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# Review on aluminium based functionally graded composites

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ABSTRACT

Functional graded composites (FGC) are artificially tailored heterogeneous materials intended to serve the demand of diverse and contradicting properties. Their application ranges from automobiles, gas and oil industries, defence to space. The research reports in this field are scattered. In order to address this, we have attempted to collect the research reports from the field of FGC and critically analysed. This review paper provides a broader picture about Aluminium-based Functionally Graded composites since Al being the lightest commercial metal. The classification of FGCs, fabrication methods used to produce Aluminium-based FGCs are discussed in brief. The properties (microstructure, tensile, wear, hardness) of aluminium-based FGCs are collated and presented. Also, an attempt is made to capture information about the effect of different parameters such as particle size and manufacturing methods on the properties of Aluminium-based FGCs. The applications of aluminium based FGCs and challenges involved in the development of aluminium based FGCs are also brought out.

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## 1. Introduction

In Functionally Graded Composites, the volume and distribution of reinforcement varies from innermost to outermost section thereby providing continuously changing properties and controlled non uniform microstructure. These FGCs have particular applications, such as in situations where higher bulk toughness and high wear resistance are required [1,2]. These days, FGCs are growing as the latest class of advanced materials with wide verity of applications in different fields of engineering and science. Properties of Functionally Graded Materials (FGMs) changes along certain direction because of the change in composition and size variation [3]. FGMs may be composite or single-phase materials whose functional properties change uniformly along one direction. By varying the composition and size of the alloying element or reinforcement in base metal, materials with unique properties can be developed. Materials can be designed for particular function and for dedicated application. The gradual variation in the volume of reinforcement with matrix constituent material forms a non-homogenous structure which provides a gradual variation in properties like wear resistance, hardness, specific heat, thermal conductivity, and different other properties which is critical in many applications [4]. These variations can be achieved by using verity reinforcement particles having different properties, size distribution and morphology in matrix material [5]. Development of different FGMs are motivated by the need for developing the properties in a material which is not available in a single material [25]. Aluminium and its alloys have a large number of applications. They are widely used in industries and for research works because of their excellent and preferable properties such as high stiffness, ductile, higher strength to weight ratio, high thermal strength, stability, conductivity and are easily available as well as less expensive than other easily available and commonly used low-density alloys (Mg, Be or Ti-based alloys) [2]. Aluminium is one of the major materials used in automobile industry. Aluminium and different aluminium alloys and composites are the most commonly utilized materials for composite fabrication [6]. Automobile components are mostly subjected to both thermal and mechanical loads. Aluminium functionally graded material can be a good choice where one material can fulfil the requirement of different properties. Development of different aluminium based FGMs/FGCs with higher desirable properties has a very high potential for future research.

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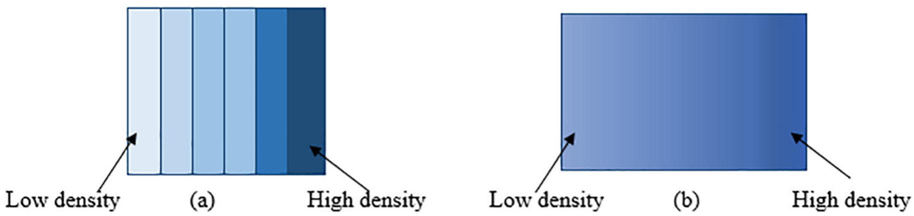


**Fig. 1.** Representation of (a) layered FGM and (b) continuous FGM.

## 2. Classification of FGMs

Different types of FGMs can be produced depending on the reinforcement distribution and manufacturing methods. FGMs are generally classified in different ways. According to the cross section FGM are classified as thin FGM's and Bulk FGMs. Thin FGMs are manufactured by vapour deposition, plasma spraying and other coating methods. Bulk FGMs can be manufactured by different methods such as centrifugal casting and powder metallurgy. Depending on the spatial distribution, they are classified into Layered FGM and Continuous Structured FGM (Fig. 1).

Fig. 1 (a) is a schematic representation of layered FGM, in which the microstructure consists of distinct layers. Layers with darker shades indicate higher density because of higher concentration of reinforcement particles. On the other hand, layers with lighter shades indicate lower density. In contrast, Fig. 1 (b) shows continuous FGM where distribution of reinforcement is not visible in layered manner, but in a seamless, continuous manner.

In layered FGMs the microstructure or distribution of reinforcement changes in layered form. There will be stepwise change in microstructure or distribution of particles. The properties of the material will also vary in the same manner. The problems with layered FGMs are weak interlayer bonding, abrupt change in thermal and mechanical properties such as coefficient of thermal expansion between the adjacent layers, change in Young's modulus. These problems can be eliminated by developing continuous structured FGMs where the composition or the microstructure of the FGM changes continuously in any direction. The continuous gradient materials possess continuous variation in properties like hardness, toughness and strength across the section [3,7]. Depending on the type of gradient FGMs are classified as Size gradient FGMs, orientation gradient FGMs, and shape gradient FGMs.

## 3. Manufacturing processes

Special manufacturing methods are required to produce functionally graded materials. Several methods can be followed like powder metallurgy, Centrifugal casting, thermal spray coating, chemical/physical vapor deposition, sol–gel process and so on are used for processing FGMs. Centrifugal casting is one of the most widely used methods to produce FGMs because of its simplicity and many other unique merits [8,9]. Additive manufacturing is also a fabrication process to develop Functionally Graded Material, from which it is possible to control various parameters like density, volume and material deposition direction by combine different materials [10]. Nair et al., have made a successful attempt to synthesis Al-based SiC reinforced functionally graded material from Gradient slurry disintegration and deposition (GSDD) process [11].

### 3.1. Centrifugal casting

Centrifugal casting is a simple processing method to develop functionally graded materials, which produces symmetric shaped products by using centrifugal force. Centrifugal casting provides upgraded mechanical properties, fine microstructure and clean cast with less porosity. The differences in densities between matrix and reinforcement is the main reason for the gradual distribution of reinforcement materials in the matrix mixture [4,12,13]. The materials with contrast densities are used as matrix and reinforcement, and this difference is favorably used in centrifugal casting. Centrifugal casting consists of pouring liquid metal in a preheated mould and letting molten reinforcement particles to move through the mould due to centrifugal force, leading to dispersal of reinforcement particles in continuously varying manner [9].

Centrifugal casting is classified into two categories based on processing temperature and the melting temperature of master alloy or reinforcement. One is the in-situ method and the other is the solid particle method. If both the matrix material and reinforcement materials are melted during the processing then it is called as in-situ centrifugal casting. If only matrix material is melted then it is called as solid particle technique. In spite of having a virtuous prospective for mass production of FGMs by using centrifugal casting, the controlled distribution of reinforcement or secondary particles is a challenging task [14]. By centrifugal casting a Functionally Graded piston is manufactured using A390 aluminium alloy is with 0.5% Mg reinforcement. Initially Al alloy was melted using a resistance heating furnace. 0.5% of Mg 18 wt % Si is added as reinforcement by gravity and poured into preheated centrifugal casting mould and spinning at 800 rpm until it solidifies completely. From this process, a piston is manufactured which possesses superior properties like excellent wear resistance and low thermal expansion [4]. Different processing parameters that affect the properties of material produced by centrifugal casting are atmosphere around the melt, pouring temperature, temperature of the mould, solidification rate, thermal gradient of the mould, centrifugal force and pouring rate [13]. Fig. 2 shows a simple centrifugal casting machine. A motor drives a preheated cylindrical mould. The molten metal alloy and reinforcement mixture is fed to the mould through a pouring cup. Idler rollers support the rotation of mould.

Boron carbide ($B_4C$) is mixed with preheated bi potassium hexaflourotitanate ($K_2TiF_6$) which acts as flux before mixing it with Aluminium 6061. The procedure used in one of the studies is as follows. An induction furnace was used to melt 5 kg of aluminium in

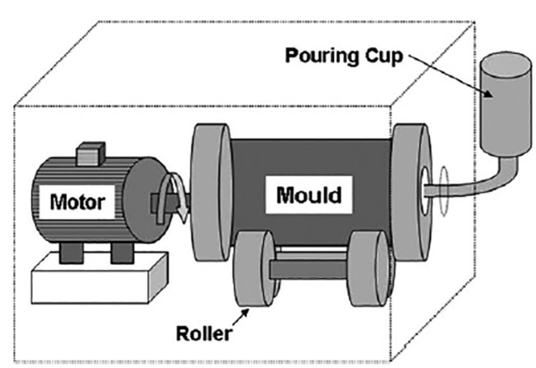


**Fig. 2.** Schematic diagram of the Centrifugal casting machine [15].

graphite crucible. A Mixture of bi potassium hexaflourotitanate (Flux) and boron carbide was then added to the melt at 900 °C. The melt and flux mix was allowed for 2 min, at that temperature for the flux metal reaction. This mixture was further poured into the mould that was preheated to 250 °C and coated with Zircon and rotated at 1100 rpm and 600 rpm to get two specimens of functionally graded materials [9].

Vieira et al., studied the influence of processing conditions such as mould rotating speed, reinforcement particle density on volume fraction of SiC particle reinforcement in aluminium metal matrix with average SiC particle size of 37.8 μm. SiC particle reinforced Aluminium functionally graded material was produced. The procedure was followed carried out in two steps. First with stir casting succeed succeeded by centrifugal casting. A homogenous metal matrix composite was produced first, then this homogeneous composite was melted at 850 °C under Ar (Argon) atmosphere. After melting, the material is casted using centrifugal casting machine which was previously rotating at a selected speed. Different speeds of 1500 rpm and 2000rpms were used to produce the samples of FGC. To compare the samples with the standard, unreinforced aluminium alloy was cast by centrifugal casting at the temperature of 850 °C and at a speed of 1500 rpm [12].

### 3.2. Powder metallurgy

Powder metallurgy is also an important manufacturing process to produce FGMs. The literature cites many works carried out using powder metallurgy. Due to the wide range of control over composition, microstructure and capability of shape forming powder metallurgy is widely used technique to produce FGMs. This process also minimizes the cost and shrinkage mismatch between the layers of FGMs [16]. Powder metallurgic method to produce FGM involves a mixture of materials in powder form according to the predefined distribution, stacking layers of materials according to the distribution requirement and finally sintering. Temperature, pressure and time of sintering process have significant influence on the properties of FGMs produced by powder metallurgical process [16]. Gorkem Kirmizi et al., has studied mechanical and ballistic behaviour of SiC reinforced aluminium foam composite. Powder metallurgical method is used to form aluminium (Al7075) and SiC layered foam composite. With five different compositions of Al7075 and SiC mixture with first layer as aluminium foam and 15, 30, 45 and 60 percentage of SiC particles by weight respectively are used for subsequent layers. Al7075 and SiC powders stacking were compressed at different pressure and sintered in multiple temperatures as a part of the powder metallurgy method, eventually, five-layered functionally graded foam materials (FGFMs) with alternate FGM layers of Al7075/SiC and AA7075 foam were obtained [17]. In another work, a new facility was designed and developed to produce FGMs by powder metallurgy (PM) processing route. AlSi graded composites with 0–2 wt% CNT (carbon nanotubes) reinforcement were used to for producing functionally graded engine piston rings [15]. Salama et al., have produced functionally graded aluminium composite with CNT as reinforcement. In this work the composition gradation was maintained along the radial direction of the functionally graded composite cylinder. For this process, the Al-CNT mixture was produced using a technique called High energy ball milling process. The cylinder was made of four layers, first and the innermost layer was made of unmilled pure aluminium, the second layer is made of milled pure aluminium third layer was made of a mixture of 1% CNT in Aluminium and the last and the topmost layer was made of 2% CNT mixed with pure aluminium. Pure unmilled aluminium was used in the innermost layer of the cylinder, to provide the overall ductility of the material. Powder metallurgical method is used to produce the composite. Test results show that the cylinder surface made of 2% CNT aluminium mixture at the top layer shows higher strength and hardness [18]. Michael et al. have studied a model to reduce porosity of particle reinforced metal-ceramic composites for functionally graded materials by the method of pressure less sintering. Nickel and alumina powders were used for pressureless sintering and changes in porosity and shrinkage were captured and mathematical models were developed to understand the behavior of porosity and shrinkage [19].

### 3.3. Thermal spraying

After the development of modern instruments and processes, thermal spraying or high-temperature coating is widely finding applications in aerospace, military and commercial applications. Many techniques are used in thermal spraying processes such as flame spray, thermal barrier coating, plasma spray, High Voltage Oxy fuel spray (HVOF) Electric arc wire spray, etc. Different methods are carried out at different operating temperatures. Plasma spraying used temperature ranging from 1200 °C to 1600 °C, whereas electric arc spray was carried out at around 4000 °C. Flame spraying and HVOF spraying uses combustion and electric arc spraying used electrical current to melt the coating materials. Plasma spray coating produces good results when it is carried out at lower-pressure which is Low pressure plasma spray (LPPS) or Vacuum Plasma Spray (VPS) system [14]. Shi et al. has fabricated functionally gradient aluminium alloy using thermal spray deposition method, SiC particles are deposited on Al6066 aluminium alloy by spray deposition technique accompanied by an automatic control system. Average size of SiC particles used were of 8 μm. A special device was employed to produce the deposition FGM. The reinforcement particles were made to deposit on molten aluminium alloy in a controlled manner to produce the FGM [5].

### 3.4. Laser cladding

In laser cladding or laser deposition method, a layer of deposition of ceramic or metal powder on the base material is carried out using high intensity of LASER. On the base metal surface, a high-power LASER beam creates a molten pool and then by using nozzles, powder materials were injected into the molten pool. On the surface of the base metal the molten pool absorbs the injected powder and creates a layer of deposit delivered by the nozzle. This method is used when there is a larger difference in melting temperatures of base metal material and reinforcement material. This can be used to deposit layers only on required specific areas also [14].

## 4. Effect of particle size on aluminium FGCs

Vieira et al. have studied the effect of SiC particle with an average particle size of 37 μm reinforced aluminium FGC. Centrifugal casting process is followed to get a gradual distribution of reinforcement material in aluminium matrix at different speeds. For a particular speed, as the reinforcement particle fraction changes from 0 to maximum percentage from inner region to the outer region, it is observed that the rate of change of wear coefficient is more only up to 5% reinforcement. The rate of change in wear coefficient was less for incorporating more than 5% of reinforcement [12]. Most of the researches in FGC concentrates on processing techniques, characterization and effect of presence of reinforcement and distribution of particles. The controlling of distribution of particles depends on process parameters used in the fabrication of materials. But there is a lot of scope for the study of effects of variation in size of reinforcement particles on different properties of FGCs. Velhinho et al., made a study on the effect of particle grain size on reinforcement distribution on Al/SiC$_p$ (Aluminium-Silicon Carbide) FGM matrix composite produced by centrifugal casting. It has been observed that reinforcement with higher particle size gives higher hardness throughout the material [13].

## 5. Properties of aluminium based FGCs

### 5.1. Microstructure

Rajan et al., has studied the distribution of SiC (Silicon Carbide) particle in Aluminium-based Functionally Graded composite used for brake rotor disc, produced from centrifugal casting method. The particle size used for the study were of 23 μm in an average [20].

It can be seen that at the region 15 mm from the surface the reinforcement particles are more when compared to the other two regions at 45 mm and 75 mm from the surface (Fig. 3). This is because of the higher density of reinforcement (SiC) particles. This higher density reinforcement particles are enriched at outer region due to the centrifugal force, as the distance from the surface increases the volume of SiC particles decreases. This change in volume fraction from the surface to the inner area influences the hardness and wear behavior of the FGM [20]. Salama et al., have fabricated CNT reinforced aluminium based FGC, by the method of powder metallurgy. Fig. 4 shows the optical microscopic images of CNT reinforced FGC aluminium material focusing the interface between different layers. It can be seen that all layers have different morphologies because of their composition and particle size [18].

X. Lin et al. have fabricated Al-Si-Mg functionally graded materials in the form of hollow cylinders reinforced with in-situ Si/Mg$_2$Si particles. Microstructure images were captured and a detailed observation of microstructure details through the wall thickness of the centrifuge cast was carried out over the entire cross-section at different regions. From the observation made from microstructural images, it is found that there was a graded distribution of primary Si (Silicon) and Mg$_2$Si (Magnesium Silicate) particles from the inner wall to the interface layer as shown in Fig. 5. Large number of primary Si particles and Mg$_2$Si particles were found in the inner layer. However, in outer layer, they were few because of the chill region [21].

### 5.2. Tensile strength

Carvalho et al. carried out works on CNT reinforced aluminium alloy for manufacturing Functionally Graded Piston Rings. In this study, Functionally Graded pistons are manufactured with 0% 2%, 4% and 6% of reinforcement which is CNT. Observations suggests that the specimen with 2% CNT (carbon Nanotubes) reinforcement shows there was a considerable increase in tensile strength value when compared to the other percentages of reinforcement. As the presence of CNT in matrix material improves its mechanical property, but a higher percentage of CNT reinforcement forms agglomeration or concentration of reinforcement particle at one place. This acts as a stress concentration zone and decreases the mechanical properties for a higher percentage of reinforcement [15]. Dinaharan has studied the effect of different ceramic particles such as $Al_2O_3$, SiC, TiC, $B_4C$ and WC on tensile strength of aluminium metal matrix composite produced by in situ stir casting method and concluded that the type of ceramic material did not considerably vary the microstructure and ultimate tensile strength, but the use of TiC reinforcement has superiorly increased hardness and wear properties of aluminium metal matrix composite [22]. Salama et al., have studied tensile behavior of CNT reinforced FGC, processed by powder metallurgical method. According to the standards, without losing the gradient behavior of the material. Care has been taken to produce specimen such that, the material gradation has not varied in the process of machining a specimen. All the specimens fractured in the middle of the specimen, the type of fracture appeared to be mixed ductile and brittle fracture. From the results of the tensile test, it is observed that when compared to

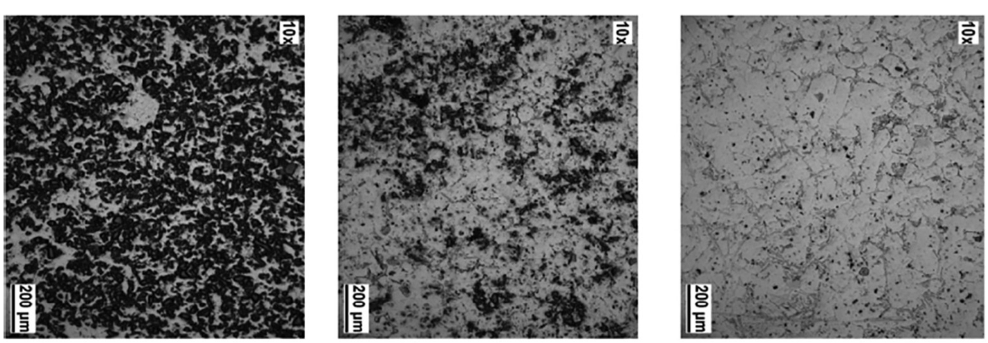


**Fig. 3.** Distribution of SiC particles at Regions (a)-15 mm from the surface (b)-45 mm from the surface (c)-75 mm from the surface [20].

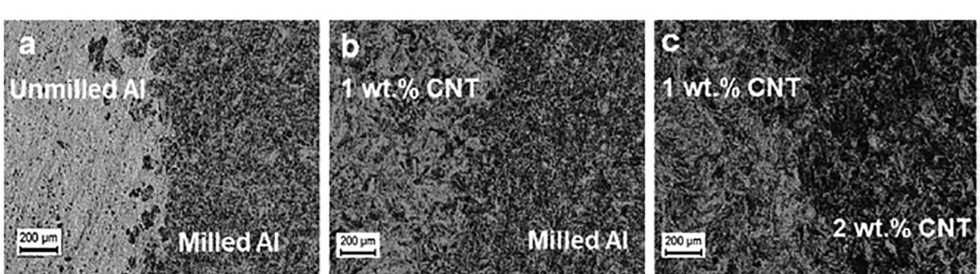


**Fig. 4.** Image showing the interface layer between unmilled and unmilled Al (a), milled Al and 1 wt% CNT (b), and 1 wt% CNT and 2 wt% CNT (c) [18].

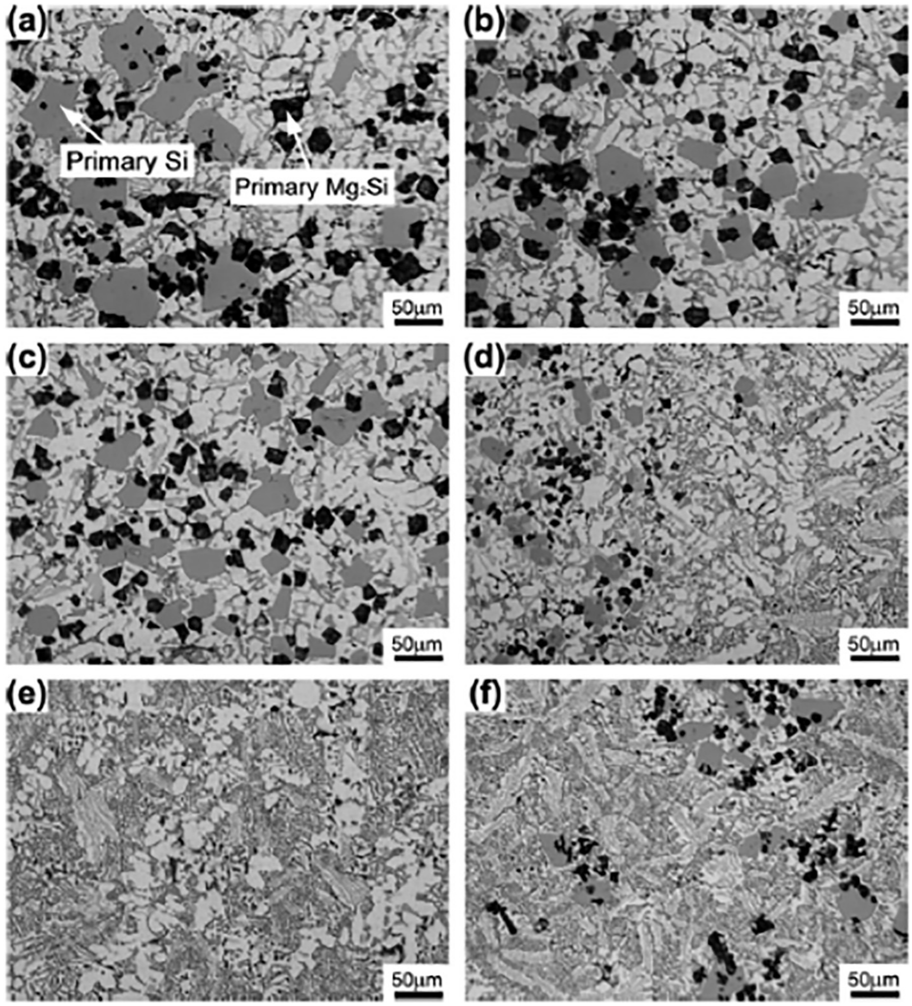


**Fig. 5.** Microstructure of Al-Si-Mg functionally graded materials of hollow cylinder shape reinforced with in-situ Si/$Mg_2Si$ particles showing different regions which are at 1.5 mm (a), 3.5 mm (b), 5.5 mm (c), 7.5 mm (d), 10.5 mm (e) and 13.5 mm (f) distance along the radial direction from inner wall [21].

1% CNT reinforced homogeneous composite material, FGC exhibited a remarkable hike in tensile strength. On average, a 107% increase in tensile strength and a 10% increase in tensile strength was observed in comparison with pure Al and 1% CNT reinforced homogeneous composite material [18].

### 5.3. Wear

Vieira et al. have studied the parameter of dry sliding wear of Functionally Graded aluminium composite reinforced with SiC (Silicon Carbide) particles. A non-commercial aluminium alloy was selected for the matrix material and particles of SiC as reinforcement. By using centrifugal casting process, a Functionally Graded material of cylindrical shape is manufactured. In the manufactured specimen, three regions are identified at three different radial distances and they have named as R1, R2 and R3 from the inner periphery. Sliding wear property of material was considered for the study using the ball on pin setup at room temperature with the load of 3 N and velocity 0.5 m/s. It is observed that only in zone R3 the coefficient of friction was high where the reinforcement SiC particle is more. This is because the very hard reinforcement particles are protruded on the surface leading to an increase the surface roughness and it protects the matrix material to come in contact with counter body reducing area of effect contact between matrix materials and counter body [12]. Humberto Melgarejo et al. have studies wear behavior of aluminium based FGC reinforced with diboride, manufactured by centrifugal casting. Unlubricated ball on disc test was conducted to both on external and internal zones of the manufactured sample. The test was conducted at a constant speed of 0.0066 $ms^{-1}$. From the results of the test, it was observed that due to the reason that volume density of boride particles are more at the external region (outer region) the wear resistance was higher. On the other hand, along the internal regions wear resistance gradually decreases, due to the gradual variation of volume percentage of boride in the FGC [1].

### 5.4. Hardness

Hardness is the fundamental mechanical properties which is affected by microstructure and internal deformation of the FGC. Different factors that influences the hardness of FGCs are particle size, relative density, sintering conditions, boundary conditions and phase transition. Chin-Yu Huang et al. have studied the different mechanical behavior of $Al_2O_3$-$ZrO_2$ (Aluminium Oxide and Zirconium oxide) 4 layer and 11 layers functionally graded material, fabricated by powder metallurgical method. It was found that the hardness of the material did not remarkably changed in both types of FGMs when compared with the non-FGM specimen. Whereas in non-FGM specimen increase in $ZrO_2$ decreases the hardness [23]. Aluminium based $SiC_p$ reinforced Functionally Graded Material is manufactured using centrifugal casting method. In this process, 15% of SiC particles are reinforced with aluminium (3 5 6) and aluminium (2124). After processing it is found that 40 to 45% of reinforcement was found near the outer periphery of the centrifugally casted material. The maximum hardness is found in the outer periphery and it was 155 BHN and145 BHN on Al (3 5 6) and Al (2124) reinforced with SiC particles respectively after heat treatment [20].

## 6. Applications of aluminium based FGCs

Functionally graded materials have pulled in light of a legitimate concern for the defence manufacturing industry, FGMs are best suited for light armours, owing to their superior properties [17]. As aluminium and its alloys are one of the lightweight materials, these will find a wide range of applications in different fields of engineering. Aluminium based functionally graded materials can be used when there is a need for material with different properties at different portions of a part. Components with high toughness in inner cross section and harder at outer cross section with enhanced wear-resistant material can be made to satisfy different applications in automobile, aerospace etc. VinothBabu et al. have fabricated SiC reinforced aluminium FGC brake rotor disc by centrifugal casting method, the characteristics were studied using optical microscope and image analysis technique. Brinell hardness test is conducted to measure the hardness of the material at different regions of the rotor disc as per ASTM E10 standards [8]. The performance of a pair of gears in terms of effectiveness, power transmission, and life of the gear relies upon its material, rotational speed and other working conditions. In applications like aerospace, it demands higher performance with lightweight materials. In such conditions, FGCs can be used. Mehdi Bayat et al., has studied stress analysis of functionally graded gear wheels with variable thickness. From the results obtained in this work we can conclude that a Functionally Graded gear wheel with hyperbolic convergent and parabolic concave thickness profile is more appropriate when compared with that of uniform thickness [24]. Piston rings are conventionally manufactured by casting process and subsequent finishing operations followed by electrodeposition and chromium coating. In order to improve wear resistance of the piston ring, it is coated with a hard coating. Main problem in this type of coating is the variation in the coefficient of thermal expansion is between metal and coated ceramic material. This results in delamination of the coating at higher temperatures. The above-mentioned problem can be eliminated if the ring provides strength and modulus and at the outer surface, it should provide wear resistance property. Carvalho et al. have developed AlSi-CNT (carbon nanotube reinforced aluminium silicate) functionally graded material with the desired properties engine piston rings [21]. Aluminium matrix composite materials and silicon alloys have found application in manufacturing of different automotive parts such as piston rings, cylinder blocks, piston, brake rotors in which wear is predominant process [6].

## 7. Challenges in aluminium based FGCs

As FGMs are being developed as one of the emerging smart materials, it is very essential to increase the number of researches on FGCs but to develop FGC there are some challenges. A few of the challenges in developing Aluminium-based FGCs are mentioned below.

- Higher density difference between aluminium and reinforcement causes difficulty in manufacturing FGC from simple processing techniques such as stir casting, injection moulding etc.
- Proper processing technique is to be developed for manufacturing Aluminium-based FGCs.
- Understanding the process parameters and the influence of process parameters on the distribution of material is difficult.
- The problem in machinability would increase because of particle size differences, hence machining parameters are to be standardized for different operations [8].

## 8. Summary

Functionally Graded Composites are growing as one of the most promising materials for different applications. The properties of functionally graded composites change with constituent materials and type of particle distribution. Manufacturing method and processing parameters have a vital role in controlling different properties of FGCs. Different manufacturing processes such as centrifugal casting, powder metallurgy, thermal deposition methods, laser cladding, thermal spraying etc., can be followed to produce aluminium based FGCs. From different literature studies, we can conclude that Powder metallurgy and Centrifugal casting are the economical and simple methods to produce aluminium based FGCs in bulk. But controlling different parameters in the process needs to be addressed. These aluminium FGCs can be used in different applications such as manufacturing of different automobile parts like piston rings, brake rotor disc, gear wheels etc., with better properties than the conventional homogeneous composite materials. The tensile strength, wear-resistance and hardness of the of aluminium based FGCs increases with increasing percentage of ceramic materials, but a higher concentration of these ceramic particles at few regions increases porosity and agglomeration which reduces the required properties. As the density of aluminium is less, controlling the distribution of reinforcement particle is one of the challenges in the production of aluminium-based FGCs. Most of the works on aluminium FGCs focuses on the effect of ceramic particles such as SiC (Silicon Carbide), $B_4C$ (Boron Carbide), TiC (Titanium Carbide), WC (Tungsten Carbide), $Al_2O_3$ (Aluminium Oxide), $Al_2Cu$ (Aluminium Copper) etc. as reinforcement in aluminium metal matrix to produce Aluminium-based FGCs. There is an opportunity to explore the effect of various materials as reinforcement on the properties of FGCs.

## CRediT authorship contribution statement

**S.N. Naveen Kumar:** Writing - original draft. **R.M. Devarajaiah:** Visualization, Supervision, Investigation, Writing - review & editing. **T. Ram Prabhu:** Conceptualization, Methodology, Supervision, Validation, Writing - review & editing.

## Declaration of Competing Interest

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

## References


[1] Z. Humberto Melgarejo, O. Marcelo Suarez, Kumar Sridharan, Wear resistance of a functionally-graded aluminium matrix composite, ScriptaMaterialia 55 (2006) 95–98.

[2] Z. Humberto Melgarejo, O. Marcelo Suarez, Kumar Sridharan, Microstructure and properties of functionally graded Al-Mg-B composites fabricated by centrifugal casting, Composites: Part A 39 (2008) 1150–1158.

[3] T. Ram Prabhu, Srikanth Vedantam, Layer-graded Cu/$B_4C$/Graphite hybrid composites: Processing characterization and evaluation of their mechanical and wear behavior, Tribol. Trans. 58 (2015) 718–728.

[4] A.G. Arsha, E. Jayakumar, T.P.D. Rajan, V. Antony, B.C. Pai, Design and fabrication of functionally graded in-situ aluminium composites for automotive pistons, Mater. Des. 88 (2015) 1201–1209.

[5] J.L. Shi, H.G. Yan, B. Su, J.H. Chen, S.Q. Zhu, G. Chen, Preparation of a functionally gradient aluminum alloy metal matrix composite using the technique of spray deposition, Mater. Manuf. Processes 26 (2011) 1236–1241.
[6] R.L. Deuis, C. Subramanian, J.M. Yellup, Dry sliding wear of aluminium composites- A review, Compos. Sci. Technol. 57 (1997) 415–435.
[7] T. Ram, Prabhu, Processing and properties evaluation of functionally continuous graded 7075 Al alloy/SiC composites, Arch. Civ. Mech. Eng. 17 (2017) 20–31.
[8] K. VinothBabu, S. Marichamy, P. Ganesan, D. Madan, M. Uthayakumar, T.P.D. Rajan Processing of functionally graded aluminium composite brake disc and machining parameters optimization Materials Today: Proceedings, (2019) in printing.
[9] A.G. Rao, M. Mohape, V.A. Katkar, D.S. Gowtam, V.P. Deshmukh, A.K. Shah, Fabrication and characterization of aluminum (6061)-boron-carbide functionally gradient material, Mater. Manuf. Processes 25 (2010) 572–576.
[10] Giselle Hsiang Loh, Eujin Pei, David Harrison, Mario D. Monzón, An overview of functionally graded additive manufacturing, Additive Manuf. 23 (2018) 34–44.
[11] S.M.L. Nai, M. Gupta, C.Y.H. Lim, Synthesis and wear characterization of Al based, free standing functionally graded materials: Effect of different matrix composition, Compos. Sci. Technol. 63 (2003) 1895–1909.
[12] A.C. Vieira, P.D. Sequeira, J.R. Gomes, L.A. Rocha, Dry sliding wear of Al alloy/$SiC_p$ functionally graded composites: Influence of processing conditions, Wear 267 (2009) 585–592.
[13] A. Velhinho, P.D. Sequeira, F. Braz, Fernandes, J.D. Botas, L.A. Rocha, Al/$SiC_p$ functionally graded metal-matrix composites produced by centrifugal casting: Effect of particle grain size on reinforcement distribution, Mater. Sci. Forum (2003) 257–262.
[14] Minoo Naebe, Kamyar Shirvanimoghaddam, Functionally Graded Materials: A review of fabrication and properties, Appl. Mater. Today 5 (2016) 223–245.
[15] O. Carvalho, M. Buciumeanu, S. Madeira, D. Soares, F.S. Silva, G. Miranda, Optimization of AlSi–CNTs functionally graded material composites for engine piston rings, Mater. Des. 80 (2015) 163–173.
[16] Zeming He, J. Ma, G.E.B. Tan, Fabrication and characteristics of alumina–iron functionally graded materials, J. Alloys Compounds 486 (2009) 815–818.
[17] Gorkem Kirmizi, Halil Arık, Henifi Cinici, Experimental study on mechanical and ballistic behaviors of silicon carbide reinforced functionally graded aluminium foam composites, Compos. Part B 164 (2019) 345–357.
[18] Ehab I. Salama, Sherry S. Morad, M.K. Amal, Esawi, Fabrication and mechanical properties of aluminium-carbon nanotube functionally-graded cylinders, Materialia 7 (2019) 100351.
[19] Michael L. Pines, Hugh A. Bruck, Pressureless Sintering of particle-reinforced metal-ceramic composites for functionally graded materials: Part I Porosity reduction models, Acta Materialia 54 (2006) 1457–1465.
[20] T.P.D. Rajan, R.M. Pillai, B.C. Pai, Characterization of centrifugal cast functionally graded aluminium-silicon carbide metal matrix composites, materials characteriz1ation 61 (2010) 923–928
[21] Xuedong Lin, Changming Liu, Haibo Xiao, Fabrication of Al–Si–Mg functionally graded materials tube reinforced with in situ Si/$Mg_2Si$ particles by centrifugal casting, Compos. Part B 45 (2013) 8–21.
[22] I. Dinaharan, Influence of ceramic particulate type on microstructure and tensile strength of aluminium matrix composites produced using friction stir processing, J. Asian Ceram. Soc. 4 (2016) 209–218.
[23] Chin-Yu Huang, Yu-Liang Chen, Effect of mechanical properties on the ballistic resistance capability of $Al_2O_3$-$ZrO_2$ functionally graded materials, Ceram. Int. 42 (2016) 12946–12955.
[24] B.B. Mehdi, Bayat, A.M.S. Sahari, M. Saleem Hamouda, E. Mahdi, On the stress analysis of functionally graded gear wheels with variable thickness, Int. J. Comput. Methods Eng. Sci. Mech. 9 (2008) 121–137.
[25] F.M. Xu, S.J. Zhu, J. Zhao, M. Qi, F.G. Wang, S.X. Li, Z.G. Wang, Effect of stress ratio on fatigue crack propagation in a FGM composite, Compos. Sci. Technol. 64 (2004) 1795–1803.