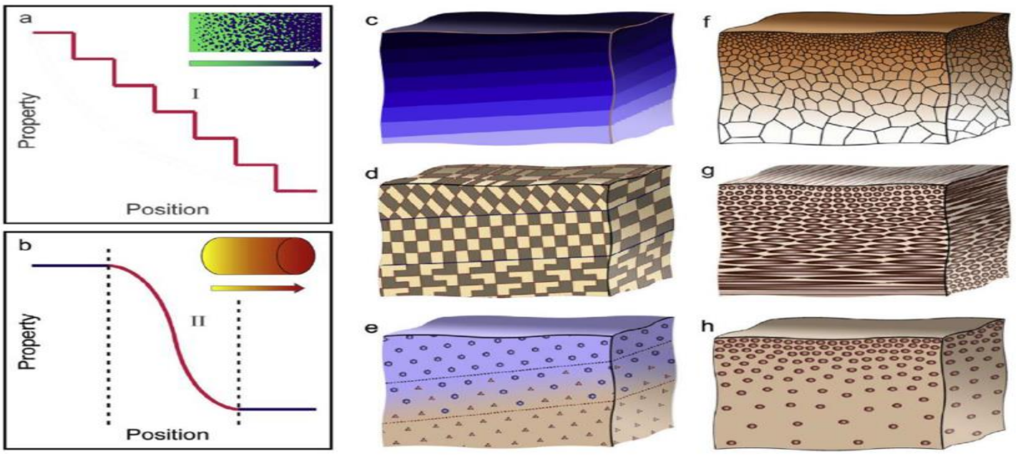


Fig. 1 Schematic diagrams of (a) discontinuous and (b) continuous gradient materials. (c), (d), and (e) show the schematics of discontinuous gradient materials consisting of interface with gradual changes in chemical composition, grain orientation, and volume fraction of two types of secondary phase particles, respectively. (f), (g), and (h) display schematics of continuous gradient materials in the absence of interface and with a slight change in grain size, fiber orientation, and volume fraction of the secondary phase particles [39].

Fourth, thin and bulk materials are created dependent on the thickness of FGM. Thin FGM is commonly seen as a coating. However, the materials have a large volume gradient defined by bulk FGMs [39].

2.3 Fabrication of functionally graded materials

FGMs may now be made utilizing various methods, including casting, powder metallurgy, physical and chemical vapor deposition, plasma spray forming, and additive manufacturing [12, 20-30, 39, 41, 46, 47]. Casting techniques are favoured for FGM alloy manufacturing because they are cost-effective and capable of creating large-scale products. Casting procedures like centrifugal casting and squeeze casting combined with stir casting are the most straightforward and cost-effective ways to make significant technical components, including pipes, shafts, gears, and bushings [12, 20-24, 39, 48, 49]. As a result, this review will focus on recent advancements in casting techniques used in producing FGMAs.

3. Casting Processes for Manufacturing Functionally Graded Metallic Alloys

As one of the first and most established FGMAs manufacturing processes, casting methods developed substantially to meet the growing development of various industrial demands [31]. This section covers the most recent advancements in casting techniques, including centrifugal casting, squeeze casting with stir casting, and decadence casting, all of which are used in manufacturing FGMAs.

3.1 Centrifugal casting method

Besides a continuous grade with particular properties suited for various industrial applications, centrifugal force is the principal engine for making FGMAs. The unequal distribution of phases based on the density of the materials along the radial direction resulted from the force of the centrifugal action for the rotation of the mold [13]. Large products such as shafting, bearings, and rolls may be mass-produced using the centrifugal casting process [50-52]. The temperature differential between the molten metal and the processing temperature is used to classify centrifugal casting. The centrifugal in-situ technique (CISM) [53] is utilized when a greater processing temperature is required. The centrifugal solid-particle technique (CSPM) [54] is used when the reinforced solid particles are included in liquid metal. Advanced centrifugal casting, also known as the centrifugal mixed-powder technique (CMPM), has recently been used [55, 56].

3.1.1 Parameters affecting on centrifugal casting method

The difference in densities of base metal and second-phase particles causes material gradation. The centrifugal force and the mold spins' speed will determine the segregation of second-phase particles [57]. Lower density reinforcements are separated to the core, whereas greater-density reinforcements are separated from the outer shell. In the preparation of aluminum tubes, reinforcements with smaller density (Mg2Si) and greater one (Al3Ti) than aluminum were employed. In that situation, it is found that reinforcements are preferentially strengthened at the tube's core or shell [58].

Centrifugal casting has the advantage of being able to produce components in large quantities. It is still difficult to precisely regulate the dispersion of particles for various combinations. The temperature of processing, rate of cooling, size, the density of reinforcements, and rotating mold velocity significantly impact gradient development in FGMAs [59, 60]. The significant variables that influence the fabrication of FGMAs by centrifugal casting are addressed below, including density, particle size, rotating mold speed, processing temperature, and cooling rate.

- *Density*

In case of two or more reinforcements are employed, the density difference of reinforcements is reflected in the gap produced in the particle segregation in the manufactured portion. Therefore, lower-density reinforcements are separated from the core, whereas more excellent-density reinforcements are separated from the outer shell. Mixed particle sizes should guarantee particle mixing and gradient dispersion [50].

- *Size of particles*

Particles size has minimal effect on segregation; a more thorough investigation of the rheological characteristics of the mold is needed to fabricate gradient structures with different particle sizes. The size of the particles utilized in FGMAs manufacturing should not be consistent. Particles of uniform size produce a particle enriched zone along a certain radius and a deficient zone in other areas. Even if the density of the particles remains the same, the distribution of particles in the produced component is affected by the contact surfaces [61].

- *Mold rotation speed*

In FGMAs component manufacturing, the speed of mold revolution is a crucial parameter for removing the impact of gravitational forces, preserving molten metal flowability, and, most significantly, particle segregation. The optimum rotation speed must be utilized to achieve the needed segregation of particles into molten metal. A narrow particle-enriched zone comes from a faster rotation speed [61].

- *Processing temperature*

The viscosity of liquid alloy, depending on its temperature, determines the reinforcement’s gradient and their segregation in FGM. The migration of dense particles towards the outer perimeter is hampered by high-viscosity molten metal, leading to a gradient of distribution in the radial direction dependent on the size of reinforcements [61].

- *Cooling rate*

Controlling the cooling rate of the manufactured specimen can improve mechanical characteristics. Slow cooling allows for the production of refined grains, which results in superior characteristics. The cooling rate is delayed by heating the spinning cylindrical mold, which allows the molten metal to flow once poured into it. The heat input is progressively reduced to allow molten metal to solidify [62]. Though it takes longer, the improved characteristics will be sufficient to eliminate the need for heat treatments such as annealing and stress relieving. The mold casting interface suffers from poor characteristics due to the rapid cooling of the outer perimeter. As a result, the force due to centrifugal action will be insufficient to drive reinforcements to the outer surface [63].

3.1.2 Centrifugal in-situ method

In CISM, the force due of centrifugal action during the process of solidification is exploited to generate a tube with graded characteristics by using low melting point reinforcement as compared with the base materials [64]. The continuous gradient will be generated through the liquid state before the main crystals crystallize according to the density variation among the matrix and reinforcement [65, 66, 67].

Arsha A.G. et al. [68] conducted research. For comparison investigations, vertical centrifugal In-situ Method casting processes were used to produce FGM pistons utilizing A390 and A390-0.5 wt.%Mg alloys, as well as two sets of homogeneous homogenous gravity cast pistons. The vertical centrifugal casting was utilized to design and manufacture FGM Al pistons in-situ. There were two distinct zones of main Si-rich zone and eutectic silicon-rich zone found. A larger concentration of primary Si particles is progressively transported to the piston's head area, resulting in improved characteristics. Magnesium strengthens and improves the precipitation-hardening stages of aluminum alloys significantly. FGM pistons that are centrifugally cast have higher hardness, heat resistance, and wear characteristics than gravity-cast pistons.

Lin Xue-dong et al. [69] investigated the production of in-situ FGM of Al–Si–Mg/Mg_2Si using a CISM. The results showed the high hardness near the inner perimeter due to the segregation of Mg_2Si particles of lower density than the outer shell.

The FGM composites based on Al– Al_2Cu were produced via CISM with approximately identical particle sizes to examine the influence of mold preheating on the concentration of Al_2Cu particles, according to Oya Y. et al. [70]. The temperature at which the mold was preheated was a crucial element in regulating the distribution of composite particles in their study.

Savas et al. [71] produced FGM composites based on Al–4 wt.% Mg/AlB_2 using the CISM. At 1400 ºC, the chemical reaction between B_2O_3 and liquid Al produced AlB_2 flakes. They discovered that FGM containing AlB_2 of 2.6 wt.% had superior mechanical resistance to wear.

The effect of the volume fraction of NbC as well as their distribution, on the wear properties of FGM high Cr white cast iron reinforced with NbC via CISM has been examined by Kan W. et al. [72]. The researchers discovered that the particles of NbC were significantly concentrated in the outer surface, resulting in the outer surface with high hardness as compared with the core, resulting in improved mechanical characteristics and wear resistance.

Using CISM, Vajda A. et al. [73] investigated FGM composites of Al–15 wt.%Mg_2Si. The scientists discovered that the action of centrifugal force led to the divorce of the light Mg_2Si particles in the direction of the inner tube surface, increasing the tensile characteristics in the inner zone of produced FGM.

Ram S. et al. [74] recently examined the influence of adding Mg on the microstructure and mechanical characteristics of FGMA of A356-Mg_2Si using CISM via vertical centrifugal casting at 1200 rpm. They also studied the heat-treatment influence on the resultant FGMA. Based on the results, the heat-treated FGMA exhibited high mechanical characteristics and resistance to wear as compared with as-cast one, particularly in the inner layer, according to a greater portion of Mg_2Si particles.

CISM was investigated by Aref Mehditabar et al. [75] as an improved material processing technology for fabricating FGM pipe of Al–26 wt.%Cu–7 wt.%Si. The results revealed that the Vickers hardness value steadily falls from 331.3 HV at the outer edge to 141.0 HV at the inside edge. Due to differences in the density of component materials, the outer layer of FGM pipe with 44.4 vol.% of Al_2Cu was achieved at the outer surface and subsequently gradually reduced in the direction of the core with 36.5 vol.%.

3.1.3 Centrifugal solid particle method

In case the matrix is an alloy with high toughness, the insertion of hard ceramic particles into a metal matrix effectively improves a material's wear performance. Still, the resulting loss in toughness is frequently significant [76, 77]. A potential solution to this problem is using a centrifugally cast of FGMAs. This could be described in applications based on the combination of high surface wear resistance and good core toughness. In such application, FGMAs should be applied because a large portion of ceramic reinforcements at the surface led to enhanced wear resistance while a small portion or none of the ceramic reinforcements within the core for good toughness [76].

In the case of CSPM, the FGMAs are achieved by using high melting point reinforcements as compared with the liquidus temperature of matrix alloy. That led to the gradient distribution of reinforcements over the radius due to the force of centrifugal action [55, 56].

Radhika N. et al. [78] investigated the centrifugal casting with hollow cylindrical components of FGM Al as a matrix and the constant additions of 12 wt.% of different reinforcements of B_4C, SiC, Al_2O_3, and TiB_2 having an average size of 10 µm, respectively. The results indicated the higher hardness of the outer shell for all composites than the matrix alloy, except the Al-B_4C composite, because B_4C particles have a lower density than the matrix, therefore their large gradient distribution of B_4C particles toward the core of the casting. The maximum hardness of the outer zone associated with using TiB_2 as the reinforcement is due to its highest hardness compared with other reinforcements. As a result, the hardness of FGM surfaces depends on the reinforcement’s type. The outer zones of all composites have a high tensile strength. The outside peripheries of all composites were subjected to abrasive wear testing, and the Al/TiB_2 composite showed the least amount of wear.

Singh S. P. et al. [79] used a CSPM to make FGM of A6061/10 wt.%Al_2O_3. The resulting microstructure along the radial direction of the FGM of A6061/10 wt.%Al_2O_3 showed the gradient arrangement of reinforcements across the radial direction with supreme alumina particle reinforcement at the outer periphery.

In another work, Karun A. et al. [80] showed that FGMAs of Al–SiCp (10, 20 wt.%) rings produced by CSPM exhibited a higher portion of SiCp towards the outer surface as compared with the inner layer. The FGMA of Al/20 wt.%SiCp had the best mechanical characteristics and resistance to wear.

Xiaoyu Huang et al. [81] compared gravity permanent mold casting to vertical centrifugal casting to manufacture hypereutectic Al–Si alloy-based composite pistons reinforced with SiC particles. The impacts of different method factors on particle segregation, such as the alloy's slurry temperature, mold temperature, and mold rotation speed, were examined, and pistons' macro morphologies and microstructures were observed. The mechanical characteristics of the piston were measured, including hardness and wear behavior throughout the piston axis, as well as the thermal expansion coefficient at the head of the piston. The results revealed that centrifugal casting might be utilized as an advanced and effective process for the production of pistons, with appropriate values for the temperature of the preheating mold and the alloy slurry addition to the velocity of the mold rotation being 600 °C, 850 °C, and 800 rpm, respectively. The hardness values of centrifugally cast pistons steadily rose from the piston skirt to the piston head. The mean value of hardness in the heads of the piston produced via centrifugal casting was enhanced by 23.7 HRB above one produced via gravity casting using a permanent mold. The wear resistance of the piston heads was outstanding, and the wear rate of the piston heads produced via centrifugally casting was reduced by 70.3% compared to the wear rate of the piston produced via gravity casting using a permanent mold. The piston head's average linear expansion coefficient was 15.3×10^{-6} K^{-1}, 23.1% lower than pistons made with gravity permanent mold casting.

Kumar R. Anil et al. [82] examined an FGM copper composite (Cu– 11wt.% Ni–4 wt.% Si) reinforced with graphite of 10 wt.% synthesized by stir casting and horizontal centrifugal casting. Microstructural investigation done radially from the outer surface revealed an increasing particle distribution gradient, with the inner surface having the highest hardness of 195 HV. The microstructural study indicated a graphite particle content gradient towards the direction of the inner surface. This was due to centrifugal force acting on high-density liquid copper alloy with low-density graphite particles, causing it to move toward the direction of the inner surface. As a result, the graphite particle gradient distribution increases from the outer surface to the interior region.

S. El-Hadad et al. [83] examined the use of CSPM to fabricate Al-5 wt.%Zr FGM. Al_3Zr particles were virtually orientated, usually to the applied centrifugal force direction, according to the findings. The increased centrifugal force also resulted in a vertical particle distribution and a reduction in the thickness of the reinforcements-rich region. Decreasing the centrifugal force reduced the wear property anisotropy of current Al/Al_3Zr FGM; as a result, the orientation of particles. The wear performance of produced FGMA was improved depending on the distribution control of both the orientation and volume percentage of Al_3Zr particles in the matrix.

Amrit Mallick et al. [84] have investigated how to make a functionally graded composite cylinder out of A356 aluminum alloy reinforced with SiC particles using a horizontal centrifugal casting. A356 cylindrical sample with 8% SiC particles are produced at an 800 rpm rotational speed in the mold. The results revealed that the hardness of the investigated FGM of cylindrical sample liner varied for three zones: particle-rich outside area, middle transitional zone, and interior particle-depleted zone. These results demonstrated that SiC effectively reinforced the liner material, which led to enhanced mechanical hardness. Thus, it could be used as an engine cylinder liner. Compared to cast A356, FGM castings reinforced with SiC demonstrated a maximum improvement in hardness of 302% in the outer area and 46% in the inner zone.

Manu Sam et al. [85] recently investigated the effect of the additions of different reinforcements, such as B_4C, SiC, and TiC, on the mechanical properties of Al-9Si-3Cu (A333) alloy hybrid composites. Horizontal centrifugal casting was used to create samples with the hollow cylindrical shape of two studied hybrid functionally graded composites of A333-6 B_4C- 4 TiC and A333-6 B_4C- 4 SiC (all additions in wt.%). On both composites, metallography examination indicated an increase in gradient distribution of reinforcement towards the direction of the outer surface. The highest micro-hardness of 198.9 HV and tensile strength of 267.9 MPa had been obtained at outer particle-rich zone at outer surface of the A333-B_4C-SiC hybrid FG composite. In contrast to the A333-B_4C-TiC hybrid composite and the base alloy, the particle-rich zone of the A333-B_4C-SiC hybrid FGM showed better hardness, tensile strength and wear resistance. Unlike TiC, this was attributed to SiC particles' greater proclivity for forming carbide lumps with B_4C particles in the outer layer.

3.1.4 Centrifugal mixed powder method

Because of the density variation among the matrix and reinforcement, particle dispersion is affected. FGMAs with nano-size reinforcements are extremely hard to achieve due to the mobility of reinforcements in molten metal governed by Stoke's rule. The G number characterizes the level of centrifugal force; here, the G number is given by the following equation 1[55]:

$$G = \frac{\omega^2 R}{g} \qquad \text{Eq. 1. [55]}$$

where R is the radius of the cast tube (in m) and ω is the mold spinning rate (in radians s^{-1}), and g is the acceleration due to gravity, equation 2 is the expression for Stoke's law which shows the velocity of particles (dx/dt) under centrifugal force [55, 86].

$$\frac{dx}{dt} = \frac{|\rho_p - \rho_m| G g D_p^2}{18\eta} \qquad \text{Eq. 2. [55]}$$

where ρ_p, ρ_m, D_p, and η are particle density, matrix density, particle diameter, and apparent viscosity of the melt. A larger dx/dt value produces a steeper compositional gradient and vice versa. It is clear from Equation 1 that the particle size has a significant impact on the compositional gradient generated by the centrifugal technique. This indicates that decreasing particle size causes a lowering in particle velocity. Gradients necessary for FGMAs on nano scales are necessary to be achieved before the applied centrifugal casting, it may be claimed. Watanabe et al. [55] proposed a novel technique for producing FGMAs with tiny particle sizes: the centrifugal mixed power method (CMPM). CMPM is described by inserting premixed powder in a spinning mold before the molten metal is poured, as shown in Fig. 2.

Y. Inaguma et al. [86] demonstrated the effects of volume fractions on particle dispersion and mechanical behavior in FGM of pure Al– TiO_2 produced through CMPM. The FGMs was achieved using 10 and 30 wt.% of TiO_2 with a mean size of 500 nm. The data revealed that the portion of TiO2 at the outer layer increases as the initial volume fraction of particles increases.

In separate research, Sato H. et al. [87] used CMPM to produce and analyze the influence of tiny particle size on FGMs of pure Cu and 29.6% SiC reinforcement with the size of 0.5, 50, and 150 µm, respectively. The results showed that SiC particles were present on the cylinder's outer surface, even though the copper density was more significant than the reinforcement owing to the application of CMPM, unaffected by density differences in the distribution. Furthermore, they discovered that FGM cylinders with tiny particle sizes (0.5 µm) had the best mechanical characteristics compared to other particle sizes (50 and 150 µm).

Watanabe et al. Y. [88], investigated the production of FG Mg/Mg_2Si composites via CMPM with approximately identical particle sizes. The size of the particles was discovered to be a key element in regulating the mechanical characteristics of the composites throughout their investigation.

El-Hadad S. et al. [89], utilizing a vacuum centrifugal investment casting method, demonstrated a novel

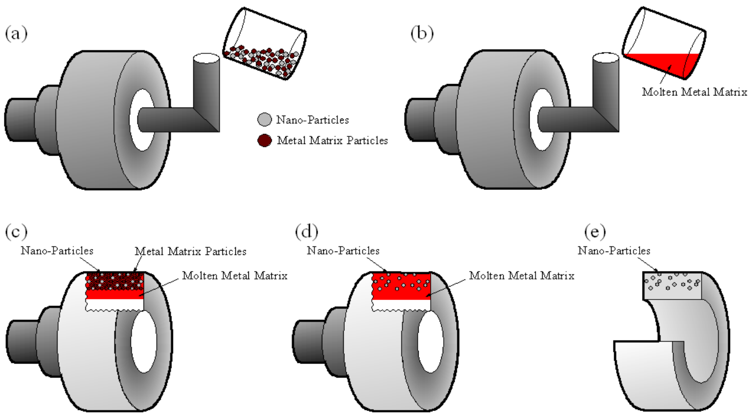


Fig. 2 The schematic illustration showing the process of the centrifugal mixed-powder method [55].

approach for casting titanium implant alloys (Ti-6Al-7Nb) and (Ti-6Al-4V) and their calcium phosphate coating. This one-step, self-coating method produced functionally graded biomaterials using calcium phosphate-Titanium alloys. They also looked at in-vitro cytocompatibility testing, in-vivo systemic toxicity testing, and osseointegration testing. These findings demonstrate that FGBMs of Ti-6Al-4V/calcium phosphate coating produced by centrifugal casting as self-coated dental implants have high bio-compatibility and osseointegration.

3.2 Squeeze casting method

Squeeze casting creates FGMAs that include melting and pouring the material into a mold, adding reinforcing particles and stirring to achieve uniform distribution, and squeezing the soft material through a die to produce the completed product. Because the material obtained is near-finished, this technique generally requires minimum post-manufacture finishing. Critical processes such as degassing, mold preheating, pouring, and squeezing are done to get excellent casting for aluminum-based FGM. For metal-ceramic FGMAs, additional procedures such as preheating the reinforcing component, adding it to the melt, and stirring it again before squeezing are done [90].

Using the squeeze casting process, Reihani et al. [91] investigated the effect of SiC reinforcing particles on the mechanical characteristics, aging behavior, and wear parameters of an aluminum-based material (A6061 alloy). According to the findings, this processing approach yielded an almost pore-free cast with a uniform dispersion of the SiC particles. In addition, the wear resistance and strength of the material appear to be increasing, while the flexibility appears to be decreasing.

3.3 Sequential casting method (The liquid-liquid casting method)

Successive Casting, also known as the liquid-liquid casting process, creates FGMAs by filling molds with liquid alloys or composites. Poor adhesion between the layers is a problem when processing FGMAs by sequential casting if the processing parameters like the pouring temperature, duration, and sequence are not controlled appropriately. Sequential casting is utilized under the most cost-effective casting processes for producing FGMAs components. According to the successive sequential casting of A319 and A390 aluminum alloys, the hardness values of the consecutive gravity cast A319 and A390 aluminum alloys are 70 HB in the A319 area and 130 HB in the A390 Al alloy zone [92].

By employing a sequential casting, Mazare L. et al. [93] demonstrated the capacity to produce copper–silver functionally graded alloys having a chemical composition gradient along one direction of the cast. The Ag-5 wt.%Cu alloy and Cu-20 wt.%Ag alloy were used as base alloys to form FGMA. This experiment achieved a progressive chemical gradient by adding the two base alloys sequentially. The results indicated that two material additions generated a smooth, controlled gradient transition in the Ag–Cu alloy system.

Liquid-liquid configuration bi-metal casting is a process that uses two separate gating systems to fill the mold cavity in two stages. The patented method (Zic et al., [94]) allows for risk-free operation with hammers made of extremely wear-resistant chromium cast iron coupled with highly impact-resistant steel. This technique enables the use of hammers that combine the abrasion resistance of chromium white iron with a hardness of up to 64 HRc and the toughness of alloyed tempered steel with a toughness of 28 – 32 HRc.

The liquid-liquid technique (obtained by pouring and casting two alloys) produced a highly hard surface area with good wear resistance and a high bending strain resistance core. This method allows the production of rolls with a working surface hardness of 100 HSH, which are more resistant to wear than rolls made from a single alloy. Bi-metal casting rolls of various cast iron grades are critical in producing rolls for various rolling-mill stands. Every detail imprints a unique macro and microstructure on each roll [95, 96].

Adel Nofal [97] studied the hard alloy iron of nickel-chromium white irons (Ni-hard cast iron) on the working layer and soft grey iron or ductile cast iron core depending on the use of double-poured cast iron rolls for steel mill stands. A high-alloy cast iron is poured into the mold to form an outer shell of the desired thickness. After that, the gray or ductile cast iron is poured to form the core and remove the remaining un-solidified high alloy cast iron through the upper outlet. High wear resistance, form stability, and an excellent surface polish are all attributes of the shell matrix with appropriate carbide and graphite dispersion. The softer core provides solid mechanical characteristics as well as heat and mechanical load resistance.

Charanjeet Singh et al. [98] showed centrifugal casting of doubly poured cast iron rolls. Dual cast iron was used in the production of the rollers. Dual cast iron comprises two layers: the outer layer is harder than the inner layer, with a hardness of 550 HB, while the inner layer is softer, with a hardness of 300 HB. The first, more rigid outer layer was poured from one side of the roller die using a hopper-like device. After pouring the harder layer from one side of the roller die, it is rotated for a while before the next layer of molten material containing silicon is poured from the opposite side of the roller die.

Mohamed Ramadan et al. [99] recently explored bimetal casting using the liquid-liquid method to create a bimetal of two hyper- and hypo-eutectic aluminum alloys: Al–21 wt% Si and Al–7.5 wt% Si, respectively. The results indicated that a bimetal material was effectively produced in a permanent mold casting utilizing a liquid-liquid casting process with a time interval of 10 s. A novel structure was created with a bimetal and a eutectic interface with a thickness of 70 µm. This structure varies significantly from that produced utilizing a more extended period of more than 10 seconds, revealing an unsatisfactory interface bond due to shrinkage cavity and oxides. The increasing hardness at the upper layer of 117.5 HV than the lower layer of 76 HV corresponds to changes in Si content and other alloying elements. The control of the solidification time and time interval during the double pouring seems to be a viable strategy for fabricating liquid–liquid bimetal materials.

3.4 Cast-decant-cast process

Scanlan et al. [100] and Chirita et al. [101] employed Cast–Decant–Cast (CDC) method to fabricate Al–Si alloy FGM pistons. To make functionally graded light alloys, the CDC method was created. According to CDC process, two alloys are poured separately. The first alloy is poured into a mold and kept for designing time to form a solidified layer of the desired thickness. Then, the remaining un-solidified molten of the first alloy is decanted, and the second alloy is poured into the mold.

Anandavel B. et al. [102] used the CDC method to study the production as well as characterization of FGM of Al–Si alloys. The CDC method made a cylindrical component of functionally gradient Al alloy with high silicon on the outside and low silicon in the center. The component was made by pouring a high Si–Al alloy into a cylindrical mold first, decanting the un-solidified liquid after the alloy solidified to the desired thickness against the mold walls, and then pouring the low Si–Al alloy at superheated temperature, causing the first alloy to partially re-melt, resulting in FGM region between the two alloys. The microstructure findings revealed a progressive shift in Si particle concentration and the existence of a coarse-grained structure. As a result, hardness fluctuated from the outer surface (94 VHN) to the core (60 VHN), corresponding to the shift in Si content in the CDC alloy. The hardness of the FGM area decreased, increasing the distance from the outside surface. The microstructural properties of the CDC alloy in the various zones were confirmed in this way.

3.5 Compound casting method (The liquid-solid casting method)

The granular or monolithic insert (the element that enriches the surface) is immediately inserted in the mold before the molten metal is poured into the compound casting process or liquid-solid production technique. Cholewa et al. [103] studied a bimetallic layer casting technique in which the working part (layer) is made of ferritic and austenitic stainless steel. In contrast, the bearing component is made of grey cast iron. Before pouring gray cast iron into the mold cavity, a surface coating of 2 or 5 mm thickness steel is applied. The best results are obtained when the plate thickness is 5mm. The use of thinner plates with a thickness of around 2 mm distorts the pouring process, disqualifying this layer casting for industrial applications.

Liquid–solid bi-casting technique for high chromium cast iron and medium carbon steel bimetal for mineral processing was developed by Xiong et al. [104]. This investigation revealed that the volume ratios of liquid to solid substantially impact interfacial microstructure. The requirement to warm the steel plate (monolithic insert) put in the mold was an economic constraint of the liquid-solid bi-metal casting technique. Preheating the plate inserts would reduce the overall yield of the production process.

Aina Opsal Bakke et al. [105] recently published a paper describing a unique hot-dip Sn-coating technique for copper as insert and A356 aluminum alloy as matrix via compound casting. This approach exhibited an excellent bond between A356 and pure copper. Tensile testing revealed that the bimetal interface could achieve a maximum tensile strength of 90.8 MPa.

Guangyu Li et al. [106] investigated the influence of using a technique of coating the insert A356 with a new Ni-Cu composite as an interlayer to improve the bonding between aluminum alloy (A356) and magnesium alloy (AZ91D) bimetal made by compound casting. The findings revealed that the interlayer of the Ni-Cu composite successfully inhibited the formation of brittle as well as hard Al-Mg intermetallic compounds.

4. Applications Areas of FGMs

A clever mix of material composition and manufacturing methods increases FGMs' economic potential. The FGM idea is a method for integrating incompatible features like wear and corrosion resistance, thermal toughness, and machinability into a single component. This has increased the use of FGMs in a variety of fields. As a result, FGMs with gradient characteristics are used in various industries, including aerospace, automotive, machinery and equipment, biomaterials, electronics, and energy [13, 31]. Table 1 shows the variety of FGMs applications [13].

5. Scope of the Research Work, the Future Trends, and Recommendations

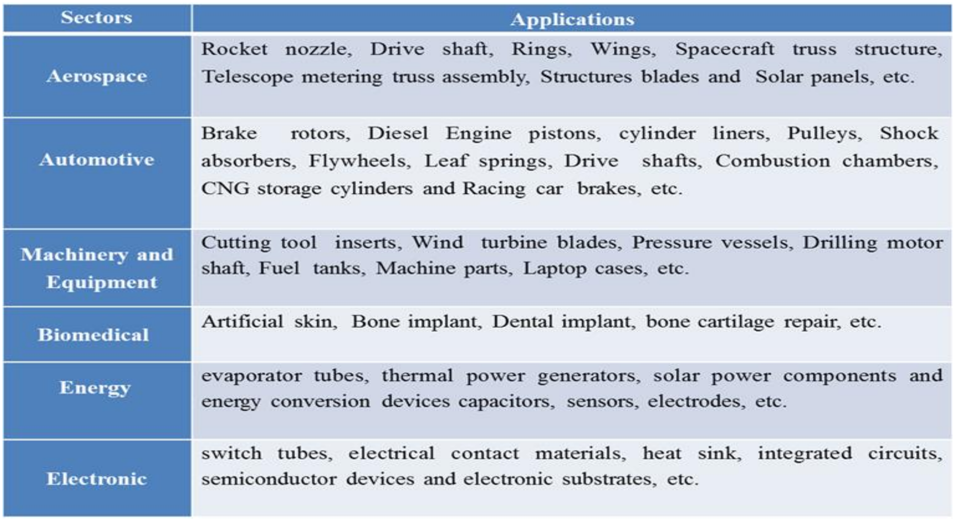
5.1 Scope of the research work

FGMAs are a novel type of heterogeneous composite materials defined by a continual change of characteristics in at least one direction to satisfy the demands of industrial development applications. However, there are still difficulties in the way of attaining this goal. Many studies on successful manufacturing methods for FGMAs are already underway; nevertheless, there are still a number of problems that need to be addressed with these emerging technologies. More research is required to build a significant database, including thorough characterization of FGMAs and the development of prediction models for optimal process management, allowing for the creation more effective FGMAs. There is a requirement for an effective feedback system in fully evolved automated production systems; consequently, a significant study is necessary for overall process control enhancement. The entire process performance will be enhanced by employing these tools, lowering the cost of FGMAs, and increasing the fabrication process' dependability.

Each established technique has its own restrictions, and further study is needed to achieve perfection in FGMAs manufacturing. Centrifugal casting is highly effective for fabricating continuous gradient FGMAs; however, the limited produced components are due to their cylindrical or symmetric shapes. Squeeze casting allows for creation of a continuous FGMAs structure with improved FGMAs characteristics. However, the reinforcing function was pre-papered due to various restrictions connected with high manufacturing costs. Although the sequential casting technique and cast-decant cast are low-cost and environmentally friendly methods, further study is needed to effectively manage processing parameters and obtain optimum thickness, bonding, and gradients. Compound casting, also known as a liquid-solid casting, is more straightforward than liquid-liquid casting. This is because the liquid–liquid method requires two furnaces for two different melting point alloys. The requirement to warm the metal insert inserted in the mold and the surface coating of the insert to promote bonding between two alloys is an economic restriction of the liquid-solid casting process.

5.2 The future trends and recommendations

Table 1 Application areas of FGMs [13]



Sectors	Applications
Aerospace	Rocket nozzle, Drive shaft, Rings, Wings, Spacecraft truss structure, Telescope metering truss assembly, Structures blades and Solar panels, etc.
Automotive	Brake rotors, Diesel Engine pistons, cylinder liners, Pulleys, Shock absorbers, Flywheels, Leaf springs, Drive shafts, Combustion chambers, CNG storage cylinders and Racing car brakes, etc.
Machinery and Equipment	Cutting tool inserts, Wind turbine blades, Pressure vessels, Drilling motor shaft, Fuel tanks, Machine parts, Laptop cases, etc.
Biomedical	Artificial skin, Bone implant, Dental implant, bone cartilage repair, etc.
Energy	evaporator tubes, thermal power generators, solar power components and energy conversion devices capacitors, sensors, electrodes, etc.
Electronic	switch tubes, electrical contact materials, heat sink, integrated circuits, semiconductor devices and electronic substrates, etc.

Future trends and suggestions for FGMAs are inclined to be in five directions based on the facts provided in this research, as the points of my perspective are as the followings:

- The characteristics of functionally graded metallic materials are optimized according to the application requirements.

- For high-quality, defect-free products, optimize the parameters-driven casting process.

- Simulation or modeling is used to improve manufacturing processes and part design.

- Development of a processing technique for mass manufacturing and upgrading current processes, repeatability, dependability, high quality, free-defect castings, and saving cost are priorities.

- Development of a novel functionally graded metallic matrix nano-reinforcement family for various applications, including aerospace, automotive, and biomaterials.

6. Conclusions and Remarks

The following conclusions may be drawn from the information presented in this review:

1. FGMs are a novel type of heterogeneous composite materials defined by a continual change of characteristics in at least one direction to satisfy the demands of industrial development applications.
2. The FGM idea integrates incompatible features like wear and corrosion resistance, thermal toughness, and machinability into a single component.
3. FGMAs with gradient characteristics are used in various industries, including aerospace, automotive, machinery and equipment, biomaterials, electronics, and energy.
4. Casting techniques are favored for FGMAs manufacturing because they are cost-effective and capable of producing large-scale products.
5. Centrifugal casting, squeeze casting with stir casting, sequential casting method (liquid-liquid casting), cast-decant-cast, and compound casting (liquid-solid casting) have all been found to be effective techniques for producing various engineering components of FGMAs, such as pipes, shafts, gears, bushings, hammers, and rolls.
6. Casting process variables optimization is the most important task for manufacturing high-quality FGMAs with required characteristics using centrifugal casting, including density, particle size, rotating mold speed, processing temperature, and cooling rate.

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